

Diet of aurochs and early cattle in southern Scandinavia: evidence from ^{15}N and ^{13}C stable isotopes

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Abstract

Stable carbon and nitrogen isotope ratios from ^{14}C dated bones of early Atlantic aurochs (*Bos primigenius* Bojanus) and late Atlantic first domestic cattle (*Bos taurus* Linnaeus) in eastern Denmark and southern Sweden are significantly different and provide information on the origin and feeding strategies of the two species.

Radiocarbon dates generally divide the bone material of aurochs and domestic cattle in three groups: aurochs older than 4000 cal yr BP, an older group of domestic cattle around 4000 cal yr BP, and a younger, less well-defined group of domestic cattle starting at around 3500 cal yr BP. The older domestic cattle are represented mainly by fragmentary bones left over from meals, and deposited in lakes at the vicinity of the settlement areas. Bones of the younger domestic cattle group occur both as settlement debris and as single articulated skeletons in bogs, commonly in association with different types of clay pots. The latter type of finds suggests that sacrifice of domestic cattle began at this time. The dating of the early domestic cattle further indicates that they were contemporaneous with or slightly younger than the elm decline, which occurred shortly after 4000 cal yr BC on the Danish island of Sjælland. Our results indicate a sudden rapid introduction of domestic cattle into Denmark, heralding the introduction of agriculture and there is no evidence for leaf foddering or domestication of aurochs. A combination of several natural events may have created the necessary open land, providing the grazing areas for the imported cattle.

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Keywords: Domestic cattle; *Bos taurus*; Aurochs; *Bos primigenius*; Mesolithic-Neolithic transition; Radiocarbon dates; Stable C and N isotopes; Diets; Scandinavia

1. Introduction

The aim of this study is to use new radiocarbon dates and stable carbon and nitrogen isotope data to throw light on three important questions:

(1) Is it possible isotopically to distinguish native aurochs (*Bos primigenius*) from contemporaneous early domestic cattle (*Bos taurus*)?

(2) When did domestic cattle arrive in southern Scandinavia, Denmark?

(3) Is there a relationship between the arrival of the first cattle and agriculture, the elm decline, the decreasing rate of sea-level rise, the change of the tidal amplitude in Danish waters and the approaching end of the mid-Holocene climate optimum?

All dates presented in the text are given in calendar years before Christ. The corresponding conventional ^{14}C years BP are provided in Table 1.

Radiocarbon dating of aurochs and early domestic cattle bones from Denmark and southern Scandinavia has been undertaken in order to narrow down the time

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Table 1
Radiocarbon dates and calibrated ages, either performed on the bone itself or taken from the dating of the site

Locality	¹⁴ C BP	Cal date BC	Bone/site date
<i>Bos primigenius</i>			
Ulkestrup Lyng Øst 23352-2	8140 ± 120	7050: 7450–6850	Site date
Ulkestrup Lyng Øst 21943	8140 ± 120	7050: 7450–6850	Site date
Ulkestrup Lyng Øst 17590	8140 ± 120	7050: 7450–6850	Site date
Ulkestrup Lyng Øst 23339-1	8140 ± 120	7050: 7450–6850	Site date
Ulkestrup Lyng Øst 1821	8140 ± 120	7050: 7450–6850	Site date
Maglemose 111	8625 ± 60	7600: 7730–7580	
Stokholthusene	9655 ± 110	8975: 9300–8650	
Rønnebæksholm	8350 ± 80	7425: 7530–7320	
Store Tåstrup	9970 ± 90	9600: 9200–10,000	
Knapstrupgård	9920 ± 45	9330: 9390–9370	
Kongsted	7630 ± 90	6490: 6590–6390	
Gundsømagle Nordmark	11060 ± 390	11,000: 11,600–10,400	
Gøderupgård	9020 ± 280	8150: 8550–7750	
Sonnerupgård	8330 ± 45	7410: 7480–7340	
Bisserup	8150 ± 70	7125: 7190–7060	
Brændholt	8580 ± 55	7610: 7680–7540	
Alsønderup	9375 ± 55	8645: 8740–8550	
Prejlerup	8410 ± 90	7500: 7580–7420	
Vig	9510 ± 115	8875: 9150–8600	
Handermelle	9840 ± 45	9275: 9310–9240	
Grønge Mose	9830 ± 60	9268: 9310–9225	
Store Damme	9520 ± 85	8825: 8920–8730	
Tangelsberg	9810 ± 60	9253: 9285–9220	
Frøbjerg Banker	9125 ± 45	8300: 8340–8260	
Knabberup	8985 ± 40	8235: 8270–8200	
Terp Mose	9845 ± 65	9270: 9320–9220	
Tranekær Mose	4455 ± 35	3280: 3330–3230	
Barritskov	9410 ± 60	8675: 8750–8600	
Bellinge	8460 ± 55	7548: 7580–7515	
Tinglev Sø	3600 ± 35	1930: 1980–1880	
Bønnerup strand (small individual)	3860 ± 35	2345: 2410–2280	
Bønnerup strand (big individual)	4525 ± 40	3205: 3240–3170	
Norsminde	6265 ± 55	5255: 5310–5200	
Karleby 10	5490 ± 55	4340: 4370–4310	
<i>Bos taurus</i>			
KLM Åmosen 50.0/76.5:13	5120 ± 65	3875: 4050–3700	Site date
KML Åmosen 49.5/76.0:5038	5120 ± 65	3875: 4050–3700	Site date
KML Åmosen 50.0/79.5:4	5120 ± 65	3875: 4050–3700	Site date
KML Åmosen 50.0/80.5:11	5120 ± 65	3875: 4050–3700	Site date
Husede I	4510 ± 90	3225: 3360–3090	
Muldbjerg Mul-I 690	5050 ± 50	3865: 3950–3780	Site date
Muldbjerg Mul-I 41247	5050 ± 50	3865: 3950–3780	Site date
Muldbjerg Mul I 6018	5050 ± 50	3865: 3950–3780	Site date
Maglemose Vedbæk I	4605 ± 80	3420: 3520–3320	
Verupgårds Mose	4480 ± 70	3245: 3340–3150	
Smakkerup huse	5060 ± 61	3870: 3950–3790	
Smakkerup Huse	5059 ± 68	3870: 3950–3790	
Øgårde (Okse II)	4675 ± 75	3445: 3530–3360	
Sandhuse Mose (Okse I)	4530 ± 70	3170: 3240–3100	
Sandhuse Mose (Okse II)	4580 ± 80	3325: 3650–3000	
Sandhuse C-LXIV	2665 ± 65	845: 900–790	
Sandhuse K-XXXIX	4230 ± 70	2745: 2820–2670	
Åkonge	5135 ± 50	3920: 4050–3790	
Holmene	4770 ± 85	3575: 3650–3500	
Holmene	4960 ± 90	3725: 3810–3640	
Maglemosegård	4620 ± 60	3700: 3760–3640	
St. Lyng	4600 ± 85	3325: 3650–3000	
Øgårde I	5030 ± 90	3830: 3950–3710	
Ærøskøbing	3705 ± 75	2110: 2210–2010	
Visborg BLN 3933	4955 ± 60	3725: 3790–3660	
Visborg CQX 3933	4925 ± 55	3705: 3760–3650	

Table 1 (continued)

Locality	¹⁴ C BP	Cal date BC	Bone/site date
Visborg FHM 3933 JOC	4650 ± 55	3435: 3540–3330	
Borremose	4575 ± 90	3275: 3650–2900	
Siggeneben-Süd SIG 75 41x	4665 ± 50	3460: 3520–3400	
S: 97.5–98 E: 143.4–144	4630 ± 50	3475: 3650–3300	
Siggeneben-Süd SIG 75 2b	4320 ± 45	2955: 3040–2870	
S: 94.5–95 E: 143.5–144	5165 ± 45	3980: 4050–3910	
Rosenhof (B) Ros 74V 880	4910 ± 50	3680: 3720–3640	
Rosenhof (A) Ros 74VI A148i	5865 ± 50	4740: 4800–4680	
Boberg	3780 ± 50	2560: 2990–2130	
Karleby Lokalitete B	4830 ± 50	3610: 3710–3510	
Löddeborg Ruta 16-18	4100 ± 50	2670: 2790–2550	
Löddeborg Provepose 1	4290 ± 150	2850: 3100–2600	

In total 72 dates from early *Bos taurus* and *Bos primigenius* mainly from Denmark and some from northern Europe.

interval for the arrival of the first cattle in Denmark (Fig. 1, Table 1). The radiocarbon dates generally divide the bone material of aurochs and domestic cattle into three groups; aurochs older than 4000 cal yr BC, earliest domestic cattle from 4000 to 3500 cal yr BC, and a younger domestic cattle group, younger than 3500. Results of stable N and C-isotope measurements are presented in Fig. 2 and Table 2. Koch [55] presented a compilation of finds of Danish domestic cattle from bog sacrifices and settlement deposits, and these data are included in Table 1. Finds and dates of early cattle from southern Scandinavia and northern Germany were discussed by Persson [80], while more recently obtained dates on cattle and other domesticates in North Germany are given by Hartz et al. [41]. An archaeological excavation of late Mesolithic and early Neolithic settlements around the small bay Saltbæk Vig in northwestern Sjælland resulted in finds of bones from very early domestic cattle at the late Mesolithic site of Smakkerup Huse (Fig. 1) [43,84].

Significant changes in stable carbon isotope ratios of red deer, roe deer, and six other mammal species over a period of around 3000 years, have already been demonstrated for the late Boreal-early Atlantic site Ulkestrup Lyng (7030 cal yr BC) and the late Atlantic-early Subboreal Muldbjerg site (3700 cal yr BC) both from the Åmose region of central Sjælland, Denmark. These changes are interpreted as reflecting environmental changes [75] (Fig. 1). The isotope values of bones of early domestic cattle from Muldbjerg and of aurochs from Ulkestrup Lyng are significantly different [75,76].

2. Archaeology and chronology

The study area includes eastern Denmark, northern Germany (specifically the northern state of Schleswig-Holstein) and southwestern Sweden (Scania) (Figs. 1 and 2). Our study focuses on the late Mesolithic-early Neolithic time interval. The early and middle phases of the Mesolithic period are represented in Denmark by

the Maglemose and the Kongemose cultures, from the beginning of the Holocene, 9500–5400 cal yr BC. In southern Scandinavia the late Mesolithic period is represented by the Ertebølle culture. The Mesolithic-Neolithic transition in this region took place at 3900–4000 cal yr BC, and slightly earlier in northern Germany [40,41,83]. The early Neolithic period is represented by the Funnel Beaker or TRB culture and comprises two divisions of importance for the discussion [50,83]. The early Neolithic I period (EN I) begins with the onset of the Neolithic and is succeeded by early Neolithic II (EN II) around 3500 cal yr BC [55]. EN I and II correspond to the ages of the two groups of early cattle (Fig. 4). The EN II ends at ca. 3300 cal yr BC with the beginning of the Middle Neolithic.

During Preboreal and Boreal times, representing the oldest part of the Mesolithic, relative sea level around Denmark was tens of metres lower than today. At that time southern Scandinavia was part of the European continent, and Denmark connected with England. This land connection was finally flooded shortly after 7000 cal yr BC followed by the Littorina transgressions during the Atlantic time [20,23,24]. The Littorina transgressions around Denmark mark the end of the major eustatic sea-level rise, a result of the down-melting of the ice caps following the Late Glacial Maximum 20,000 years earlier [35]. However, the rapid isostatic rebound of Denmark postponed the effects of the eustatic sea-level rise to late Boreal and Atlantic times.

2.1. The Mesolithic

The early phase of Mesolithic human occupation of southern Scandinavia is known primarily from inland hunting and fishing summer sites. Major game animals included elk, aurochs, red deer, roe deer and wild boar [73,75]. Later Mesolithic human populations intensively occupied the newly formed extensive coastal habitat created by the rising sea level as Denmark ceased to be part of the European continent and became an archipelago [58,82]. They exploited the marine and

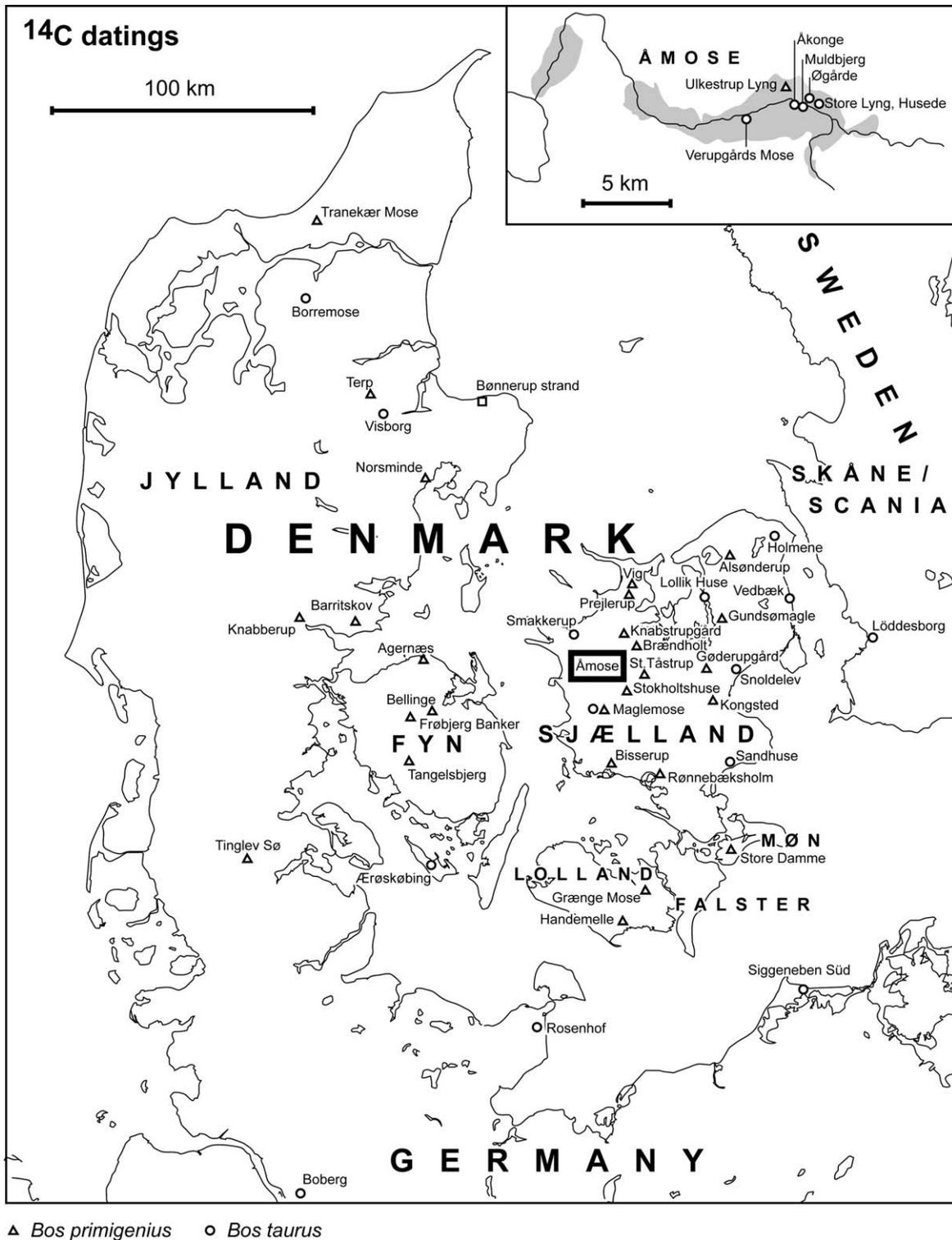


Fig. 1. Map of Denmark showing site locations and ¹⁴C dates of early *Bos taurus* and *Bos primigenius*. Insert map shows localities in the Åmose bog.

terrestrial resources by collecting large quantities of bivalves and by hunting marine mammals, large and small terrestrial game and birds [11,74,75,81,87]. In addition, hazel nuts and a variety of other food plants contributed to the diet. The Mesolithic period was characterized by an elaborate flint technology, boats,

paddles, bows and arrows, art, decoration, and domesticated dogs [9,20,74–76,101]. Pottery and scattered foreign imports appeared in the late Mesolithic, indicating connection with farmers to the south, at least 500 years before the arrival of domesticates to Denmark [36,84].



$^{15}\text{N}/^{13}\text{C}$: ▲ *Bos primigenius* ○ *Bos taurus*

^{13}C only: ▲ *Bos primigenius* ● *Bos taurus*

Fig. 2. Map showing site location of the *Bos primigenius* and early *Bos taurus* providing the stable isotope data of $^{14}\text{N}/^{15}\text{N}$ and ^{13}C . Insert map shows localities in the Åmose bog.

Table 2

Isotope data, bone element, province and lab. no. from 45 individuals of early *Bos taurus* and *Bos primigenius* in Denmark, Scania and Germany

Locality	Dated bone element	Province	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	Atomic C/N%	Lab. no.
<i>Bos primigenius</i>						
Ulkestrup Lyng Øst 23352-2	vertebra cervicalis IV/V	Sealand	-23.00	4.6	2.81	528
Ulkestrup Lyng Øst 21943	astragalus dex.	Sealand	-23.57	6.42	2.85	529
Ulkestrup Lyng Øst 17590	scapula sin.	Sealand	-23.49	5.57	2.80	530
Ulkestrup Lyng Øst 23339-1	costa affixi dex.	Sealand	-23.57	5.59	2.85	527
Ulkestrup Lyng Øst 1821	humerus dex.	Sealand	-23.26	6.74	2.82	531
Maglemose 111	astragalus dex.	Sealand	-24.17	6.99	3.11	992
Stokholthusene	tibia dex.	Sealand	-20.72	4.51	2.89	1023
Rønnebæksholm	pelvis sin.	Sealand	-22.56	5.83	2.89	1024
Store Tåstrup	tibia dex.	Sealand	-20.92	4.00	2.86	1026
Knapstrupgård	femur	Sealand	-21.83	4.25	3.11	1059
Kongsted	metacarpus dex.	Sealand	-22.43	5.91	3.10	1057
Gundsømagle Nordmark	tibia	Sealand	-20.17	5.05	3.12	1062
Sonnerupgård	metatarsus	Sealand	-22.77	7.65	3.07	1069
Bisserup	humerus	Sealand	-22.66	7.61	3.11	1053
Alsønderup	bone	Sealand	-18.96	6.08	3.07	1096
Store Damme	tibia dex.	Møn	-22.22	4.66	2.85	1025
Frøbjerg Banker	humerus sin.	Fyn	-21.7	5.08	3.09	1052
Knabberup	astragalus	Jylland	-22.25	7.2	3.09	1072
Tranekær Mose	metatarsus	Jylland	-21.61	4.69	3.09	1061
<i>Bos taurus</i>						
KLM Åmosen 50.0/76.5:13	skull fragment	Sealand	-21.93	4.79	2.83	676
KML Åmosen 49.5/76.0:5038	metacarpus	Sealand	-22.00	4.8	2.84	985
KML Åmosen 50.0/79.5:4	mandibula	Sealand	-21.53	4.38	2.93	986
KML Åmosen 50.0/80.5:11	astragalus	Sealand	-22.26	4.42	2.81	987
Husede I	mandibula dex.	Sealand	-21.92	4.53	3.05	988
Muldbjerg Mul-I 690	pelvis	Sealand	-21.54	5.04	3.16	931
Muldbjerg Mul-I 41247	humerus	Sealand	-21.66	5.54	3.57	933
Muldbjerg Mul I 6018	femur dex.	Sealand	-21.89	4.99	2.79	612
Maglemose Vedbæk I	tibia dex.	Sealand	-22.40	4.98	2.84	1028
Verupgårds Mose	tuberculum articularis	Sealand	-21.78	5.06	2.86	1034
Smakkerup huse	radius	Sealand	-21.36	5.17	2.81	1036
Øgårde (Okse II)	tuberculum articularis	Sealand	-22.16	4.25	2.91	1029
Sandhuse Mose (Okse I)	condylus occipitalis	Sealand	-21.54	7.17	2.89	1030
Sandhuse Mose (Okse II)	tuberculum articularis	Sealand	-21.64	5.61	4.29	1031
Sandhuse C-LXIV	humerus sin.	Sealand	-21.71	5.81	2.98	1032
Sandhuse K-XXXIX	tuberculum articularis	Sealand	-21.57	7.1	2.84	1033
Ærøskøbing	tuberculum articularis	Ærø	-21.18	6.88	2.81	1027
Visborg BLN 3933	metacarpus	Jylland	-21.97	4.39	2.81	989
Visborg CQX 3933	metacarpus	Jylland	-22.47	3.88	3.16	990
Visborg FHM 3933 JOC	metatarsus	Jylland	-21.25	4.68	2.90	991
Siggeneben-Süd SIG 75 41x	tibia sin.	Germany	-21.60	4.00	2.85	976
S: 97.5–98 E: 143.4–144	tibia sin.	Germany	-22.29	4.64	2.88	977
Siggeneben-Süd SIG 75 2b	metatarsus dex.	Germany	-22.46	4.76	2.82	978
S: 94.5–95 E: 143.5–144	radius dex.	Germany	-22.44	4.73	2.82	979
Rosenhof (B) Ros 74V 880	metacarpus sin.	Germany	-22.33	4.51	2.80	980
Rosenhof (A) Ros 74VI A148i	metatarsus dex.	Germany	-24.54	4.79	2.79	981

2.2. The Neolithic

The Neolithic was characterized by introduction of agriculture and appearance of several distinctive new types of artifacts. Agriculture included cultivated plants, such as wheat and barley, and domesticated animals, including cattle, pig, sheep and goat, associated with the arrival of the early Neolithic Funnel Beaker culture (TRB), the EN I culture [83]. This TRB culture is characterized by distinctive pottery styles, production of polished flint axes, and new forms of burial and sacrifice [55]. Early Neolithic settlements are commonly small,

inland, and for the most part seasonal and ephemeral, such as the sites of Muldbjerg [75,99,100,102,103] and Åkonger [36].

Pollen samples from beneath long barrows reflect very local floral conditions, indicating two primary modes of agriculture during the Neolithic (EN I) involving clearance of lime forest for pasture, and burn and slash cultivation of cereals in burned-over birch woodlands [12–14]. Cleared areas were small in size and characteristically subdivided into a mosaic of small fields, fallows, and pastures, within the larger context of the Subboreal forest. Micro-wear analysis of early

Neolithic sickles, however, reveals little evidence of grain harvesting and these implements were used primarily for cutting of reeds and rushes [52,53]. Hunting and gathering continued to be important although adaptation of domestic cattle was already in progress from at least around 3950 cal yr BC. Substantial evidence for domesticates and land clearance does not appear until the second phase of the early Neolithic, EN II, after 3500 cal yr BC [12,26,67]. The early Neolithic EN I–EN II transition is further marked by changes in settlement size and construction, subsistence, tomb type, increased cattle herding, introduction of the ard plough, and initial settlement on clay soils. The number of known sites increased from EN I to II time, and there is more substantial evidence for occupation. Settlement size varies from small hunting sites of 100 m² to residential sites up to 8000 m². In some areas, a pattern of permanently inhabited sites at 2 km intervals is identified, each with one or more large tombs and offering sites [60,61]. Most of the megalithic tombs that are scattered over the Danish landscape were erected during this brief period. Prestige items, including copper axes and jewellery, long thin-butted flint axes, and objects of amber were also more common.

3. Early domesticates

The earliest domesticated animal in northern Europe was dog, which probably arrived with the first hunters at the end of the Pleistocene [63,105]. Current evidence for the date of appearance of several other domesticated animal species of agricultural importance in Denmark, nearly all concentrates around 3900–4000 cal yr BC, based on direct ¹⁴C dating of samples of animal bone and cereal grains. An unpublished find at the locality Lollikhuse at Roskilde Fjord on Sjælland (Fig. 1), suggests that sheep and early cattle might have appeared as stray finds already around 4600 cal yr BC year (Søren Sørensen, pers. comm., 2004).

It has been suggested that local plant food production took place in the late Mesolithic, based on the assumed presence of cereal pollen samples from the late Atlantic period [39,54,56,94]. These claims have been discounted, mainly because cereal pollen is difficult to distinguish from those of other grasses and because of uncertainties in the stratigraphical contexts of the samples (e.g. [33,88]). However, cereal impressions have been found in presumed late Ertebølle pottery at one or two sites in southwestern Sweden. In Denmark, the earliest known direct date of cereal is 3800 cal yr BC year from the Limensgård site on the island of Bornholm in the Baltic [68]. Another early date of 3700 cal yr BC is reported from the site Mossby in Scania [80].

There have been numerous claims for in situ animal domestication or husbandry in the Mesolithic of Europe

(see review by Zvelebil [112]). However, with the exception of dog, there are apparently no reliable cases of actual domestication and intermediate forms are not well documented. Several examples suggest, however, the presence of domesticated species in pre-Neolithic contexts in northern Europe [89,109].

Early domesticated animals appeared in northern Europe shortly after 4000 cal yr BC [83]. Early dates for domesticated sheep/goat include examples from the German site Rosenhof B, 3950 cal yr BC [41,44], and from Jordløse Mose in western Sjælland, Denmark, 3790 cal yr BC [45,55]. Sheep and goat have no wild ancestral forms in northern Europe and are readily distinguished as imported domesticated species.

Domestic cattle and pig, on the other hand, had wild relatives living in southern Scandinavia during the Holocene, and aurochs, *B. primigenius*, and wild boar, *Sus scrofa*, were common Mesolithic prey. They are not easy to distinguish from their domestic relatives [27,70,88]. A pig from the German site Rosenhof has been described as transitional between wild and domestic [69], but it overlaps in dimensions/characters with wild boar from the Danish Ringkloster site [88]. Because of the problems associated with distinguishing domestic pig from wild boar, to a large extent due to the likelihood of interbreeding, we have not yet investigated the question of the earliest domesticated pigs in detail.

Similar problems exist with the distinction between aurochs and domestic cattle, due to the pronounced sexual dimorphism of both species. Aurochs lived throughout Europe until the 17th century, when the last animal reportedly died in Poland. Aurochs was present in Jylland in Denmark and in northern Germany at the same time when domestic cattle were first introduced. However, aurochs became locally extinct on the Danish island of Sjælland and in southern Sweden during the early Atlantic period, perhaps due to impeded immigration and over-hunting in combination with decreasing food resources in the newly formed, rapidly forest-covered islands [1,3,34,75]. As a consequence, post early Atlantic bones of *Bos* in Sweden and on several of the Danish islands belong most likely, after that date, to domestic cattle. They are nevertheless re-dated here and stable isotope values measured. Aurochs, red deer, roe deer and wild boar from the island of Fyn had similar sizes as the contemporaneous large animals from Jylland, indicating free migration between Fyn and Jylland in contrast to the small-sized animals isolated on the island of Sjælland [75,87].

Aurochs and domestic cattle are anatomically very similar and their correct identification has been much discussed [9,10,27]. Identification of domestic cattle is based mainly on animal size, domesticated varieties usually being smaller than their wild relatives [21]. There are, however, no metrical criteria allowing a clear distinction of aurochs from domestic cattle as sexual dimorphism results in a considerable overlap in size

between wild female aurochs and male domestic cattle [88]. There is accordingly no firm evidence for domestic cattle in the Danish Ertebølle period [27,88].

The earliest domesticated cow known from Denmark, prior to this study, was found at the site of Øgaard in central Sjælland, 3810 cal yr BC [27]. Very early dates for domestic cow at Rosenhof in northern Germany (ca. 4700 cal yr BC) are controversial and are considered in more detail below.

4. Material

Basic information on the samples used in this study, including location, setting, dates and isotope values is presented in Tables 1 and 2. Below we discuss the localities of the finds, the radiocarbon dates, and the $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ isotope data. The material was chosen from a variety of depositional settings, such as single finds and settlement waste deposits. We have, however, focused mainly on material from eastern Denmark, especially the island of Sjælland, where the earliest domestic cattle arrived 800–1000 years after the disappearance of the last aurochs, thus assuring that we have clean isotope signals for both species. Studies are underway on material from the peninsula of Jylland, where aurochs and domestic cattle seem to occur together at some sites most often at shell midden sites covering a large time span.

We are investigating the origin of the two species in Denmark on the basis of both stable isotopes and DNA analyses.

4.1. Archaeological sites

Finds of aurochs and cattle in southern Scandinavia comprise fractured bones scattered among other types of debris from settlements, and essentially complete skeletons found in bog deposits (Tables 1 and 2).

4.1.1. Settlement debris

The studied sites are located in eastern Denmark, northern Germany and southwestern Sweden (Fig. 1). They were selected because they contain reliably identified remains of aurochs or early domestic cattle. The aurochs remains are mainly from early Mesolithic sites, which were often situated near lakes or bogs. The bone material of the early cattle is mostly from settlement sites and was fragmented and discarded in the same way as the remains of contemporaneous game, including red deer, roe deer and wild boar. Our selection of cattle remains includes samples from early Neolithic sites, some of which have been previously published and dated.

4.1.2. Single bog finds

Aurochs and domestic cattle are also found in bogs as essentially complete, individual skeletons. The

predominance of bog finds on Sjælland may be due to the intensity of peat cutting before and during the Second World War, and the excellent preservation conditions. Single, well-preserved aurochs finds, such as the ones from Vig [72] and Prejlerup [2] probably represent wounded animals, which escaped their hunters and died in small lakes or bogs. In contrast, the more or less complete domestic cattle skeletons found in bog deposits are commonly associated with complete clay pots, intact polished flint axes, amber beads, and human skeletons, some with leather cords around their necks, and are generally interpreted as bog sacrifices [55]. This type of domestic cattle material is in most cases a little younger than the earliest domestic cattle. The bones of the domestic cattle skeletons are largely unbroken, except for lethal fractures in the forehead of several individuals, e.g. the Sandhuse finds (Fig. 3). The unhealed wounds indicate that the animals were purposely killed, and there are no cut marks on the bones indicating removal of meat.

5. Radiocarbon dates

A total of 72 radiocarbon dates of aurochs and early domestic cattle are presented as ^{14}C yr BP and as



Fig. 3. A skull of *Bos taurus* with an injury in the frontal bone from the younger group of early *Bos taurus*. Single bog finds. Zoological Museum, Copenhagen Denmark.

calibrated years BC in Table 1. The sample context, whether settlement or single bog find, is also indicated. The analyses were made at the AMS laboratories of the Universities of Århus, Denmark and Uppsala, Sweden. For calibrated dates we have listed either the single cal year BC date provided by the dating laboratory, or in case of several possible date ranges, we have listed the whole range. The calibration is from OX cal [98] and the dates are rounded to the nearest decade.

The new radiocarbon data document the presence of domestic cattle in Denmark back to at least 3950 cal yr BC. The first appearance is almost simultaneous across eastern Denmark (Fig. 1). All the early *B. taurus* finds are from settlement deposits; finds from sacrificial settings have so far not been recorded in this older group of cattle. However, a large part of the group of younger domestic cattle finds represents individual bog finds of almost intact skeletons (Table 1). The sacrificial single bog finds thus clearly concentrate in the younger group, beginning around 3500 cal yr BC year, and the pattern does not appear to result from sample bias, as the finds are randomly distributed throughout Denmark. Rather, it appears to reflect new ceremonial activities and perhaps religious beliefs introduced at the beginning of the second part of the early Neolithic.

6. Stable isotope ratios

Carbon and nitrogen stable isotopic analyses are important components in studies of human palaeodiets, animal food webs, palaeoecology and climate changes [5,6,17,22,29,31,32,74,75,90,92,93,95,110].

In this study we use the stable isotopes of C and N measured on bone collagen. Extraction follows the method of Longin [59], Chrisohm et al. [19], DeNiro [28], Ambrose and DeNiro [5], and combustion follows Stump and Frazer [97] and Northfelt et al. [77]. Ultra filtering was applied following Brown et al. [18]. Isotopic measurements were made at the Waterloo Stable Isotope Laboratory, Canada and some at the Isotope centre of the University of Copenhagen, Denmark.

The atomic C/N ratio of collagen in the samples varies between 2.79 and 3.16 (Table 1). Only one sample has an atomic C/N ratio falling outside this range (Sandhuse = 4.29). Thus, virtually all of the samples fall well within the expected range for well-preserved bone, reflecting a low probability for diagenetic alteration [110]. Most of the organic remains from settlement sites are found in lake and bog deposits adjacent to the settlement area, where waterlogged conditions have preserved the material. Thus, the depositional and taphonomic contexts of settlement dump and single bog finds are similar and preservation in general is good, whereas bones left on land around the site are poorly preserved [75].

6.1. Carbon

During photosynthesis, C3 and C4 plants discriminate differentially against the heavier ^{13}C isotope relative to $\delta^{13}\text{C}$ in atmospheric CO_2 , so that C3 plants have an average $\delta^{13}\text{C}$ value of -26‰ , whereas C4 plants have an average of -12‰ . In northern Europe, C3 plants dominate and include trees, shrubs, and most non-woody plants. Only C3 plants are of relevance to this study. A 5‰ enrichment in $\delta^{13}\text{C}$ and bone collagen compared to the diet of the larger herbivores is assumed [30,57,107,108]. Thus, herbivores feeding on C3 plants can be expected to exhibit a $\delta^{13}\text{C}$ bone collagen value of about -21‰ .

C3 plants growing in shaded environments may have more negative $\delta^{13}\text{C}$ values than plants even of the same species growing in open areas [37,38]. In forests of C3 plants, a dense canopy may retard free circulation and mixing with atmospheric CO_2 , resulting in recirculation of already depleted CO_2 . Decomposition of leaf litter on the forest floor also produces depleted CO_2 , and together with restricted circulation creates a depleted CO_2 concentration which is most pronounced at the forest floor level. Both recirculation of already depleted CO_2 and extensive shade will result in more negative $\delta^{13}\text{C}$ values in the plants of the forest floor and thus in the bone collagen of the animals feeding upon them. In a dense forest, ultimately a tropical rain forest, the forest floor vegetation may show $\delta^{13}\text{C}$ values as low as -5‰ , and values from leaves in the lower canopy may be as low as -30‰ . In a temperate forest the values of forest floor vegetation are less negative and may only occasionally approximate -30‰ [37,38,64–66,75].

6.2. Nitrogen

Nitrogen isotope ratios ($^{15}\text{N}/^{14}\text{N}$) distinguish herbivores from carnivores and leguminous plants from species that fix nitrogen directly from the atmosphere. The $\delta^{15}\text{N}$ values average 0‰ in legumes, whereas grasses, herbs and other plants have higher values around $+3\text{‰}$ or more. A $3\text{--}5\text{‰}$ increase in $\delta^{15}\text{N}$ has been observed between diet values and bone collagen in larger mammals [4,17], and a stepwise enrichment in $\delta^{15}\text{N}$ of 3‰ was found between each trophic level from legume values about 0‰ , and C3 plants about 3‰ over herbivores between 3 and 8‰ , and carnivores between 9 and 12‰ , to 12 and 15‰ in man [7,91,95]. However, recent studies based on modern material indicate a wider range of values from one trophic level to another [17].

The standard for nitrogen is AIR [46]. The highest $\delta^{15}\text{N}$ values in plants appear to be associated with saline soils and arid environments [5,6,42,47,95]. The lowest $\delta^{15}\text{N}$ values in non-leguminous plants are found in moist forests and in mountain areas [7]. In Denmark there are no mountains, the climate was humid during the

Atlantic period, and very few forested areas with salty environment existed; so other explanations have to be sought when interpreting the observed range and high $\delta^{15}\text{N}$ values between +4 to +7‰ for aurochs and early cattle. Red deer from temperate areas in northern Europe shows a variation of up to 6‰ in nitrogen isotopic composition through time interpreted to reflect changes in intensity of N-cycling following changes in vegetation [32]. Nitrogen isotopes can thus be used as a tool for palaeodiet analysis and for climate and environmental reconstructions in addition to and in combination with ^{13}C isotope analysis.

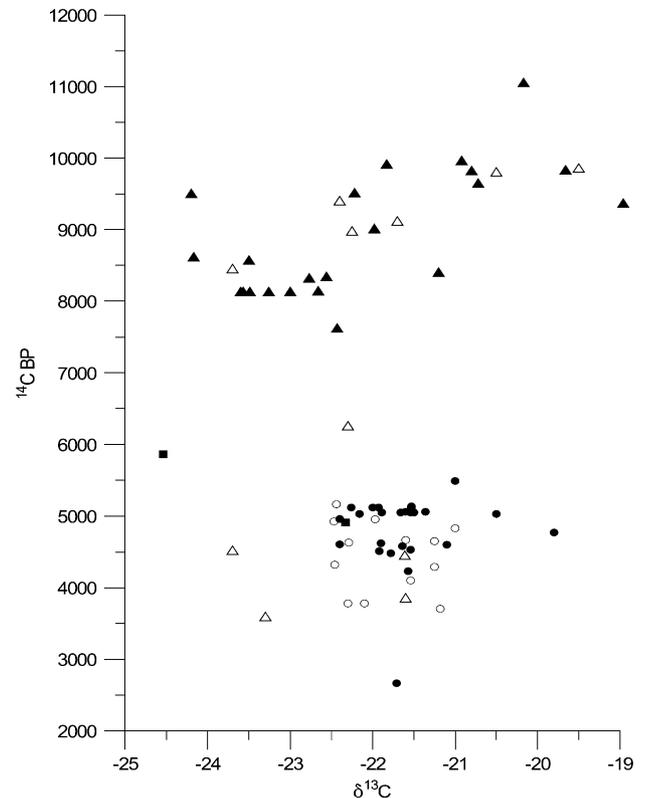
7. Results

7.1. Carbon isotopes

All the available Danish radiocarbon dates on aurochs and early cattle are shown in Table 1, including new and published data. Stable carbon isotope measurements on dated cattle and aurochs are shown in Fig. 4, and dated material with ^{15}N measurements is shown in Fig. 5. Table 2 lists only those samples for which both carbon and nitrogen isotope data and the C/N ratio have been obtained. A total of 45 measurements of the stable ^{15}N and ^{13}C isotopes were made on *B. taurus* (27) and *B. primigenius* (22) from eastern Denmark (Figs. 2 and 6).

Four trends emerge in a scatter plot of all available $\delta^{13}\text{C}$ data from ^{14}C dated aurochs and cattle (Fig. 4). The values of the domestic cattle range from -22.5‰ to -19.8‰ $\delta^{13}\text{C}$. Within the carbon isotope range for the cattle, the majority of measurements fall between -21.5‰ and -22.5‰ . There is a large group around -22‰ , primarily comprising the earliest domestic cattle; the younger cattle show a more scattered isotope pattern. There is almost no overlap in $\delta^{13}\text{C}$ values between the earliest cattle and the latest aurochs on Sjælland.

The $\delta^{13}\text{C}$ values of aurochs range between -19‰ and -24.5‰ with the majority between -21‰ and -24‰ and change through time towards more depleted values. The aurochs values in general are shifted towards more negative values compared to the range of early cattle, but show a considerable overlap. The trend of the C-isotope values of aurochs indicates a transition from a diet of grass supplemented by browsing in the light and open Preboreal environment, toward a mixed diet obtained in the dense Atlantic forest with values probably further modified by the canopy effect [75]. This change in vegetation is corroborated by evidence from pollen analyses (e.g. [49]). The Preboreal pollen spectrum indicates the presence of a light, open forest with birch and pine interspaced with grasses, herbs and shrubs. In contrast, the late Boreal–Atlantic pollen



▲ *Bos primigenius*, Sjælland. △ *Bos primigenius*, Jylland, Fyn, Germany and Sweden.
● *Bos taurus*, Sjælland. ○ *Bos taurus*, Jylland, Fyn, Germany and Sweden.
■ *Bos*, Rosenhof.

Fig. 4. Distribution of ^{13}C values of early *Bos taurus* and *Bos primigenius* over time. Note the clumped distribution of the early *B. taurus* values. Numbers refer to data in Table 2.

spectrum documents an increasingly closed forest with a dense canopy through which only little light penetrated to the forest floor, resulting in a dramatic fall in plant species diversity [78]. Large herbivores were thus forced to obtain a major part of their food within and at the edge of the dense forest and along lakes and watercourses. They were also forced to eat grass and herbs from the shaded forest floor with an increasing contribution from browsing.

The trends in aurochs towards more negative $\delta^{13}\text{C}$ values through time already began in Boreal times, when most of the tall, true forest trees such as lime, oak, and elm immigrated and became established in southern Scandinavia. There is no overlap in $\delta^{13}\text{C}$ values of late Boreal–early Atlantic aurochs from Sjælland and late Atlantic–Subboreal early domestic cattle. In contrast, there is a clear overlap between the late Atlantic–Subboreal early group of domestic cattle and Preboreal aurochs (Fig. 4).

Some of the latest aurochs from Sjælland are from the early Atlantic site Ulkestrup Lyng and exhibit very light $\delta^{13}\text{C}$ isotope values around -23‰ to -24‰ (Figs. 2 and 4) [75]. The $\delta^{13}\text{C}$ values obtained from the aurochs from Ulkestrup Lyng dated to 7210 cal yr BC thus

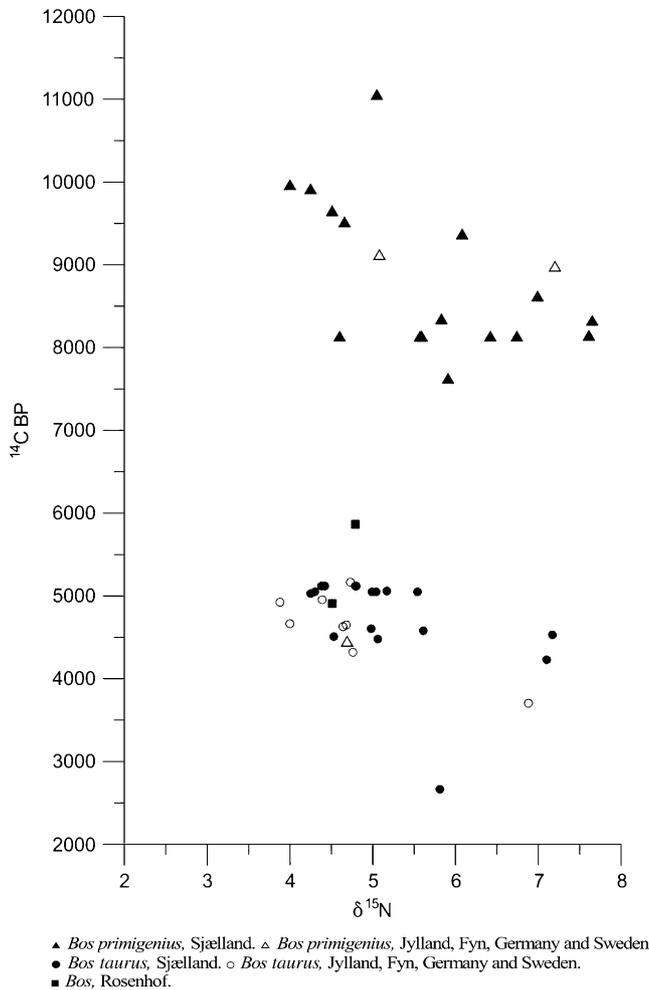


Fig. 5. Distribution of ^{15}N values of early *Bos taurus* and *Bos primigenius* over time. Note the restricted distribution of the early *B. taurus* compared to the scatter of *B. primigenius*. Numbers refer to numbers in Table 1.

indicate a diet of rather $\delta^{13}\text{C}$ -depleted food, most likely obtained from the forest floor and the lower part of the canopy, where there was constant shade and recirculation of already depleted CO_2 from the decomposition of litter. Some browsing might also have taken place at the edge of the forest. The distinct difference in $\delta^{13}\text{C}$ values between early domestic cattle and late Boreal-early Atlantic aurochs in eastern Denmark indicates that the diets of the two groups were isotopically different.

A radiocarbon date of 4850 cal BC year of a bone from an alleged domesticated cattle from Rosenhof, would confirm an association between domesticated animals and the late Mesolithic culture [44]. The Rosenhof site in Holstein, NW Germany contains a stratified section containing material from a late Mesolithic occupation [41]. The original identification of the cattle bones at Rosenhof was made by Nobis [69,71] and has later been questioned. Two of the early *Bos* at Rosenhof may in fact be from aurochs based on the size

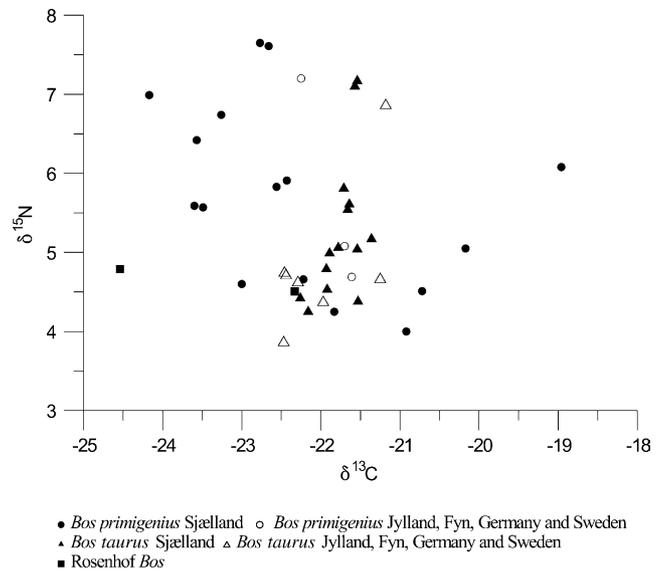


Fig. 6. Cross plot of ^{15}N and ^{13}C of *Bos primigenius* and early *Bos taurus*.

of the metacarpals [88]. The putative *B. taurus* from Rosenhof (A), designated as Ros 74 VIA148i, has $\delta^{13}\text{C}$ values, comparable to the Danish aurochs, indicating that it might in fact be from an aurochs (Figs. 4 and 6), and thus confirming the interpretation of Rowley-Conwy [88]. The Rosenhof B 4910 \pm 50 ^{14}C yr BP or 3750 cal yr BC have a $\delta^{13}\text{C}$ value of -22.31% only slightly less negative than Rosenhof A. In contrast the Rosenhof $\delta^{15}\text{N}$ values are closer to those from the Danish early domestic cattle.

7.1.1. $\delta^{13}\text{C}$ values from red deer

We have compared aurochs data with data from contemporaneous forest-dwelling red deer from the same locality in the Åmose basin in order to examine if the change in $\delta^{13}\text{C}$ values actually results from a change in aurochs diet towards forest-dominated food (Fig. 7) [75]. The marked change in $\delta^{13}\text{C}$ values observed in the Åmose red deer population from the late Boreal Ulkestrup Lyng and early Atlantic Kongemose sites to the $\delta^{13}\text{C}$ values from the late Atlantic Præstelyng and early Subboreal Muldbjerg sites has been interpreted as reflecting changes in diet $\delta^{13}\text{C}$, resulting from increasing forest cover and canopy effect [75].

The early Boreal landscape was still dominated by an open pine and hazel forest interspersed with grazing areas, whereas all the climax forest trees had immigrated to southern Scandinavia by the end of the Boreal, resulting in a dramatic drop in light demanding species, including grasses. Red deer is mainly a grazer and subordinate browser [51,75]. In the Boreal, grazing possibilities were still good and the forest provided cover for a large red deer population of big animals. They fed mostly on grass, supplemented with forest browsing,

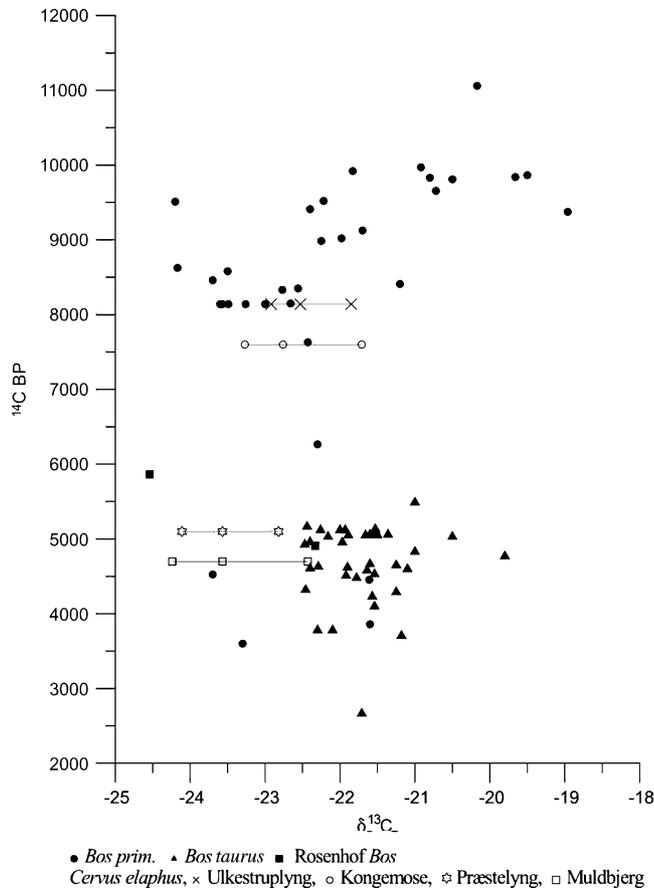


Fig. 7. Comparison of ^{13}C values of *Bos primigenius* and *Bos taurus* and average ^{13}C values from contemporaneous *Cervus elaphus*.

and the average $\delta^{13}\text{C}$ of bone collagen was -22.53‰ , ranging from -21.8‰ to -22.9‰ . Late Boreal and early Atlantic red deer thus have less depleted $\delta^{13}\text{C}$ values than contemporaneous aurochs (Fig. 7). The last aurochs on Sjælland were obviously more attached to the dense forest than the contemporaneous red deer population. In contrast, the average red deer $\delta^{13}\text{C}$ values of -23.5‰ , ranging from -22.7‰ to -24.3‰ at the younger late Atlantic–Subboreal sites is almost identical to the late Boreal aurochs values of -23.44‰ . The interpretation of the isotopic changes in the red deer population of the Åmose area over 3500 years may also be valid in the interpretation of the differences in carbon isotope values through time for aurochs. The change in aurochs $\delta^{13}\text{C}$ values is thus considered to reflect changes in isotope values of the diet and in diet composition, resulting from increasing forest cover and density from Preboreal to early Atlantic time.

The difference in stable carbon isotope values between the youngest aurochs and the earliest domestic cattle on Sjælland probably reflects differences in feeding strategy and location. The early cattle most likely fed on grass along the forest edge, in clearances possibly maintained by man, or on the newly created grass and

herb-covered coastal areas, whereas coeval aurochs fed mainly within the forest.

There is virtually no overlap in $\delta^{13}\text{C}$ values between contemporaneous red deer and domestic cattle. The cattle appear right from the beginning to have been feeding mainly in grass and herbs-covered open areas. This interpretation of the feeding strategy of the early cattle stands in marked contrast to the leaf fodder hypothesis of Troels-Smith [99,103], Iversen [49] and Rasmussen [85]. The isotope data from Boreal and earliest Atlantic aurochs show an almost complete overlap with those of the late Atlantic red deer, indicating similarities in diets (Fig. 7). The very negative $\delta^{13}\text{C}$ values show that they fed in the forest and on the forest floor on a diet influenced by the canopy effect (cf. [62,75,106,107]).

7.1.2. Nitrogen isotopes

The $\delta^{15}\text{N}$ values of aurochs are rather positive and range between $+4\text{‰}$ and $+7\text{‰}$. The four lowest aurochs values, which overlap with the N-isotope range of early domestic cattle, are all from Preboreal aurochs (Fig. 5). The $\delta^{15}\text{N}$ values of aurochs increased through time to just above $+7.2\text{‰}$ in the late Boreal to early Atlantic time. The $\delta^{15}\text{N}$ data from domestic cattle range between $+3.9\text{‰}$ and $+5.8\text{‰}$, with the majority of the measurements falling between $+4\text{‰}$ and $+5\text{‰}$ for the early domestic cattle group. The three cattle values of about $+7\text{‰}$ are exceptions; two are from the same site (Sandhuse) but from different animals, while the third sample is from the small island of Ærø.

In those samples where both C and N isotope ratios are available, the $\delta^{15}\text{N}$ values are more widely scattered than the $\delta^{13}\text{C}$ values. An exception is the clumping of $\delta^{13}\text{C}$ values from early domestic cattle, ranging between -21.5‰ and -22.5‰ , and with ^{15}N values between $+4\text{‰}$ and $+5\text{‰}$ (Figs. 5 and 6).

In general the $\delta^{15}\text{N}$ values are higher and more scattered in aurochs than in early cattle. Overlapping aurochs and cattle values are from early individuals that lived in the open Preboreal landscape. The data from early domestic cattle represent a time interval of only about 500–700 years, from the late Atlantic to the early Subboreal. In contrast the aurochs data considered here range in time over 3000–4000 years and stem from animals that lived under a variety of climatic conditions, from the early Preboreal cool and dry climate with low nutrition soil, through the dry, warm Boreal period with high nutrient soil, to the warm, humid Atlantic period. These changing environments may well account for the large variation observed in the ^{15}N values of aurochs.

The similarity in both $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values for the bulk of the early domestic cattle indicates intake of a similar, uniform diet from their first appearance (Fig. 6). The most positive ^{15}N values, correlating with

the most negative ^{13}C values, are found in aurochs from the Atlantic period.

The co-variation of ^{13}C and ^{15}N and the positive correlation between low ^{13}C and high ^{15}N values as observed in Danish aurochs are also found in red deer from the northern Jura in France, where the more positive ^{15}N values in the youngest aurochs correspond to the more negative ^{13}C values [32].

8. Discussion

Values, ranges and palaeoenvironmental interpretations of nitrogen isotopes have been much debated, most recently by [32]. Values of $\delta^{15}\text{N}$ in plants depend on the source of nitrogen, on its chemical form, and on its assimilation. The large majority of plants use mainly organic nitrogen or inorganic nitrogen in soil in the form of NH_4^+ and NO_3^- [111]. During the biochemical cycle of nitrogen, organic nitrogen is mineralized by microorganisms as ammonia NH_4^+ and oxidized into nitrate NO_3^- . During these processes a progressive depletion of $\delta^{15}\text{N}$ occurs relative to the substrate. The $\delta^{15}\text{N}$ values of plants reflect those of their nitrogen source in the soil. If nitrogen cycling is stimulated, residual inorganic nitrogen will be enriched [32]. The nitrogen cycling may be stimulated by increasing fertilization, e.g. by fires. The $\delta^{15}\text{N}$ values may then increase in the vegetation growing on the forest floor litter with high N-cycling in a warm humid climate. A similar correlation between low $\delta^{13}\text{C}$ values and high ^{15}N values has been reported for red deer [32]. This compares well with our results from aurochs in Denmark. The latest aurochs on Sjælland in Denmark, from the early Atlantic period, have $\delta^{13}\text{C}$ values around -24.6‰ and (corresponding) ^{15}N values above $+7\text{‰}$.

The interpretation of the $\delta^{15}\text{N}$ data supports the pattern observed in $\delta^{13}\text{C}$, as both data sets indicate a change towards a dense forest cover with recirculation of depleted CO_2 , high nitrogen recycling rate, production and circulation. The late Boreal and especially the Atlantic forests in Denmark were characterized by accumulation and decomposition of litter on the forest floor in a warm, humid local climate under low light conditions. Accumulation of nitrogen-rich organic material from the litter may account for the high $\delta^{15}\text{N}$ values of the soil and later in the forest floor vegetation and ultimately in the early Atlantic aurochs. A pattern of frequent and repeated visits with browsing in the few open areas with grass and at forest rims may further have increased nitrogen fertilization of the soil by droppings and urination, thus increasing the $\delta^{15}\text{N}$ values in the eaten vegetation.

A modern, controlled feeding study based on herbivore hair samples indicates that dietary protein levels influence $\delta^{15}\text{N}$ values. Grazers living on high

protein diets have higher $\delta^{15}\text{N}$ values than browsers [96]. This conclusion does not fit very well with the Danish material as the most positive values are from animals eating from and in the forest. The $\delta^{15}\text{N}$ values of herbivores show the greatest similarity for periods where the climate is mild and water plentiful [6,96]. This is in accordance with the uniform distribution of the data from the early cattle (Fig. 5).

Iacumin et al. [47] measured $\delta^{13}\text{C}$ for a stratified series of 110 samples of aurochs bones from a cave in southern Italy dating from 32,600 to 13,350 cal yr BP. Values ranged from -19.5‰ for the oldest bones, over -18.5‰ in bones from the Late Glacial Maximum around 20,000 cal yr BP, to -20.4‰ for the youngest bones around 13,350 cal BP. Iacumin et al. [47] distinguished two isotopic minima (at 16,300 and 13,200 cal yr BP) and two maxima (18,200 and 15,700 cal yr BP) in $\delta^{15}\text{N}$ in the aurochs bone collagen covering the total time span. Both maxima fall within the Greenland stadial 2 of Björck et al. [16]. The 15,700 cal yr BP maximum is coeval with the last cold spell before the Bølling Greenland Interstadial 2, and the 18,200 cal yr BP falls at the end of the Late Glacial Maximum. Precipitation was reduced during these cold and dry periods. In contrast the 13,200 cal yr BP minimum occurred within the Allerød Interstadial, the Greenland Interstadial 1, whereas the 16,300 cal yr BP minimum occurs in a warmer part of Greenland Stadial 2.

Heaton et al. [42] suggested that the $\delta^{15}\text{N}$ in mammal collagen increased with decreasing precipitation and/or under very dry conditions, and that water stress seems to be related to nitrogen metabolism [8]. Water stress can, however, be ruled out as the sole factor for high nitrogen isotopic values in the Danish material from the warm and humid Atlantic period, when the aurochs with the most negative $\delta^{13}\text{C}$ and the most positive $\delta^{15}\text{N}$ roamed.

It is an important question why the human population changed their feeding strategy at all from a hunter-gatherer to an agricultural mode of life at the Atlantic–Subboreal transition at around 4000 years cal yr BC. The change might have been due to pure cultural influence, but three major environmental changes also took place during the later Atlantic time. The Holocene climatic optimum came to an end, the rate of sea-level rise decreased, and a major outbreak of elm disease occurred.

Temperature data from the GRIP 2 Greenland ice cores clearly show the onset of a decrease in average temperature ending the climatic optimum towards the end of the Atlantic period [25]. Decreasing rate of eustatic sea-level rise associated with isostatic uplift resulted in a rapid progradation of the coastline into the shallow coastal waters, creating new unforested land areas, to which grass and herbs could immigrate and form the basis for the grass-eating early cattle. The elm decline at the Atlantic–Subboreal transition might have triggered the changes in human and/or animal feeding

strategies by providing open areas with grasses and herbs and thus suitable for cattle herding and cereal cultivation. Iversen [48] suggested that the elm decline and the contemporaneous decline in ivy, which is sensitive to cold winters, probably was a result of a change toward a cooler climate. Troels-Smith [99,103,104] in contrast suggested that the elm decline was the result of leaf foddering of early domestic cattle, which were kept in fenced enclosures and were fed with leaves, but added that elm disease might have played a substantial role in the lower elm pollen production. The disease is inflicted by the fungus *Ophistoma ulmi*, which destroys the bark and the layer just below, preventing water transport in the trunk, resulting in withering of leaves and branches and eventually in the death of the tree. The fungus is spread by a variety of elm beetles and other possible carriers [79,86]. Iversen [49] subsequently reconsidered his climate hypothesis, and suggested that human influence most likely was the main factor causing the elm decline. The elm decline was further discussed by Berglund [15], who described it as a period of unstable forest ecosystems, with the first indications of cultivation and pasture. The elm decline, caused by the elm disease, is supported by a study from Diss Mere in England of annually laminated Atlantic and Subboreal lake deposits. Here the most dramatic changes in forest composition including decline of elm took place within a period of only six years [79]. The infection spread with remarkable speed across northwestern Europe, and it is considered unlikely that climate change or cattle foddering could have had that effect within such a short time span. A piece of elm wood with feeding traces from larvae of the small elm beetle was found at the late Atlantic site of Præstelyngen at the Åmose dated to 3870 cal BC, confirming the presence of the beetles in that period [86]. Our data do not provide any indications of leaf foddering or of cattle kept in enclosures. If this had been the case, the ^{15}N values would have been more positive in the domestic cattle bones and the ^{13}C more negative.

The sum of evidence thus clearly indicates that the elm disease was the main reason for the elm decline. The death of the elm trees would leave openings in the otherwise dense climax forest, where grass, herbs and new young trees got a chance to grow. Humans may then have taken advantage of the new openings and kept the new vegetation low, creating possibilities for the growth of hazel bushes with their nuts, berries and grass, which could be used as food for both man and cattle.

Another question is why did the elm disease start and spread with such a speed. In Denmark, the ongoing Atlantic sea-level rise probably destabilized and weakened the coastal forest, including the elm population, due to rising ground-water level. The death and possibly later burning of exposed trees created pathways into the high and dense forest, which might have facilitated the attack of the elm beetle. In northern Sjælland, the late

Atlantic Littorina transgression reached its highest level, and raised beach deposits are found 4–6 m above present day sea level (Fig. 9). At the site Tengslemark in northern Sjælland, the elm decline took place right after the onset of the late Atlantic/Subboreal Littorina transgression. A pronounced rise in charcoal dust is seen in the pollen record just before and during the elm decline (M. Mortensen pers. commun., 2003), so man probably also played a role in the decrease of elm trees or he just took advantage of the dead elm wood, or both. Elm decline and introduction of agriculture may then have resulted from a combination of changes in climate, ecology, sea level and human cultural influences, but these factors may also have worked independently.

9. Conclusions

In southern Scandinavia native aurochs (*B. primigenius*) may be separated from domestic cattle (*B. taurus*) on the basis of ^{15}N and ^{13}C isotopes. Results from France indicate that this distinction may be valid for most of Europe, and the alleged old *B. taurus* from Rosenhof A (4850 cal yr BC) is more probably an aurochs.

The time trend in isotopic values from aurochs indicates a change in diet concomitant with increasing forest cover, forcing the aurochs to seek food in and immediately around the forest.

The age of the earliest domestic cattle in Denmark falls in time, around 4000 cal yr BC, with only one exception, the well-dated domestic cow from Lollikhuse. The first domestic cattle occur contemporaneously with the elm decline, contemporaneously with the onset of a decline of the mid-Holocene climatic optimum, and not least with a dramatic change in the tidal amplitude in Danish waters, indicating a possible connection between these events. The decrease in rate of sea-level rise and the rapid spreading of grass and herb onto the newly formed marine foreland, provided the possibilities for cattle herding.

On Sjælland both the early and late groups of domestic cattle had significantly less negative $\delta^{13}\text{C}$ values than the youngest late Boreal and early Atlantic aurochs from the same region, indicating a clear difference in feeding habits between the two species. Stable carbon isotope ratios in the earliest *B. taurus* clearly reflect feeding in open grassland with scattered trees from the very beginning. Even *B. taurus* from the heavily forested Åmose basin has an average carbon isotope value of -22.2‰ , indicating that the cattle fed on open grass areas in and around the forest or in its near neighborhood.

The Mesolithic–Neolithic transition in southern Scandinavia has been extensively debated, both in terms of timing and context. Our isotope data and the new

radiocarbon dates of *B. taurus* from eastern Denmark, northern Germany and southern Sweden suggest that the transition occurred almost simultaneously around 3900–4000 cal yr BP years in this larger region.

An intermediate or transitional cattle breeding phase between the late Mesolithic and the early Neolithic cannot be recognized, whereas there is a lag of about 400 years from the first introduction of domestic cattle until the full impact of the Neolithic culture in terms of weapons, burials, offerings and farming took place.

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