University of Groningen

FOSSIL BONES FROM THE NORTH SEA

Van Der Plicht, J.; Kuitems, M.

Published in:
Radiocarbon

DOI:
10.1017/RDC.2022.9

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2022

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Van Der Plicht, J., & Kuitems, M. (2022). FOSSIL BONES FROM THE NORTH SEA: RADIOCARBON AND STABLE ISOTOPE (^{13}C/^{15}N) DATA. *Radiocarbon*, *64*(3), 633-668. https://doi.org/10.1017/RDC.2022.9

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license. More information can be found on the University of Groningen website: https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment.

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Download date: 30-04-2023

Radiocarbon, Vol 64, Nr 3, 2022, p 633–668 DOI:10.1017/RDC.2022.9

FOSSIL BONES FROM THE NORTH SEA: RADIOCARBON AND STABLE ISOTOPE (^{13}C/^{15}N) DATA

J van der Plicht* • M Kuitems

Centre for Isotope Research, University of Groningen, the Netherlands

ABSTRACT. The North Sea is considered a unique heritage site that yielded a huge amount of zoological and archaeological data. More than 200 palaeozoological and archaeological fossil bone samples from the North Sea bed are dated by ^{14}C. About 2/3 of these dated bones are Pleistocene in age; the majority of the bones are from extinct species (in particular woolly mammoth); about 1/3 of the sample date to the Holocene. The presented dataset is important in its kind, but interpretation is limited because of a lack of context of the finds. The stable isotopes (^{13}C, ^{15}N) of the dated samples provide additional information on palaeoenvironmental conditions and dietary habits in the past. We present primarily a Groningen list of data; a few fossils dated in other laboratories are included for completeness.

KEYWORDS: fossil bones, Holocene, Late Pleistocene, North Sea, radiocarbon, stable isotopes ^{13}C/^{15}N.

INTRODUCTION

During the last ice age, large volumes of water were stored in the continental ice caps. As a consequence, sea levels were roughly 100 m lower than today. At that time, the southern North Sea was a diverse landscape inhabited by a rich fauna. It was in fact part of the Mammoth Steppe (Mol et al. 2006a, 2008, 2010a; Lister and Bahn 2007; Kuitems 2020), and the area is considered a unique and rich heritage site that was inhabited by humans, in particular during the Mesolithic (Peeters 2011; Roebroeks 2014; Meiklejohn et al. 2015; van der Plicht et al. 2016). Recent investigations have increased our insights into geographical aspects of this now submerged landscape (Gaffney et al. 2007; Sturt et al. 2013; Cohen et al. 2014; van Heteren et al. 2014). Nevertheless, still a lot of unanswered questions exist about the animals and people who occupied the area despite the large quantities of fossil bones and occasional artifacts extracted from the seabed (Glimmerveen et al. 2006; Mol et al. 2008, 2010a).

The main reason is that most of the finds derive from unknown stratigraphical, geographical, and archaeological contexts (Peeters 2011). As a result of natural erosion and sedimentation, finds are not in situ. In addition, the vast majority of finds has been brought up in fishing nets or came ashore in sand dredged from the seabed for the purpose of coastal reinforcement and land reclamation. An example of the latter is the Zandmotor (sandmotor) located on the coast near Den Haag (The Hague). But also several zones in the southern North Sea, for instance the Brown Bank and Eurogeul, are known as palaeontological and/or archaeological "hot spots" which have been subject to targeted "fishing" expeditions. A rare location where research of *in situ* contexts has been conducted is Rotterdam-Maasvlakte in the Netherlands (Moree and Sier 2015). Figure 1 shows a map of the North Sea with relevant locations.

A major aspect concerns the establishment of the age of the fossil finds. Over the last decades, many samples have been submitted for ^{14}C dating, which has resulted in an important and unique series of dates. For ^{14}C dating, also the stable isotope ^{13}C is measured for

---

*Corresponding author. Email: J.van.der.Plicht@rug.nl

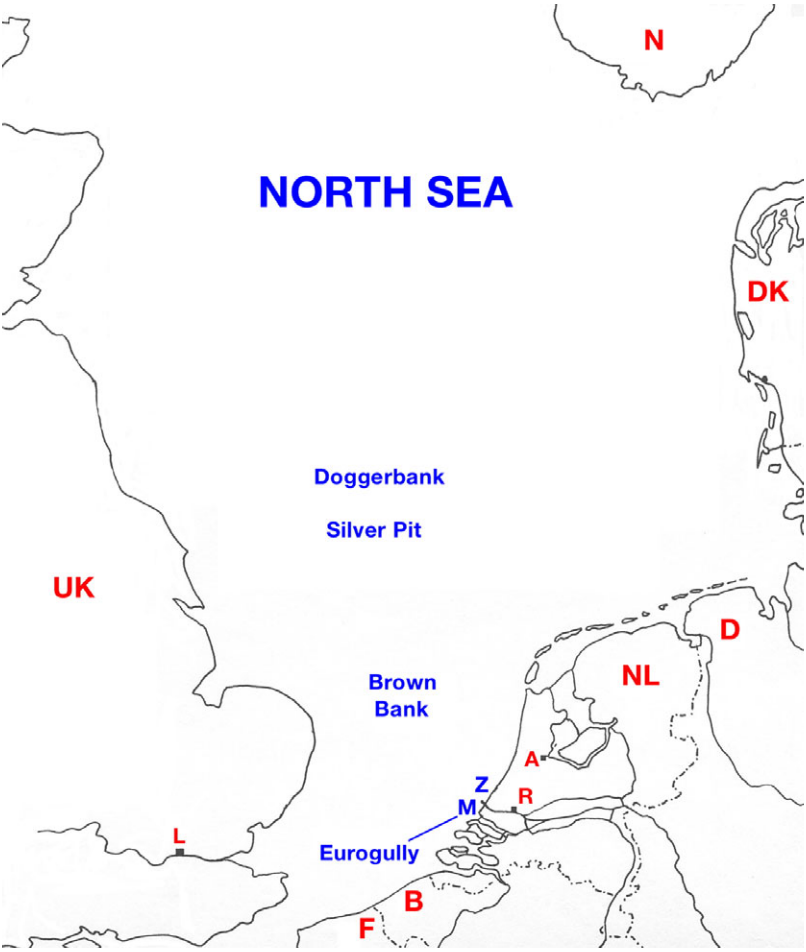

Figure 1 Map of the North Sea showing the most relevant find locations of fossil bones: M: Maasvlakte, Z: Zandmotor, B: Belgium, D: Germany, DK: Denmark, F: France, N: Norway, NL: Netherlands, UK: United Kingdom, A: Amsterdam, L: London, R: Rotterdam.

fractionation correction; analysis of the stable isotope ^{15}N of the dated bone collagen was introduced later, in the 1990s. Both stable isotopes are proxies used for reconstruction of, and for information on (palaeo)climatological and environmental change (e.g., Fry 2008). A good example concerns the Mesolithic hunter-gatherers of Doggerland. Analysis of the ^{13}C and ^{15}N isotope contents of their bones indicates that their major food resource was freshwater fish (van der Plicht et al. 2016).

This contribution presents an overview of fossil bones analyzed for their natural isotopes. It comprises more than 200 animal bone dates. It provides a catalog of samples measured over the last decades, with ^{14}C dates measured both conventionally and by AMS, most of them also providing the stable isotopes ^{13}C and ^{15}N. The majority of the measurements were done in Groningen. For the purpose of completeness these were supplemented by available data from other laboratories. The isotopic data provide a major contribution towards an integrated understanding of the North Sea in the past. Detailed palaeontological, archaeological, and geophysical interpretations of the North Sea finds can be found in the extensive literature.

METHODS

Techniques and Conventions

For isotope analysis, the collagen fraction of the bone is isolated. This is done generally by following an improved version of the method originally developed by Longin (1971). In brief, the sample is first entirely released from bioapatite and contaminants such as humic acids. Subsequent heating at 90°C causes gelatinization of the collagen (Mook and Streurman 1983; Mook and van de Plassche 1986). For a complete description of sample pretreatment aspects we refer to Dee et al. (2020).

The list of data comprises measurements performed over decades at 3 separate laboratories: conventional (until 2011, Groningen code GrN) and AMS (by 2 machines: Tandetron 1994–2017, code GrA and Micadas, since 2017, code GrM). Large samples have been measured by radiometry. The collagen is combusted to produce CO_2; the ^{14}C activity is measured using proportional counters. The $\delta^{13}C$ ratio is measured by mass spectrometry (IRMS). For more technical details of the conventional method we refer to Mook and Streurman (1983) and Cook and van der Plicht (2013).

Small samples (and large ones since 2011) are measured by AMS. The first AMS was a 2.5MV Tandetron (van der Plicht et al. 2000). The present AMS is a Micadas system (Synal et al. 2007). Both employed a combination of Elemental Analyser/Mass Spectrometer (EA-IRMS). The EA combusts the collagen into CO_2 which is subsequently reduced into graphite (Aerts et al. 2001). The graphite is pressed into targets, mounted in a sample wheel before it is loaded into the ion source of the machine. The IRMS measures the stable isotope ratios $\delta^{13}C$ and $\delta^{15}N$.

Stable isotope concentrations are measured by mass spectrometry, based on molecular gases. The stable Carbon isotope (^{13}C) content of the sample is measured in CO_2 by IRMS (isotope ratio mass spectrometry) upon combustion of the pre-treated ^{14}C sample material (such as collagen, prepared from fossil bone). Thus, the same CO_2 is used for both isotope measurements, ^{13}C and ^{14}C dating—either by AMS or by the conventional method. For the nitrogen isotope ^{15}N, also IRMS is used. In this case, N_2 gas prepared from the same collagen sample is used.

The stable isotopic content of the samples is expressed in delta (δ) values, which are defined as the deviation (expressed in per mil) of the rare to abundant isotope ratio from that of a reference material where $\delta = [(^{a}R/^{b}R)_{sample}/(^{a}R/^{b}R)_{reference} - 1]$; ^{a}R is the rare-, and ^{b}R the abundant isotope ratio. For carbon, the reference material is belemnite carbonate (V-PDB); for nitrogen, the reference is ambient air (Mook 2006). The analytical error is 0.1‰ and 0.2‰ for $\delta^{13}C$ and $\delta^{15}N$, respectively. The ^{14}C dates are reported in BP by convention (Mook and van der Plicht 1999), using the oxalic standard and Libby halflife and including normalization for fractionation. The ^{14}C dates are calibrated using IntCal20 (Reimer et al. 2020) and OxCal software (Bronk Ramsey 2009). Calibrated dates are reported in calBP, i.e., calendar age relative to 1950 AD.

Bone Quality Aspects

Bone collagen is sensitive to degradation. The most common indicators for collagen integrity are the carbon and nitrogen extraction yields of the collagen, denoted as %C and %N, respectively. These numbers are provided by the mass spectrometer. Also, the atomic C/N ratio, C/N = (%C/%N) × (14/12) is a widely accepted quality parameter. Based on comparison with the chemical composition of collagen extracted from fresh bone using the same purification treatment, the carbon content of genuine collagen should be around 30-40 % and its nitrogen content around 11–16% for reliable results (van Klinken 1999). The C/N ratio for well-preserved bone collagen is 2.9–3.6 (DeNiro 1985; Ambrose 1991). The weight proportion of the extracted collagen in relation to the initial sample weight (% yield) is preferably minimally 0.5 (van Klinken 1999). For fresh bone, this number is about 20%.

In terms of contamination, one can calculate how much contamination is needed to explain aberrant dates. It obviously depends on the age of the contaminant, which theoretically can be any age between modern and fossil. Let us assume here modern contamination, then a contamination of 1% modern Carbon a sample of 50,000 BP will be measured as 35,000 BP. More examples can be found in Mook and Streurman (1983) and Mook and van de Plassche (1986), both written for the conventional dating method, using large samples. For our example, 1% foreign Carbon for a 1-gram sample is 10 mg, which is relatively much. The same calculations apply to AMS but the samples are much smaller. Here, a contamination of 1% foreign Carbon for a 1 mg sample is only 10 µg; therefore, AMS is much more sensitive for contamination (Lanting and van der Plicht 1994).

In natural circumstances, contamination can be caused by processes such as degradation which can enable invasion of carbon containing matter from the environment (Mook and Streurman 1983). This is particularly true for Pleistocene samples. We do not have an example where this is clearly shown, because of the lack of context for the North Sea samples. The key for successful dating is quality control, in particular the Carbon content of the collagen (Mook and Streurman 1983; Olsson 2009), later supplemented by the Nitrogen content. Also, the $\delta^{13}C$ and $\delta^{15}N$ values must be in certain ranges (van Strijdonck et al. 1999). For example, a $\delta^{13}C$ value of say –25‰ for bone can be suspect, in particular when the C content is low; contamination with material having low $\delta^{13}C$ values, like soil components, is then not unlikely. When the conservation circumstances are excellent, like in the permafrost, the collagen is usually perfect for dating, allowing dating to very old ages (slightly over 50,000 BP). An example is the Arilakh mammoth (Mol et al. 2006b). Together with discussions concerning which samples should be used as blank (background) for the ^{14}C method, made us argue to set the upper limit for bone dating at 45,000 BP. For details see van der Plicht and Palstra (2016).

RESULTS

The vast majority of data is in this overview is obtained by the Groningen laboratory. Limited data for the North Sea are available from other laboratories, which are included here to provide a date list for the North Sea which is as complete as possible. The laboratories can be recognized by internationally assigned laboratory codes as follows:

GrN	Groningen (Netherlands)	Conventional (until 2011)
GrA	Groningen (Netherlands)	AMS (1994–2017)
GrM	Groningen (Netherlands)	AMS (since 2017)
AA	Tucson (Arizona, USA)	AMS
K	Copenhagen (Denmark)	Conventional
KIA	Kiel (Germany)	AMS
M	Mannheim (Germany)	AMS
OxA	Oxford (UK)	AMS
UtC	Utrecht (Netherlands)	AMS

Some codes/laboratories are no longer in use or active today: GrN, GrA, K, and UtC (see the list of lab codes at www.radiocarbon.org).

The main result of ^{14}C measurement is, of course, the dating itself: a direct measurement of the age of the sample, which is otherwise difficult or impossible to establish. This is especially true for the North Sea finds because there is in general a lack of context like stratigraphy and/or associations. The results are shown in Tables 1 and 2 (see Appendix). They show the results for animal bones, sorted to ^{14}C age. Table 1 shows the animal bone results for ages older than the Holocene era; Table 2 for the Holocene era.

Laboratory code, locality, ^{14}C age and its uncertainty, species and skeletal element are shown, as well as the C and N contents and stable isotope ratios δ^{13}C and δ^{15}N of the collagen, when available. Some dates close to the dating limit are reported with asymmetric uncertainties, shown as $\sigma(-)$ and $\sigma(+)$. The ^{14}C dates are calibrated using the IntCal20 curve (Reimer et al. 2020) and are given as the 95% confidence range in calBP. The numbers are rounded to significant values.

The tables also include a parameter "quality" which we have defined as follows. Accepted dates are indicated by "a". They all meet the established quality aspects concerning C and N. The label "1" means that not all criteria are known. For example, for samples measured by other laboratories in we only have the ^{14}C dates and not the other data. Mostly, the δ^{13}C values are not published or otherwise available. The label "2" means that not all criteria are strictly met, but the outcomes are reasonable. For example, a C/N ratio of 2.8 is strictly taken not acceptable. But one has to take into account that the C% and N% measurements from which the C/N ratio is calculated are not very precise. In practice, there is no good reason for rejection. The label "3" means that only the C isotopes are measured (^{14}C and ^{13}C). This is related to the historical developments of the radiocarbon method. During the early decades of the method, the N isotopes of collagen has not been measured. This applies to almost all conventional dates and the early AMS dates. The measurement of N isotopes gradually became standard since the 1990s. The measurements that are "crossed out" are shown for completeness but rejected because of unacceptable sample quality. In all cases, we have used 0.5% collagen yield of the raw bone material as acceptance threshold.

In Figure 2 we show an overview of all dated bones, sorted taxonomically. A grand total of 144 Pleistocene and 71 Holocene accepted faunal dates (including duplicates) is represented. Figure 2 also includes human bone data from the North Sea; these are not further discussed here (see van der Plicht et al. 2016). In Figure 2, the ^{14}C ages (BP) are given instead of calibrated dates (calBP) to avoid reservoir effect ambiguities and still existing uncertainties in the oldest part of the calibration curve. The marine species are subject to a reservoir effect. This also applies to the giant auk. For the Holocene North Sea, for the reservoir effect a general number of 400 years can be taken. For the Pleistocene this number can vary significantly, depending on time and location. For a detailed discussion see Heaton et al. (2020) and references therein. For non-marine aquatic species (in terms of diet), an unknown reservoir effect applies. This is the case for the otter. Also, humans with a significant subsistence of freshwater/marine fish have an unknown reservoir effect.

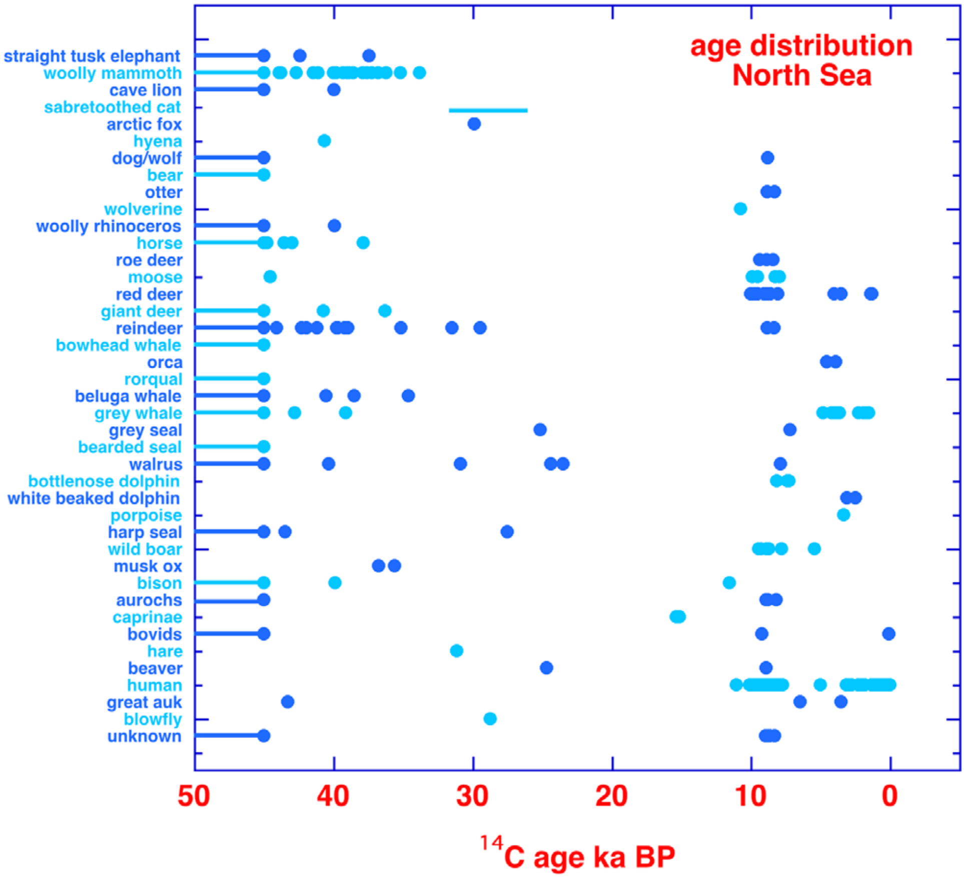

Figure 2 Age distribution of all dated bones from the North Sea, organised by species or taxonomical family. The horizontal lines at the left side of the figure correspond to ages larger than 45,000 BP. Dates reported as finite and older than 45,000 BP are truncated at 45,000 BP.

DISCUSSION: RADIOCARBON DATES OF THE FAUNA

Some General Observations for the ^{14}C Dates

The data (Tables 1–2 and Figure 2) show that the majority (about 2/3) of the fossils date to the Pleistocene. These are all faunal samples and include true ^{14}C dates and ages which are infinite on the ^{14}C time scale. A second group (about 1/3) represent the Holocene. These concern both human and animal fossil bones, including artifacts made of bone. It appears that the LGM (Last Glacial Maximum) period around 20,000 BP seems to be more less devoid of fossils. For the Holocene there are also human fossil bones; there is a group dating to the Mesolithic, and a (larger) group which is (sub)recent. For these data we refer to van der Plicht et al. (2016). After the Mesolithic the region became uninhabitable due to the sea level rise. Concerning the Glacial record, we note here a particular important example GrA-58271, a Late Glacial parietal bone which dates 11,050 ± 50 BP and is described in detail by Amkreutz et al. (2018). There is one Neandertal skull find known from the North Sea (Hublin et al. 2009). Unfortunately, as this sample did not contain collagen, it could not be dated. All other human bones assessed as possibly Neandertal based on their patina were dated as Mesolithic.

Terrestrial animals dated thus far are straight tusked elephant, woolly mammoth, cave lion, saber-toothed cat, arctic fox, hyena, dog/wolf, bear, otter, wolverine, woolly rhinoceros, horse, roe deer, moose, red deer, giant deer, reindeer, wild boar, musk ox, bison, aurochs, caprinae, other bovids, hare, and beaver. Marine animals are bowhead whale, orca, common rorqual, beluga whale, grey whale, grey seal, bearded seal, walrus, bottlenose dolphin, white beaked dolphin, porpoise, and harp seal. The dataset contains one bird species (great auk).

It is of interest here to note that Late Pleistocene and Early Holocene mammals from two different sites in the Netherlands show many similarities. The faunal composition of the dredged site De Groote Wielen (near Den Bosch) and the Eurogully (North Sea) is almost identical. The ^{14}C dates show that the mammoth fauna are more or less of the same age. The results from De Groote Wielen, in particular for woolly mammoth (*Mammuthus primigenius*) and woolly rhinoceros (*Coelodonta antiquitatis*) can be found in Mol et al. (2010b).

However, aspects such as taphonomic processes, choices for sediment used for sand suppletion projects, mesh size of fishing nets, detection of finds by (often amateur) collectors, and the glamour of specific finds dramatically determine the type of North Sea finds that are finally submitted for radiocarbon dating. Hence, the composition of the current dataset is biased, which affects the representation of species and periods. For instance, small, fragile fish and bird bones are just sporadically submitted for radiocarbon dating. First of all, classical, precise excavation and sieving methods cannot be applied within the North Sea area, limiting the recovery of smaller sized finds. Moreover, often the collagen of such remains does not preserve well enough for dating purposes.

Samples of cervids are represented in relatively high numbers in the radiocarbon dataset. Many of these are modified antlers. But also artifacts made of cervid bones and skeletal elements of bovids and horses have been submitted for age determination. A prime example is a decorated, Late-Glacial bovid metatarsus which dated 11,560 ± 50 BP (GrA-28364) see Amkreutz et al. (2018).

Many finds come from a limited number of regions from the North Sea area, specifically locations that are frequently exploited by fishermen and that are suitable for sand extraction purposes. Indeed, more than a third of the samples come from the important fishing areas Eurogully and the Brown Bank (see Figure 1). Also, a large part comes from the Dutch province Zuid-Holland, where many large sand suppletion projects took place in recent years, in particular Maasvlakte and Zandmotor (Figure 1).

Although this dataset reflects a biased composition of dwellers of the North Sea area in the past, it gives insight in aspects such as species present in different periods and chemical conservation of fossil remains, helps to solve geological puzzles of the North Sea bottom, and reveals some spectacular discoveries.

Context of the Material

A difficult issue has always been the context of the finds from the North Sea. Only recently, a detailed stratigraphic framework has been made for the Eurogeul region (Hijma et al. 2012) and for a small region offshore of the Maasvlakte area (Busschers et al. 2013). The defined lithostratigraphic units show signs of repeated, severe reworking during various fluviatile and/or marine depositional phases. Therefore, is likely that none of the North Sea assemblages, including the dated samples discussed in this paper, are pristine and free from mixing.

The geological framework presented by Hijma et al. (2012), even implies that all Late Pleistocene terrestrial mammals dating older than around 30,000 years must have been redeposited from their original location. However, overall, the skeletal remains from the North Sea are well preserved with just few signs of weathering and little or no rounding (Kuitems et al. 2013a). Such taphonomic characteristics indicate that the skeletal material did not lie on the surface for long, nor was it transported over large distances. Therefore, many finds may derive from eroded, large lumps of such reworked sediments (Kuitems et al. 2013b).

Besides the depositional history of the material, the way the fossils have been retrieved hampers assigning palaeontological and archaeological finds to a precise stratigraphic unit. That is, most fossils of large mammals are collected during fishing expeditions (Mol et al. 2008; Mol and Post 2010a). The rough location of the ship was reported along with many of the samples that were found in fishing nets. But, even the most detailed data available on location and depth of the nets are far from precise enough to link a find to a specific stratigraphical layer (Kuitems et al. 2013b). However, combining the radiocarbon dates, ship's coordinates, geological information and knowledge of ecological preferences and restrictions of species, a number of finds can be assigned to a specific lithological unit. Below, selected results of the isotope date list for the North Sea fossil bones are discussed and highlighted in more detail.

Unique Samples

Unique finds are first finds of certain species of the Mammoth steppe in the North Sea. Among these is a first find of a hare (*Lepus* Sp.) from the bottom of the North Sea, found at the Zandmotor. It is a mandible, ^{14}C dated to 31,140 (–190, +200) BP (GrA-54021). For more details we refer to Mol and van der Plicht (2012a). This result represents a first such old date for this species for the North Sea.

Also finds of bones from an otter (*Lutra lutra*) yield the first dates for this species from the North Sea. They were recovered from the sand suppletion area for the Maasvlakte (Mol and van der Plicht 2012b). Two specimens date to the Early Holocene: 8825 ± 45 BP (GrA-52432) and 8300 ± 40 BP (GrA-52433). This result provides a clear answer to the question whether these animals date to the mammoth fauna or not.

Another first age-establishment for a species in this particular area concerns an arctic fox (*Alopex*) from the Zandmotor, in the suppleted sand originating from the Eurogully (Langeveld et al. 2018). It is dated to 29,900 (–490, +550) BP (GrA-69520). We note that an even younger arctic fox is known from De Groote Wielen near 's-Hertogenbosch in the southern Netherlands, about 90 km inland. The ^{14}C date is 21,890 ± 100 BP (GrA-35484; Verhagen and Mol 2009).

A series of 11 fossil bones from the giant auk (*Pinguinus impennis*) from the North Sea region was submitted for ^{14}C dating (Langeveld 2015). Unfortunately, only three samples appeared datable; the collagen yield of the others was too low. The collagen of the three analysed samples was of good quality (see C and N parameters, Table 1 and 2). Two samples from the Zandmotor dated Holocene, the youngest 3505±45 BP (GrA-65546). One bone dated

Pleistocene: 43,290 (–380, +400) BP (GrA-64453). The latter was found on the beach of Hoek van Holland. The stable isotope ($\delta^{13}C$ and $\delta^{15}N$) results of the three auk samples indicate a pure marine diet, as expected. That means that the dates need to be corrected for the reservoir effect. For the Holocene the correction is 400 years. Thus, the youngest sample is 3105 ^{14}C years old, which calibrates into 1425–1300 BC.

A unique find of importance is a fossil bone (mandible with teeth) of a sabertoothed cat (*Homotherium*) from the Brown Bank. A series of six samples was dated by AMS in Utrecht, resulting in a final date of ca. 28,000 BP (Reumer et al. 2003). These six dates range between 26,700 and 31,300 BP, with uncertainties ranging between 220 and 400 BP. A few samples of mandible and tooth were dated with varying results in $\delta^{13}C$ and ^{14}C age. Hence, the six dates cover a significant range, which is indicated in Figure 2 as a horizontal bar because it concerns here only one specimen. However, no further quality parameters of the collagen are available.

Relevant Dates for Non-Bone Samples

There are a few samples with a North Sea context that were radiocarbon dated which are not bone or another skeletal part, but are relevant: wood artifacts, fly pupae, coprolites, and plant remains. Here we discuss only finds which are faunal related.

Fly pupae (*Protophormia terraenovae*) were found in a skull from a woolly mammoth dredged from the Eurogully. They were dated by ^{14}C to 28,740 (–180, +190) BP (GrA-50454; Table 1) (van der Plicht et al. 2012). Like many other ^{14}C dates, this is younger than stratigraphic inferences for the Eurogully (Hijma et al. 2012). The importance of this fly pupae date that it is not obtained from fossil bone. Pleistocene bone collagen is often a subject of deliberations in terms of degradation and/or contamination (e.g., van der Plicht and Palstra 2016). There is no reason at all to “suspect” the fly pupae date in this respect. We note that there is one other fly pupae date known from “de Groote Wielen” near Den Bosch, the Netherlands, that was found in association with Late Pleistocene mammal bone. The date is 26,660 ± 150 BP (GrA-35816) (Verhagen and Mol 2009). This date shows the same general timerange as that of the Eurogully.

A few coprolites of Hyena (*Crocuta crocuta*) are found, and dating has been attempted. However, because of the nature of the sample material this appeared problematic. One coprolite (found on the Brown Bank) contained a small bone and a small piece of wood. The latter dates to 18,310 ± 150 BP (GrA-59740). The bone appeared not datable. A coprolite found on the Maasvlakte (in sand originating from the Eurogully) was dated as “organic matter,” yielding a ^{14}C age of 35,050 (–240, +250) BP (GrA-56323). The C content was low (4.9%), the $\delta^{13}C$ value –16.43‰.

A recent find is a molar from a giant deer (*Megaloceros giganteus*). It was found in sandy deposits of the North Sea, about 10 km west of the present coastline. Unfortunately, the collagen preservation of the molar appeared very poor. This sample is not included in the datatable and figures. However, plant remains were preserved in the deep folds of the molar. This shows that the animal foraged in a steppe environment, eating *Artemisia*. For details we refer to van Geel et al. (2018). The plant remains are ^{14}C dated to 38,750 (–290, +300) BP (GrA-68256), corresponding to Greenland Interstadial 11.

Anomalous ^{14}C Dates

A striking example is a worked reindeer bone with cut marks displaying a human face. Archaeologically this is potentially a sensational sample, believed to date to the Mesolithic. But it dated to 1310 ± 60 BP (GrA-20291). Technically, this was a problematic sample because the bone had been treated with preservatives, and the material was very delicate. It was established by radiocarbon that the artifact was not as old as was hoped; it is not related to ancient people living in what is today the North Sea area. A duplicate dating yields essentially the same date (GrA-22093, 1370 ± 40 BP). This pair of ^{14}C dates was the reason to change the determination from reindeer to red deer. Assuming the contamination was removed adequately, of course. The preservative applied is known as Stelfon, which is of fossil origin (i.e., does not contain ^{14}C). So, in contrast to most collagen-containing contaminants, if any contamination was left on the material after pretreatment it measures older than its actual age, its true age being even more recent.

Another anomalous date concerns a "goat-like animal" (Caprinae) from the Brown Bank, which could not be further identified. It dates to the Late Glacial: 15,190 ± 60 BP (GrA-38211) which is impossible, or at least not very likely based on present palaeontological understanding. The sample was dated again, even in threefold, all with the same result (Table 1). There is no reason to doubt the dating; there are no signs of contamination, and the sample quality parameters are good. In theory the species identification could be problematic but that is not known. This sample is a mystery which still remains to be resolved.

Issues Near the ^{14}C Limit

Many of the (Late) Pleistocene fossils belonged to typical so-called mammoth steppe fauna. Moreover, a large number of Pleistocene fossils are from marine mammals. The set of ^{14}C dates for large marine mammals have raised questions, which still need to be resolved. That is, many whales date between 35,000 and 45,000 BP and walruses between 25,000 and 30,000 BP. However, following Hijma et al. (2012), the marine fauna should be about 60–85,000 years old. Therefore, these ^{14}C dates have been criticized (Rijsdijk et al. 2013). Could contamination possibly cause anomalously young dates such that fossils of say 80,000 years old date 40,000 in the laboratory? This question has been raised earlier for the *Homotherium* (dating around 28,000 BP) and *Elephas antiquus* (37,440 ± 310 BP, GrA-25815). These samples should perhaps be redated for confirmation, applying compound specific dating (Devièse et al. 2018).

The above was a motivation to study in depth some technical issues concerning ^{14}C dating of Pleistocene (i.e., "old") samples. This concerns laboratory intercomparisons, backgrounds, contamination and pretreatment. A series of mammoth bones from the North Sea has been investigated for this purpose. This "test series" resulted in valid dates which are shown in Tables 3 and 4 and concerns GrA-56655, 56656, 55658, 56660, 56661, 56662, 56664, 56674, 56675, and 56676. Incidentally, of our test series GrA-56660 (a mammoth humerus from the Eurogully) showed bite marks of Hyena. Hence, the ^{14}C date provides a date for this species, i.e., *Crocuta crocuta spelaea*, as well.

Radiocarbon laboratories regularly organize an exchange of samples varying in age and material to compare dating protocols (Scott et al. 2010). The latest intercomparison program is known as SIRI (Sixth International Radiocarbon Intercomparison; see www.radiocarbon.org). The sample dated as GrA-56658 is already in use for the purpose and is now known as sample B for SIRI. Other bones from the North Sea bones were also shipped to the Glasgow laboratory (the coordinating laboratory for ^{14}C intercomparisons) for possible future use.

Some samples are just lightly touched by glue, which is supposedly efficiently removed, in particular with an extra chemical cleaning called "Soxhlet" (Bruhn et al. 2001). Such contamination was applied to a series of samples from Great Yarmouth (6 miles east off the coast): GrA-39962, 39964, 39965, 39966, and 39121. Indeed, the resulting collagen parameters are well in their acceptable ranges, and the dates appear reasonable. For more details concerning the Soxhlet procedures applied in Groningen we refer to Dee et al. (2020).

Apart from the official intercomparison program which includes samples of all ages and materials, Pleistocene bones are often dated by more than one laboratory to compare protocols. This is particularly done for samples which are unique. Examples can be found in the literature (Semal et al. 2009; Crevecoeur et al. 2010; Maroto et al. 2012; Fiedel et al. 2013; Huels et al. 2017; Kuzmin et al. 2018). Of particular interest here is the so-called ultrafiltration method (Bronk Ramsey et al. 2004) which was introduced to further purify (i.e., remove remaining contaminants) from bones treated by the classic Longin (1971) method. However, the effectiveness of ultrafiltration is not without controversy (Huels et al. 2009; Fülöp et al. 2013; Minani et al. 2013).

The laboratory intercomparisons show that for good quality bone, no additional treatments are necessary (van der Plicht and Palstra 2016). Furthermore, we mention here a relatively new development: compound specific dating. Separated amino acids from collagen, in particular hydroxiproline (known as HYP) are the most reliable datable fraction of (partially) degraded bone (Devièse et al. 2018).

Another important methodological aspect is the dating limit of the ^{14}C method, and reporting dates close to that limit. The measurement errors become asymmetric, leading to the so-called 2-sigma criterion: when the measured activity becomes smaller than 2 times its measurement error, the age is given as this limit (Olsson 1989; van der Plicht and Hogg 2006). As stated above, a proper background determination is essential as well. In any case, dates like KIA-25281 reported as a finite number 54,010 (–2630, +3940) BP (see Table 1) we consider not realistic.

DISCUSSION: STABLE ISOTOPES OF THE FAUNAL BONES

Along with radiocarbon, stable carbon and often nitrogen isotopes have been measured for many of the organic remains. The stable isotope (^{13}C, ^{15}N) signal of fossil animal bones is a powerful tool for investigating ancient environments, ecosystems, and the reconstruction of the diet and ecological preferences of species (e.g., Drucker et al. 2010). For animals and humans, the isotopic values of fossil distinguish herbivores, omnivores, carnivores, C3 and C4 plant consumers, and terrestrial and aquatic diets—to mention the main categories. Such analyses are based on the principle that the organic tissues of an organism (bone collagen and teeth) reflect the composition of the food and water the organism ingested during its life (Kohn 1999; Fry 2008). Well known is the large distinction in δ^{13}C values between C3 and C4 plants, which utilize a different photosynthesis process. These values are reflected in the tissues of consumers (e.g., Vogel and van der Merwe 1977; Fry 2008).

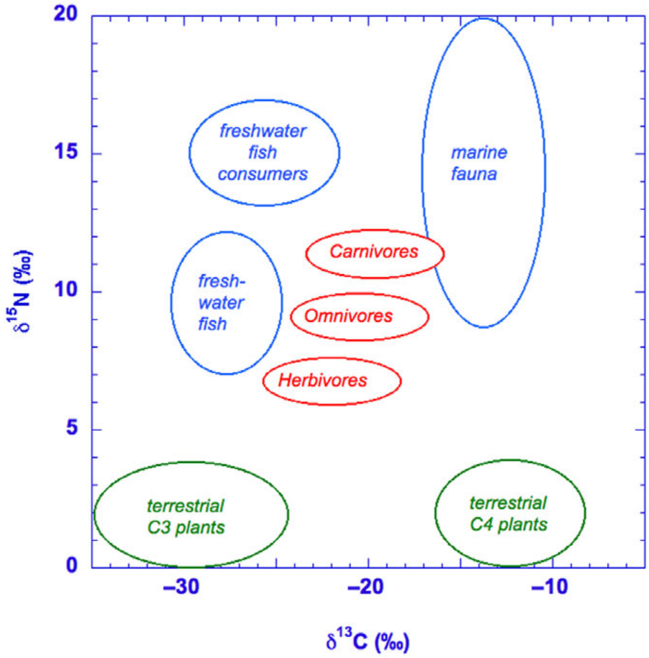

Figure 3 Schematic representation of (part of) the food web, indicating the relative ranges of $\delta^{13}C$ and $\delta\ ^{15}N$ values.

Distinctive $\delta^{15}N$ values are observed between trophic levels. The isotopic enrichment of the $\delta^{15}N$ value is larger than that of $\delta^{13}C$, about 3–5‰ for each trophic level shift (Bocherens and Drucker 2003; Hedges and Reynard 2007). This means for instance, that in general the bone collagen of a carnivore is enriched in ^{15}N relative to ^{14}N in comparison with the $^{15}N/^{14}N$ ratio ($\delta^{15}N$) originally present in the prey species, and herbivores have higher $\delta^{15}N$ values than the plants they consume (Bocherens 2003). Distinctive $\delta^{13}C$ values are also observed between trophic levels. The isotopic signatures of food sources are passed along the food chain to their consumers, with an enrichment of the $\delta^{13}C$ value by about 1‰ for each trophic level shift (Lanting and van der Plicht 1998).

A distinctive environment is the aquatic one. For freshwater reservoirs, typical isotope values for animals and humans are around –25‰ and +13‰ for $\delta^{13}C$ and $\delta^{15}N$, respectively (e.g., Philippsen 2013; Cook et al. 2001; Arneborg et al. 1999). For the marine reservoir, these are around –11‰ and +13‰ for $\delta^{13}C$ and $\delta^{15}N$, respectively (e.g., van der Plicht et al. 2016). Figure 3 shows an example of general ranges for terrestrial fauna, humans consuming terrestrial food, freshwater food, and marine food.

The dataset consists of data of terrestrial and aquatic organisms. For the latter, the ^{14}C dates need correction for reservoir effects in order to derive absolute ages. This also applies to terrestrial organisms with a significant aquatic food subsistence. The latter is not simply 400 years (the general marine Holocene value) but can be riverine (or a mixture of both) since the Early Holocene landscape of the present North Sea region was a delta. The stable isotopes $\delta^{13}C$ and $\delta^{15}N$ are a necessary tool to quantify reservoir effects. The present tables consist for a major part of unpublished ^{14}C, ^{13}C, and ^{15}N data, and can be used in the future to further zoom in on this question. In all figures and tables, the ^{14}C ages (BP) are given instead of calibrated dates (calBP) to avoid reservoir effect ambiguities.

The data represents marine carnivores, terrestrial carnivores, omnivores (incl. humans), herbivores, and one bird species (Tables 1 and 2). The majority of the animal samples correspond to the Pleistocene. Indeed, many samples belong to typical Late Pleistocene mammoth steppe fauna, including woolly mammoth, cave lion, arctic fox, hyena, woolly rhinoceros, horse, giant deer, reindeer, and bison. In addition, the dataset includes 19 marine animals with a Pleistocene age, such as bowhead whale, common rorqual, beluga whale, grey whale, grey seal, harp seal, walrus, and great auk.

The rest of the samples correspond to the Holocene era: 61 animal skeletal remains, including 25 artifacts/worked items made of antler and bone. There is also a significant dataset of human bones. Here we will only use their average values of stable isotope ratios, for comparison with those of the fauna. For more details we refer to van der Plicht et al. (2016). Many finds come from a relatively limited number of areas from the North Sea, specifically locations that are frequently exploited by fishermen and that are suitable for sand extraction purposes. Indeed, about a third of the samples come from the important fishing areas Brown Bank (n = 53) and Eurogully (n = 43). Also, a large part (n = 38) comes from the Dutch province Zuid-Holland, in which many large sand suppletion projects took place in recent years (Maasvlakte, Zandmotor; see Figure 1).

Table 3 (see Appendix) shows an overview summary of the analysed species, number of samples, class, environment (marine or terrestrial) and trophic level, with the (averaged) value of δ^{13}C and δ^{15}N. Figure 4 shows the mean δ^{13}C and δ^{15}N values for the samples, roughly ordered per trophic niche. In general, the isotope signals of most species fit into broad groups as shown in Figure 3. As expected, the marine carnivores show the highest δ^{13}C and δ^{15}N values. Their δ^{13}C values range between –16.7 and –11.4 ‰, and the δ^{15}N values between +9.3 and +17.7‰. The terrestrial herbivores show δ^{13}C values ranging from –23.3 to –18.9‰. The δ^{15}N values cover a large range of 9.9‰, the lowest being +1.7‰ and the highest δ^{15}N value (+11.6‰) being higher than those of the terrestrial omnivorous animals and terrestrial carnivores in the current dataset.

Apart from the humans, the terrestrial omnivores data fall within the range of these of terrestrial herbivores; δ^{13}C values range between –22.3 and –20.3‰, and δ^{15}N between +3.5 and +7.7‰. The humans show large ranges of both isotope values (see van der Plicht et al. 2016). The terrestrial carnivores have δ^{13}C and δ^{15}N values between –25.6 and –19.2‰ and between +7.7 and +10.2‰, respectively. The dataset consists of two samples of a freshwater carnivore, an otter, with a δ^{13}C value of –26.2‰ and –24.8‰, and a δ^{15}N value of +8.6‰ (the δ^{15}N of only one sample has been measured). These categories of trophic level/habitat are composed of a variety of species from different time periods. In the following, results of a number of species will be discussed in more detail. This selection is primarily based on the number of available samples per species.

The data for the Pleistocene samples are shown in Figure 5. As can be seen, the δ^{15}N values of straight-tusked elephant (+7.5 to +11.6‰) and many of woolly mammoth (+5.0 to +9.1‰) exceed these of other herbivores. Relatively high δ^{15}N values are commonly observed for woolly mammoths (e.g., Bocherens 2003; Kuitems et al. 2015a) and has also been observed for Middle-Pleistocene straight-tusked elephants from Germany (Kuitems et al. 2015b). The current dataset also includes woolly mammoth samples with lower δ^{15}N values. This has also been observed for Late-Glacial woolly mammoths in the Ukraine (Drucker et al. 2014),

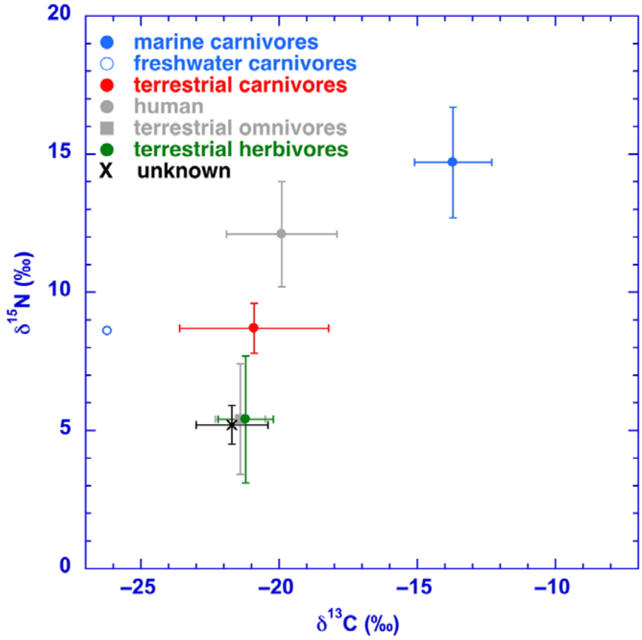

Figure 4 Mean stable isotope ($\delta^{13}C$ and $\delta^{15}N$) values with one sigma standard deviation for all animal samples, ordered per trophic level (herbivore, carnivore, omnivore) and habitat (marine, terrestrial). All samples are from mammals.

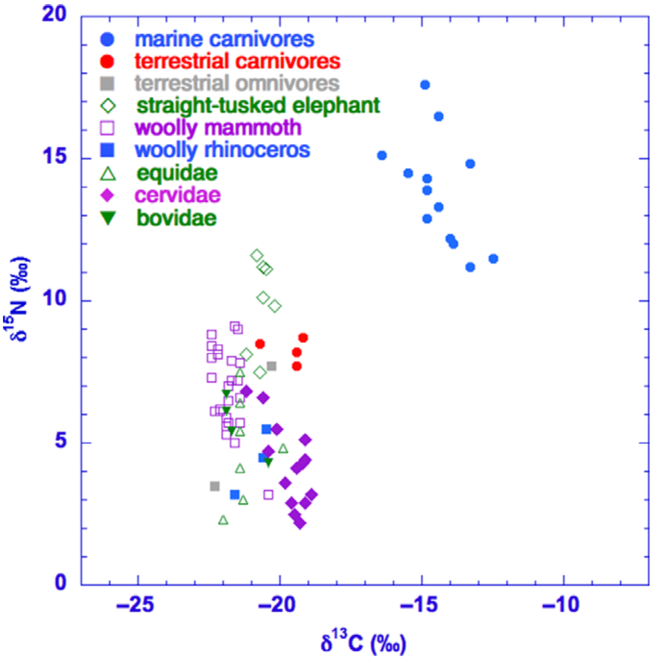

Figure 5 Stable isotope ($\delta^{13}C$ and $\delta^{15}N$) values for Pleistocene mammal samples from the North Sea.

and has been associated with changing environments and/or climates and changes of niche occupation after the Last Glacial Maximum (LGM). Pre-LGM values of mammoths from Europe (including samples from the Ukraine) show higher δ^{15}N values, ranging between 6.7‰ and 11.1‰ (Drucker et al. 2014). The current dataset of the North Sea contains only mammoth samples dating pre-LGM, the majority being older than the ^{14}C background (>45,000 BP). The woolly mammoth samples with the lowest δ ^{15}N values (between +5.0 and +6.0‰) are all older than 45,000 years BP.

The δ^{13}C values of woolly mammoths (–22.4 to –21.4‰) are rather negative compared to these of other herbivores, including straight-tusked elephants (–21.2 to –20.2‰). Also, this picture (woolly mammoths are depleted in δ^{13}C compared to other herbivores) is known for other localities and has tentatively been linked to seasonally metabolism of stored fat (Bocherens 2003; Szpak et al. 2010).

All horses ($n = 6$) in this dataset originate from the (Late) Pleistocene. Their δ^{15}N and δ^{13}C values range from +2.3 to +6.4‰ and from –22.0 to –19.9‰, respectively. The general view of the horse diet is that it consists predominantly of grasses. However, dental wear studies on molars from Middle Pleistocene horses from Europe, with considerably low δ^{15}N values, indicated that these specimens were mainly browsing (Rivals et al. 2015). The lower δ^{15}N values have also been interpreted as the result of a browsing diet for these specimens (Kuitems et al. 2015b), since usually browsers tend to have lower δ^{15}N values than grazers (and lower δ^{13}C values; e.g., Drucker et al. 2010). Another recent study on a Middle Pleistocene site from France (Richards et al. 2017) revealed that stable isotope values from horse dentine samples in a temporal sequence followed environmental and possibly climatic changes through time. Here, the lowest δ^{15}N values (about +2 to +3‰) are linked to low temperatures. The lowest δ^{15}N values of horse samples in the current dataset from the North Sea can either be caused by a specific diet (i.e., browsing) or low temperatures and/or high amounts of precipitation (i.e., affecting the δ^{15}N values of plants they are feeding on), or by a combination of these factors.

Well-defined temporal changes in the distribution of δ^{13}C and δ^{15}N values have been observed for several species within North-western Europe, related to the climatic and environmental differences during the Late-Glacial and/or around the Pleistocene-Holocene boundary. These include changes in atmospheric CO_2 concentrations (Richards and Hedges 2003; Stevens and Hedges 2004), climatic variation on a local-scale including soil moisture conditions (Stevens and Hedges 2004; Fox-Dobbs et al. 2008), and forest development after the LGM (Drucker et al. 2003, 2008), leading to depleted δ^{13}C values in the Holocene.

Indeed, the Pleistocene-Holocene boundary is characterized by severe climatic and environmental changes for the area of the current North Sea. In general, the onset of the Holocene is characterized by wetter and warmer climatic circumstances, sea level rise and forest development. The current stable isotope record for the North Sea does not allow for statements on temporal trends: none of the species is represented (in appropriate numbers) in both Pleistocene and Holocene. Moreover, in general, samples from the last part of the Late-Pleistocene, i.e., the LGM and the Late Glacial, are lacking (see Tables 1 and 2 and Figure 2).

In contrast to the characteristic Pleistocene “mammoth steppe fauna,” generally thriving in open landscapes, the Holocene samples represent specimens from temperate species and forest dwellers. This is illustrated by the North Sea samples of cervids: Pleistocene samples are chiefly from reindeer, and consists further of giant deer and moose, whereas the

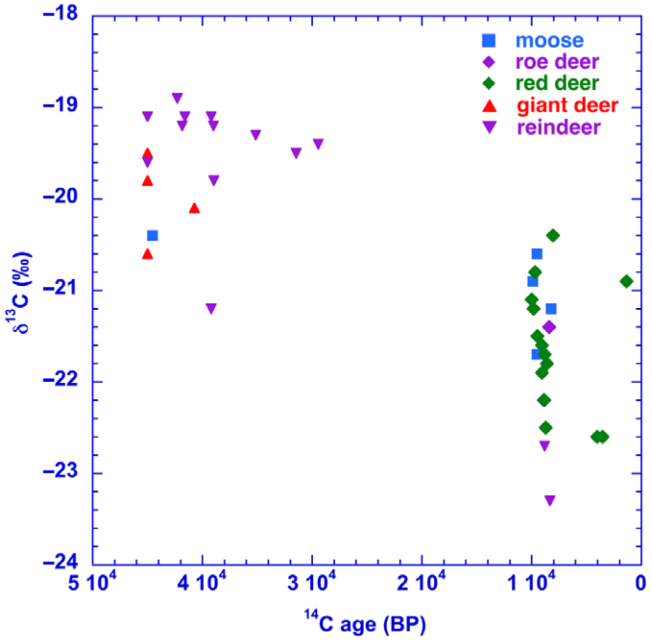

Figure 6 Stable isotope δ^{13}C values for samples of cervids from the North Sea through time.

Holocene samples of cervids predominantly consists of red deer, and further include moose and roe deer. As shown in Figure 6, the δ^{13}C values of samples from Holocene cervids (n = 22, average = –21.7‰) are considerably more negative than those of the Pleistocene cervids (n = 20, average = –19.7‰).

This difference can partly be ascribed to the changed δ^{13}C values of plants caused by the climatic shift from the Pleistocene to the Holocene. Moreover, this difference can be explained by dissimilarities between the species, such as niche occupation, physiology and dietary composition. For instance, in general the diet of reindeer consists for a significant part of lichens, which commonly yield higher δ^{13}C values than vascular plants (Ben-David et al. 2001; Drucker et al. 2003).

Due to the sea level rise, samples of marine mammals recur in the Holocene record. Considering the marine bone samples, a number of the walruses (*Odobenus rosmarus*) has a low nitrogen isotope ratio (n = 4; average = +12.1‰) compared to most other marine mammals (average = +14.5‰). This might be ascribed to the feeding on food sources of a low trophic level, such as clams and other molluscs (Dehn et al. 2007).

The freshwater species is only represented by two samples from a Holocene otter. Also, the stable isotopes of the Holocene dog/wolf (*Canis* sp.; GrA-24209) show mainly a freshwater signal (Figure 7). This is not surprising, since the Holocene dog lived together with humans, as is known from other sites in Northwestern Europe (e.g., Noe-Nygaard 1983, 1988; Schulting and Richards 2002; Fischer et al. 2007). In general, freshwater fish was an important part of the diet of Mesolithic humans in this area (see next paragraph). Their dogs might have consumed the "rest" of the human meal (Noe-Nygaard 1983), causing a

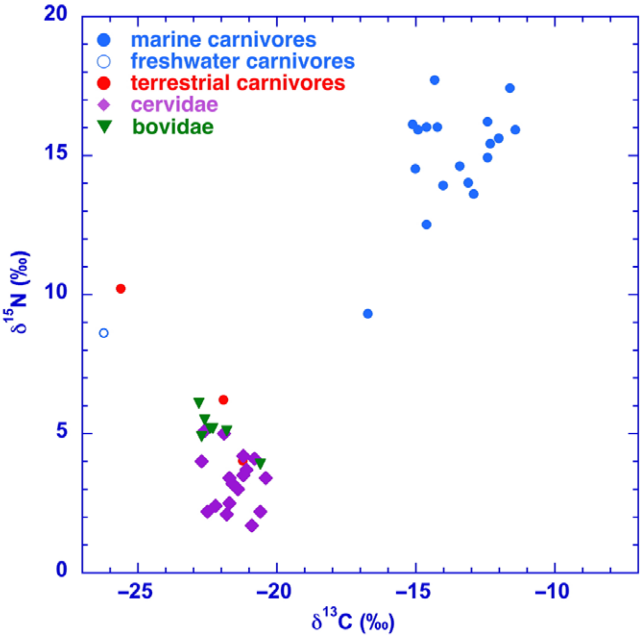

Figure 7 Stable isotope (δ^{13}C and δ^{15}N) values for Holocene animal samples from the North Sea.

freshwater signal. Besides numerous samples from human skeletal remains, abundant finds of stone tools indicate the presence of Mesolithic hominins in the North Sea area.

Indeed, during the Mesolithic the higher areas in the coastal landscape of the North Sea, such as river dunes were inhabited. A well-known example is the archaeological site Hardinxveld-Giessendam De Bruin (Louwe Kooijmans et al. 2001). Among the faunal remains that were submitted for radiocarbon dating are numerous pieces of worked bone and antler, including artifacts. These comprise long bones of bovids, equids, and cervids, and antler predominantly of red deer. The bone material from six of such objects could not be identified at species level. These are plotted as "unknown." The δ^{13}C and δ^{15}N values fall within the ranges of terrestrial herbivores. This is not surprising as artifacts were usually made from cervid bone.

CONCLUSIONS

The North Sea region was dry land during the last glacial period and was inhabited by a rich fauna. This yields large quantities of fossil bones recovered from the present seabed. Over the years, more than 200 animal bones are dated by ^{14}C, including a significant amount from extinct species. These were dredged up from the sea bottom or are found on the beach or on sand suppleted areas. Since the finds are recovered without a clear context, the dates yield crucial information for reconstructions of the past environment in a multidisciplinary setting.

We discuss here the available dates and show that most fossil bones provide important information on palaeontology, palaeoecology, landscape, and archaeology for this unique heritage site. The stable isotope ratios δ^{13}C and δ^{15}N of the dated bones illustrate that a collection of stray finds without context nevertheless can lead to inference of past environments in a multidisciplinary approach. For most of the animal remains from the North Sea, this is the first time that the stable isotope values are discussed. This consists of information on both extinct and extant terrestrial and aquatic species. The extinct species include straight-tusked elephant, woolly mammoth, woolly rhinoceros, and cave lion.

As a heritage site, the North Sea area has been archaeologically and palaeonotlogically extensively explored by both classic methods and modern techniques. Radiocarbon dates and stable isotope data add valuable information on environmental conditions and dietary habits in this area through time.

REFERENCES

Aerts-Bijma AT, van der Plicht J, Meijer HAJ. 2001. Automatic AMS sample combustion and CO_2 collection. Radiocarbon 43:293–298.

Amkreutz L, Verpoorte A, Waters-Rist A, Niekus M, van Heekeren V, van der Merwe L, van der Plicht J, Glimmerveen J, Stapert D, Johansen L. 2018. What lies beneath… Lateglacial human occupation of the submerged North Sea landscape. Antiquity 92:22–37.

Ambrose SH. 1991. Effects of diet, climate and physiology on nitrogen isotope abundances in terrestrial foodwebs. Journal of Archaeological Science 18:293–317.

Arneborg J, Heinemeier J, Lynerup N, Nielsen HL, Rud N, Sveinbjornsdotir AE. 1999. Change of diet of the Greenland Vikings determined from stable carbon isotope analysis. Radiocarbon 41:157–168.

Ben-David M, Shochat E, Adams L. 2001. Utility of stable isotope analysis in studying foraging ecology of herbivores: examples from moose and caribou. Alces 37:421–434.

Bocherens H. 2003. Isotopic biogeochemistry and the paleoecology of the mammoth steppe fauna. In: Reumer JWF, De Vos J, editors. Advances in mammoth research. Proceedings of the Second International Mammoth Conference, Rotterdam, May 16–20, 1999, Vol. 9. Rotterdam: DEINSEA. p. 57–76.

Bocherens H, Drucker D. 2003. Trophic level isotopic enrichments for carbon and nitrogen in collagen: case studies from recent and ancient terrestrial ecosystems. International Journal of Osteoarchaeology 13:46–53.

Bronk Ramsey C, Higham T, Bowles A, Hedges R. 2004. Improvements to the pretreatment of bone at Oxford. Radiocarbon 46:155–163.

Bronk Ramsey C. 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51:337–360.

Bruhn F, Duhr A, Grootes PM, Mintrop A, Nadeau MJ. 2001. Chemical removal of conservation substances by soxhlet-type extraction. Radiocarbon 43:229–237.

Busschers F, Westerhof W, van Heteren S. 2013. Het stratigrafisch raamwerk voor de geologische opbouw van het zandwingebied Maasvlakte 2. Rapport 1 van het geoarcheologisch en paleontologisch onderzoek zandwingebied en buitencontour Maasvlakte 2. Utrecht: TNO. In Dutch.

Cohen KM, Gibbard PL, Weerts HJT. 2014. North Sea palaeo-geographical reconstructions for the last 1 Ma. Netherlands Journal of Geosciences 93:7–29.

Cook GT, Bonsall C, Hedges REM, McSweeney KM, Boronean V, Pettitt PB. 2001. A freshwater diet-derived ^{14}C reservoir effect at the Stone Age sites in the Iron Age gorge. Radiocarbon 43:453–460.

Cook GT, van der Plicht J. 2013. Radiocarbon dating. Encyclopedia of Quaternary Science. 2nd revised edition. p. 305–315.

Crevecoeur I, Bayle P, Rougier H, Maureille B, Higham T, van der Plicht J, De Clerck N, Semal P. 2010. The Spy VI child: a newly discovered Neandertal infant. Journal of Human Evolution 59:641–656.

Dee MW, Palstra SLW, Aerts-Bijma AT, Bleeker MO, de Bruijn S, Ghebru F, Jansen HG, Kuitems M, Paul D, Richie RR, Spriensma JJ, Scifo A, van Zonneveld D, Verstappen-Dumoulin BMAA, Wietzes-Land P, Meijer HAJ. 2020. Radiocarbon dating at Groningen: new and updated chemical pretreatment procedures. Radiocarbon 62:63–74.

Dehn LA, Sheffield GG, Follmann EH, Duffy LK, Thomas DL, O'Hara TM. 2007. Feeding ecology of phocid seals and some walrus in the Alaskan and Canadian Arctic as determined by stomach contents and stable isotope analysis. Polar Biology 30:167–181.

DeNiro MJ. 1985. Postmortem preservation and alteration of in vivo bone collagen isotope ratios in relation to paleodietary reconstruction. Nature 317:806–809.

Devièse T, Comeskey D, McCullagh J, Bronk Ramsey C, Higham T. 2018. New protocol for compound-specific radiocarbon analysis of archaeological bones. Rapid Communications of Mass Spectrometry 32:373–379.

Drucker DG, Bidault A, Hobson KA, Szuma E, Bocherens H. 2008. Can carbon-13 in large herbivores reflect the canopy effect in temperate and boreal ecosystems? Evidence from modern and ancient ungulates. Palaeogeography, Palaeoclimatology and Palaeoecology 268:69–82.

Drucker DG, Bocherens H, Billiou D. 2003. Evidence for shifting evironmental conditions in Southwestern France from 33000 to 15000 years ago derived from carbon-13 and nitrogen-15 natural abundances in collagen of large herbivores. Earth and Planetary Science Letters 216:163–173.

Drucker DG, Bocherens H, Péan S. 2014. Isotopes stables (^{13}C,^{15}N) du collagène des mammouths de Mezhyrich (Epigravettien, Ukraine): implications paléoécologiques. L'anthropologie 118:504–551.

Drucker DG, Hobson KA, Ouellet JP, Courtois R. 2010. Influence of forage preferences and habitat use on ^{13}C and ^{15}N abundance in wild caribou (*Rangifer tarandus caribou*) and moose (*Alces alces*) from Canada. Isotopes in Environmental and Health Studies 46:107–121.

Fiedel SJ, Southon JR, Taylor RE, Kuzmin YV, Street M, Higham TFG, van der Plicht J, Nadeau MJ, Nalawade-Chavan S. 2013. Assessment of interlaboratory pretreatment ptotocols by radiocarbon dating an elk bone found below the Laacher See Tephra at Miesenheim I (Rhineland, Germany). Radiocarbon 55:1443–1453.

Fischer A, Olsen J, Richards M, Heinemeier J, Sveinbjornsdottir AE, Bennike P. 2007. Coast-inland mobility and diet in the Danish Mesolithic and Neolithic: evidence from stable isotope values of humans and dogs. Journal of Archaeological Science 34:2125–2150.

Fox-Dobbs K, Leonard JA, Koch PL. 2008. Pleistocene megafauna from eastern Beringia: Paleoecological and paleoenvironmental inerpretations of stable carbon and nitrogen isoope and radiocarbon records. Palaeogeography, Palaeoclimatology and Palaeoecology 261:30–46.

Fry B. 2008. Stable isotope ecology. Springer. ISBN 0-387-30513-0.

Fülöp RH, Heinze S, John S, Rethemeyer J. 2013. Ultrafiltration of bon samples is neither the problem nor the solution. Radiocarbon 55:491–500.

Gaffney V, Thomsen K, Fitch S, editors. 2007. Mapping Doggerland: the Mesolithic landscapes of the southern North Sea. Oxford: Archaeopress.

van Geel B, Sevink J, Mol D, Langeveld, BW, van der Ham RWJM, van der Kraan CJM, van der Plicht J, Haile JS, Rey-Iglesia A, Lorenzen ED. 2018. Giant deer (*Megaloceros giganteus*) diet from Mid-Weichselian deposits under the present North Sea inferred from molar-embedded botanical remains. Journal of Quaternary Science 33:924–933.

Glimmerveen J, Mol D, van der Plicht J. 2006. The Pleistocene Reindeer of the North Sea: initial paleontological data and archaeological remarks. Quaternary International 142–143:242–246.

Heaton TJ, Köhler P, Butzin M, Bard E, Reimer RW, Austin WEN, Bronk Ramsey C, Grootes PM, Hughen KA, Kromer B, Reimer PJ, Adkins JF, Burke A, Cook MS, Olsen J, Skinner LC. 2020. Marine 20—the marine Radiocarbon age calibration curve (0–50,000 ca BP). Radiocarbon 62:779–820.

Hedges REM, Reynard LM. 2007. Nitrogen isotopes and the trophic level of humans in archaeology. Journal of Archaeological Science 34:1240–1251.

van Heteren S, Meekes JAC, Bakker MAJ, Gaffney V, Fitch S, Gearey BR, Paap BF. 2014. Reconstructing North Sea palaeolandscapes from 3D and high-density 2D seismic data: an overview. Netherlands Journal of Geosciences 93:31–42.

Hijma MP, Cohen KM, Roebroeks W, Westerhoff WE, Busschers FS. 2012. Pleistocene Rhine-Thames landscapes: geological background for hominin occupation of the southern North Sea region. Journal of Quaternary Science 27:17–39.

Hublin JJ, Weston D, Gunz P. 2009 Richards M, Roebroeks W, Glimmerveen J, Anthonis L. Out of the North Sea: the Zeeland Ridges Neandertal. Journal of Human Evolution 57:777–785.

Huels MC, Grootes PM, Nadeau MJ. 2009. Ultrafiltration: boon or bane? Radiocarbon 51: 613–625.

Huels MC, van der Plicht J, Brock F, Matzerath S, Chivall D. 2017. Laboratory intercomparison of Pleistocene bone radiocarbon dating protocols. Radiocarbon 59:1543–1552.

Kohn MJ. 1999. You are what you eat. Science 283:335–336.

Kuitems, M, De Loecker, D, van Kolfschoten T, Borst W, van Doesburg J, van der Es HP, Opdebeeck J, Otte A, Reumer JWF, van Tongeren O, Weerts HJT, Wesselingh F. 2013a. Succesvol botvangen. Rapport 4 van het geo-archeologisch en paleontologisch onderzoek zandwingebied en buitencontour Maasvlakte 2. Leiden: Faculty of Archaeology, Leiden University.

Kuitems M, van Kolfschoten T, De Loecker D, Busschers FS. 2013b. Synthese van het geo-archeologisch en paleontologisch onderzoek zandwingebied en buitencontour Maasvlakte 2. Leiden: Faculty of Archaeology, Leiden University.

Kuitems M. 2020. Analysis of ^{13}C and ^{15}N isotopes from Eurasian Quaternary fossils [PhD thesis]. Leiden University.

Kuitems M, van Kolfschoten T, van der Plicht J. 2015a. Elevated δ^{15}N values in mammoths: a comparison with modern elephants. Archaeological and Anthropological Sciences 7:289–295.

Kuitems M, van der Plicht J, Drucker DG, van Kolfschoten T, Palstra SWL, Bocherens H. 2015b. Carbon and Nitrogen isotopes of well preserved Middle Pleistocene bone collagen from Schoningen (Germany) and their palaeoecological implications. Journal of Human Evolution 89:105–113.

Kuzmin YV, Fiedel SJ, Street M, Reimer PJ, Boudin M, van der Plicht J, Panov VS, Hodgins GWL. 2018. A second round of laboratory intercomparison of AMS ^{14}C dating of bones of the Miesenheim IV elk (Rhineland, Germany) and its implications for the date of the Laacher See eruption. Quaternary Geochronology 48:7–16.

Langeveld B. 2015. Vondsten van de reuzenalk Pinguinus impennis uit het Eurogeulgebied. Cranium 32:19–27. In Dutch.

Langeveld B, Mol D, van der Plicht J. 2018. Arctic fox Alopex lagopus from the North Sea. Deinsea 18:1–5.

Lanting JN van der Plicht J. 1994. ^{14}C-AMS: pros and cons for archaeology. Palaeohistoria 35/36:1–12.

Lanting JN, van der Plicht J. 1998. Reservoir effects and apparent ^{14}C ages. Journal of Irish Archaeology 9:151–165.

Lister A, Bahn P. 2007. Mammoths, giants of the ice age. Marshall editions. ISBN 978-0-7112-2801-6.

Longin R. 1971. New method of collagen extraction for radiocarbon dating. Nature 230:241–242.

Louwe Kooijmans LP, Ball EA, Brinkkemper O, van Wijngaarden GJ, Bakels CC, Beerenhout B, Hänninen K. 2001. Hardinxveld-Giessendam De Bruin: een kampplaats uit het Laat-Mesolithicum en het begin van de Swifterbant-cultuur (5500-4450 v. Chr.): Rapportage Archeologische Monumentenzorg 88. In Dutch.

Maroto J, Vaquero M. Arrizabalaga A, Baena J, Baquedano E, Jorda J, Julia R, Montes R, van der Plicht J, Rasines R, Wood R. 2012. Current issues in late Palaeolithic chronology: new assessments from Northern Iberia. Quaternary International 247:15–25.

Meiklejohn C, Niekus MJLT, van der Plicht J. 2015. Radiocarbon dating of Mesolithic human remains in the Netherlands. Mesolithic Miscellany 23:3–48.

Minami M, Yamazaki K, Omori T, Nakamura T. 2013. Radiocarbon dating of VIRI bone samples using ultrafiltration. Nuclear Instruments and Methods B294:240–245.

Mol D, Post K, Reumer JFW, van der Plicht J, de Vos J, van Geel B, van Reenen G, Pals JP, Glimmerveen J. 2006a. The Eurogeul – first report of the palaeontological, palynological and archaeological investigations of this part of the North Sea. Quaternary International 142–143:178–185.

Mol D, Tikhonov A, van der Plicht J, Kahlke RD, DeBruyne R, van Geel B, Pals JP, de Marliave C, Reumer JFW. 2006b. Results of the Cerpolex/Mammuthus expeditions on the Taimir peninsula, arctic Siberia, Russian Federation. Quaternary International 142–143:186–202.

Mol D, de Vos J, Bakker R, van Geel B, Glimmerveen J, van der Plicht J, Post K. 2008. Kleine encyclopedie van het leven in het Pleistoceen: mammoeten, neushoorns en andere dieren van de Noordzeebodem. Veen publishing, ISBN 9789085710981. In Dutch.

Mol D, Post K. 2010a. Gericht korren op de Noordzee voor de zoogdier paleontologie: een historisch overzicht van de uitgevoerde expedities. Cranium 27:14–28. In Dutch.

Mol D, Verhagen A, van der Plicht J. 2010b. Mammoeten en neushoorns van twee vindplaatsen uit het stroomgebied va de Oer-Maas gecorreleerd. Cranium 27:49–57. In Dutch.

Mol D, van der Plicht J. 2012a. Een haas (Orde Lagomorpha, Familie Leporidae, Geslacht Lepus) van de Laat-Pleistocene fauna van de Noordzeebodem. Cranium 29/2:33–35. In Dutch.

Mol D, van der Plicht J. 2012b. Fossiele otters uit het Noordzeebekken dateren van ca. 9000 jaar geleden. Straatgras 24:3–5. In Dutch.

Mook WG, Streurman HJ. 1983. Physical and chemical aspects of radiocarbon dating. PACT publications 8:31–55.

Mook WG, van de Plassche O. 1986. Radiocarbon dating. In: van de Plassche O, editor. Sea level research: a manual for the collection and evaluation of data. Norwich, UK: Geo Books. ISBN 0860941876. p. 525–560.

Mook WG, van der Plicht J. 1999. Reporting ^{14}C activities and concentrations. Radiocarbon 41: 227–239.

Mook WG. 2006. Introduction to Isotope Hydrology. Taylor and Francis, London. ISBN 0415381975.

Moree JM, Sier MM, editors. 2015. Interdisciplinary Archaeological Research Programme Maasvlakte 2, Rotterdam. BOOR report no. 566. Part 1: Twenty meters deep! The mesolithic period at the Yangtze Harbour site – Rotterdam Maasvlakte, the Netherlands (= BOORrapporten 566). Rotterdam, Netherlands: Bureau Oudheidkundig Onderzoek Rotterdam.

Noe-Nygaard N. 1983. The habitation pattern of Mesolithic man; an analysis of the importance of aquatic resources on Danish inland sites. In: Clutton-Brock J, Grigson C, editors. Animals and archaeology. Vol. II: Shell middens, fishes and birds. Oxford: BAR Oxford Publication. p. 124–142.

Noe-Nygaard N. 1988. δ^{13}C-values of dog bones reveal the nature of changes in man's food resources at the Mesolithic-Neolithic transition, Denmark. Chemical Geology: Isotope Geoscience section 73:87–96.

Olsson IU. 1989. The ^{14}C method, its possibilities and some pitfalls. PACT Publications 24:161–177.

Olsson IU. 2009. Radiocarbon dating history: early days, questions, and problems met. Radiocarbon 51:1–43.

Peeters JHM. 2011. How wet can we get? Approaches to submerged prehistoric sites and landscapes on the Dutch continental shelf. In: Benjamin J, Bonsall C, Pickard C, Fischer A, editors. Submerged prehistory. Oxford: Oxbow Books. p. 55–64.

Philippsen B. 2013. The freshwater reservoir effect in radiocarbon dating. Heritage Science 1:24.

Reimer PJ, Austin WEN, Bard E, Bayliss A, Blackwell PG, Ramsey CB, Butzin M, Cheng H, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Hajdas I, Heaton TJ, Hogg AG, Hughen KA, Kromer B, Manning SW, Muscheler R, Palmer JG, Pearson C, van der Plicht J, Reimer RW, Richards DA, Scott EM, Southon JR, Turney CSM, Wacker L, Adolphi F, Büntgen U, Capano M, Fahrni SM, Fogtmann-Schulz A, Friedrich R, Köhler P, Kudsk P, Miyake F, Olsen J, Reinig F, Sakamoto M, Sookdeo A, Talamo S. 2020. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). Radiocarbon 62(4):725–757. doi: 10.1017/RDC.2020.41.

Reumer JWF, Rook L, van der Borg K, Post K, Mol D, de Vos J. 2003. Late Pleistocene survival of the saber-toothed cat *Homotherium* in northwestern Europe. Journal of Vertebrate Paleontology 23:260–262.

Richards MP, Hedges REM. 2003. Variations in bone collagen $\delta^{13}C$ and $\delta^{15}N$ values of fauna from Northwest Europe over the last 40000 years. Palaeogeography, Palaeoclimatology, Palaeoecology 193:261–267.

Richards MP, Pellegrini M, Niven L, Nehlich O, Dibble H, Turq A, McPherron SJP. 2017. Temporal variations in Equus tooth isotope values (C,N,O) from the Middle Paleolithic site of Combe Grenal, France (ca. 150,000 to 50,000 BP). Journal of Archaeological Science: Reports 14:189–198.

Rijsdijk KF, Kroon IC, Meijer T, Passchier S, van Dijk TAGP, Bunnik FPM, Janse AC. 2013. Reconstructing Quaternary Rhine-Meuse dynamics in the southern North Sea; architecture, seismo-lithofacies associations and malacological biozonation. Journal of Quaternary Science 28:453–466.

Rivals F, Julien MA, Kuitems M, van Kolfschoten T, Serangeli J, Bocherens H, Drucker DG, Conard N. 2015. Investigation of the horse paleodiet from Schoningen 13 II-4 through dental wear and isotopic analysis and its archaeological implications. Journal of Human Evolution 89:129–137.

Roebroeks W. 2014. Terra incognita: The Palaeolithic record of northwest Europe and the information potential of the southern North Sea. Netherlands Journal of Geosciences 93:43–53.

Schulting RJ, Richards MP. 2002. Finding the coastal Mesolithic in southwest Britain: AMS dates and stable isotope results on human remains from Caldey Island, south Wales. Antiquity 76:1011–1025.

Scott EM, Cook GT, Naysmith P. 2010. The Fifth International Radiocarbon Intercomparison (VIRI): an assessment of laboratory performance in stage 3. Radiocarbon 52:859–865.

Semal P, Rougier H, Crevecoeur I, Jungels C, Flas D, Hauzeur A, Maureille B, Germonpre M, Bocherens H, Pirson S, Cammaert L, de Clerck N, Hambucken A. Higham T, Toussaint M, van der Plicht J. 2009. New data on the Late Neandertals: direct dating of the Belgian Spy fossils. American Journal of Physical Anthropology 138:421–428.

Stevens RE, Hedges REM. 2004. Carbon and nitrogen stable isotope analysis of northwest European horse bone and tooth collagen, 40,000 BP-present: palaeoclimatic interpretations. Quaternary Science Reviews 23:977–991.

Sturt F, Garrow D, Bradley S. 2013. New models of North West European Holocene palaeogeography and inundation. Journal of Archaeological Science 40:3963–3976.

Synal HA, Stocker M, Suter M. 2007. MICADAS: a new compact radiocarbon AMS system. Nuclear Instruments and Methods B259:7–13.

Szpak P, Gröcke DR, Debruyne R, MacPhee RD, Guthrie RD, Froese D, Zazula GD, Patterson WP, Poinar HN. 2010. Regional differences in bone collagen $\delta^{13}C$ and $\delta^{15}N$ of Pleistocene mammoths: implications for paleoecology of the mammoth steppe. Palaeogeography, Palaeoclimatology, Palaeoecology 286:88–96.

van der Plicht J, Wijma S, Aerts AT, Pertuisot MH, Meijer HAJ. 2000. The Groningen AMS facility : status report. Nuclear Instruments and Methods B172:58–65.

van der Plicht J, Hogg A. 2006. A note on reporting radiocarbon. Quaternary Geochronology 1:237–240.

van der Plicht J, Post K, Mol D. 2012. Over aasvliegen en een mammoetkalf uit de Eurogeul. Cranium 29:14–19. In Dutch.

van der Plicht J, Amkreutz LWSW, Niekus MJLT, Peeters JHM, Smit BI. 2016. Surf'n turf in Doggerland: dating, stable isotopes and diet of Mesolithic human remains from the southern North Sea. Journal of Archaeological Science: Reports 10:110–118.

van der Plicht J, Palstra SWL. 2016. Radiocarbon and mammoth bones: what's in a date. Quaternary International 406:246–251.

van Klinken GJ. 1999. Bone collagen quality indicators for palaeodietary and radiocarbon measurements. Journal of Archaeological Science 26:687–695.

van Strijdonck M, Nelson DE, Combré P, Bronk Ramsey C, Scott EM, van der Plicht J, Hedges REM. 1999. What's in a ^{14}C date. Proceedings third conference on ^{14}C and Archaeology, Lyon (France). p. 433–440.

Verhagen A, Mol D. 2009. De Groote Wielen: er was eens… wie woonden er in De Groote Wielen in de ijstijd? Drukware, Norg. ISBN 9789078707066. In Dutch.

Vogel JC, van der Merwe NJ. 1977. Isotopic evidence for early maize culture in New York state. American Antiquity 42:238–242.

APPENDIX

Table 1 Data for North Sea fossil animal bones, selected for Late Pleistocene and for infinite ^{14}C age (>45,000 BP). The table contains a column indicating the quality aspect of the measurement, wherein “a” means accepted, “1” accepted but not all criteria known, “2” not all criteria met but accepted, “3” accepted but only C isotopes measured. The calibrated dates are shown at 95% confidence level (“low” to “high”).

Lab code	Locality	Age BP	σ(–)	σ(+)	C%	δ^{13}C (‰)	N%	δ^{15}N (‰)	C/N ratio	calBP low	calBP high	Species	Skeletal element	Remarks	Quality
KIA-25281	North Sea	54010	2630	3940						>54500		*Delphinapterus leucas*	Atlas		1
UtC-3751	Brown Bank	50000	2000	2800						>54500		*Odobenus rosmarus*	Pelvis		1
UtC-3747	Outer Rough	50000	2000	3000						>54500		*Erignathus barbatus*	Pelvis		1
UtC-3749	Denkmark, Helgoland	47400	1600	2100						>47350		*Odobenus rosmarus*	Vertebra		1
UtC-7880	Borkum	46400	1700	1700						46080	52770	*Erignathus barbatus*	Vertebra		1
GrA-32597	Eurogully	>45000			36.6	–19.1	15.1	2.9	2.8	>46790		*Rangifer tarandus*	Metatarsal		2
GrA-20303	Brown Bank	>45000			39.7	–19.6				>46790		*Rangifer tarandus*	Metacarpal		3
GrA-20475	Brown Bank	>45000			32.4	–19.6	15.2	2.9	2.5	>46790		*Rangifer tarandus*	Unknown		2
GrN-28544	Southern Bight	>45000			40.5	–16.5				>46790		*Delphinapterus leucas*	Vertebra		3
GrA-22179	Eurogully	>45000			40.9	–14.8	12.8	13.9	3.7	>46790		*Delphinapterus leucas*	Axis		2
GrA-25849	Borkumrif	>45000			44.6	–14.4	17.3	16.5	3.0	>46790		*Delphinapterus leucas*	Vertebra		a
GrA-22182	Eurogully	>45000			42.2	–14.4	14.8	13.3	3.3	>46790		*Eschrichtius robustus*	Vertebra		a
GrA-34348	Zuid-Holland, Scheveningen	>45000			44.3	–14.8	16.6	12.9	3.1	>46790		*Eschrichtius robustus*	Vertebra		a
GrA-34381	Southern Bight	>45000			42.1	–13.3	16.2	14.8	3.0	>46790		*Eschrichtius robustus*	Axis		a
GrN-28546	Southern Bight	>45000			43.9	–15.8				>46790		*Pagophilus groenlandica*	Humerus		3
UtC-7883	Brown Bank	>45000								>46790		*Pagophilus groenlandica*	Femur		1

Table 1 (*Continued*)

Lab code	Locality	Age BP	σ(–)	σ(+)	C%	$\delta^{13}C$ (‰)	N%	$\delta^{15}N$ (‰)	C/N ratio	calBP low	calBP high	Species	Skeletal element	Remarks	Quality
GrA-22178	Eurogully	>45000			45.6	–12.5	14.6	11.5	3.6	>46790		*Odobenus rosmarus*	Cranium		a
GrN-28548	Southern Bight	>45000			41.9	–14.1				>46790		*Odobenus rosmarus*	Femur		3
GrA-59468	Eurogully	>45000			42.2	–13.3	15.5	11.2	3.2	>46790		*Odobenus rosmarus*	Mandible		a
GrA-50465	Brown Bank	>45000			43.0	–20.3	14.3	7.7	3.5	>46790		*Ursus arctos*	Mandible		a
GrA-25816	Eurogully	>45000			35.9	–22.3	14.2	3.5	3.0	>46790		*Ursus* species	Unknown		a
GrA-22183	Eurogully	>45000			43.4	–19.4	15.4	7.7	3.3	>46790		*Canis lupus*	Femur		a
GrA-23151	Eurogully	>45000			39.9	–19.2	15.7	8.7	3.0	>46790		*Panthera spelaea*	Ulna		a
GrA-56674	Zuid-Holland, Maasvlakte	>45000			40.0	–21.3	14.8	3.0	3.2	>46790		*Equus* species	Tibia		a
GrA-30740	Zeeland, Westerschelde	>45000			46.9	–20.7	17.5	7.5	3.1	>46790		*Elephas antiquus*	Unknown		a
GrA-30590	Zeeland, Westerschelde	>45000			48.7	–21.2	17.3	8.1	3.3	>46790		*Elephas antiquus*	Unknown		a
GrA-30591	Zeeland, Westerschelde	>45000			45.5	–20.6	15.7	10.1	3.4	>46790		*Elephas antiquus*	Unknown		a
GrA-30592	Zeeland, Westerschelde	>45000			41.6	–20.6	13.7	11.2	3.5	>46790		*Elephas antiquus*	Unknown		a
GrA-56664	Zuid-Holland, Maasvlakte	>45000			39.1	–20.2	14.1	9.8	3.2	>46790		*Elephas antiquus*	Cranium		a
GrA-38353	Eurogully	>45000			43.0	–20.6	15.2	6.6	3.3	>46790		*Megaloceros giganteus*	Cranium		a
GrA-32601	Eurogully	>45000			45.7	–19.5	14.9	2.5	3.6	>46790		*Megaloceros giganteus*	Antler		a
GrA-32685	Eurogully	>45000			40.5	–19.8				>46790		*Megaloceros giganteus*	Unknown		3
GrA-34338	Southern Bight	>45000			40.9	–14.8	12.7	14.3	3.3	>46790		*Balaena mysticetus*	Radius		a
GrA-37034	Southern Bight	>45000			46.0	–12.6				>46790		*Balaenoptera physalus*	Thoracic vertebra		3
GrA-34524	Brown Bank	>45000			37.5	–21.9	13.2	6.1	3.3	>46790		Bovidae	Unknown		a

(*Continued*)

Table 1 (*Continued*)

Lab code	Locality	Age BP	σ(–)	σ(+)	C%	$\delta^{13}C$ (‰)	N%	$\delta^{15}N$ (‰)	C/N ratio	calBP low	calBP high	Species	Skeletal element	Remarks	Quality
GrA-34531	Brown Bank	>45000			39.2	–21.7	14.3	5.4	3.2	>46790		Bovidae	Unknown		a
GrA-34533	Brown Bank	>45000			42.1	–21.9	15.1	6.7	3.2	>46790		Bovidae	Unknown		a
GrN-28261	Eurogully	>45000			50.7	–19.6				>46790		*Bison priscus*	Lendal vertebra		2
GrA-37797	Stekels	>45000			45.9	–20.4	17.9	4.3	3.0	>46790		*Bos primigenius*	Femur		a
GrN-32392	Eurogully	>45000			44.4	–20.7				>46790		*Coelodonta antiquitatis*	Unknown		3
GrA-52410	Eurogully	>45000			35.3	–20.8	16.4	11.6	2.5	>46790		*Elephas antiquus*	Molar root		2
GrA-59476	Brown Bank	>45000			42.7	–21.4	15.4	7.8	3.2	>46790		*Mammuthus primigenius*	Tusk		a
GrA-50851	Eurogully	>45000			47.9	–22.3	15.9	6.1	3.5	>46790		*Mammuthus primigenius*	Tibia		a
GrA-50847	Eurogully	>45000			46.9	–22.1	15.8	6.2	3.5	>46790		*Mammuthus primigenius*	Tibia		a
GrA-50854	Brown Bank	>45000			40.0	–21.7	14.8	7.2	3.1	>46790		*Mammuthus primigenius*	Tooth		a
GrA-50860	Brown Bank	>45000			41.3	–21.5	14.3	9.0	3.4	>46790		*Mammuthus primigenius*	Tooth		a
GrA-50848	North Sea	>45000			43.2	–22.2	13.4	8.3	3.7	>46790		*Mammuthus primigenius*	Tooth		2
GrA-52416	Brown Bank	>45000			46.0	–21.6	15.9	9.1	3.4	>46790		*Mammuthus primigenius*	Tooth		a
GrA-50846	Brown Bank	>45000			40.3	–22.4	15.2	8.0	3.1	>46790		*Mammuthus primigenius*	Tooth		a
GrA-50843	Brown Bank	>45000			45.1	–22.4	14.1	8.4	3.7	>46790		*Mammuthus primigenius*	Tooth		2
GrA-11640	Brown Bank	>45000			47.9	–22.4				>46790		*Mammuthus primigenius*	Epistropheus		3
GrA-56656	Brown Bank	>45000			40.3	–21.9	14.9	5.9	3.2	>46790		*Mammuthus primigenius*	Unknown		a
GrA-56660	Eurogully	>45000			39.6	–21.9	14.6	5.6	3.2	>46790		*Mammuthus primigenius*	Humerus	Hyena marks	a

Table 1 (*Continued*)

Lab code	Locality	Age BP	σ(–)	σ(+)	C%	$\delta^{13}C$ (‰)	N%	$\delta^{15}N$ (‰)	C/N ratio	calBP low	calBP high	Species	Skeletal element	Remarks	Quality
GrA-56661	Eurogully	>45000			41.4	–21.8	15.1	5.7	3.2	>46790		*Mammuthus primigenius*	Humerus		a
GrA-56675	Zuid-Holland, Maasvlakte	>45000			41.8	–21.6	15.4	5.0	3.2	>46790		*Mammuthus primigenius*	Femur		a
GrA-43620	Stekels	>45000			36.6	–23.0	13.7	4.6	3.1	>46790		Unknown	Unknown	Possible artifact	a
GrA-40522	Brown Bank, SW	>45000			38.9	–20.6	14.4	5.2	3.2	>46790		Unknown	Cf tibia	Marrow expl?	a
GrA-39965	Great Yarmouth	>45000			42.0	–20.6	4.8	4.5	3.3	>46790		*Coelodonta antiquitatis*	Mandible	Soxhlet	a
GrA-20475	Brown Bank	>45000			32.4	–19.6				>46790		*Rangider tarandus*	Bone		3
GrA-42704	Southern Bight	>45000			36.4	–21.4	12.7	6.4	3.3	>46790		*Equus* species	Metacarpal	Donkey, Palaeolithic	a
GrA-23582	Brown Bank	44780	1550	1920	40.7	–21.4	14.4	5.4	3.3	44580	54330	*Equus caballus*	Tibia		a
GrA-23581	Brown Bank	44560	1490	1840	43.9	–20.4	15.3	4.7	3.3	44450	54280	*Alces alces*	Antler		a
GrA-20254	Eurogully/Brown Bank	44100	1100	1250	41.1	–19.1				44630	49600	*Rangifer tarandus*	Calcaneum		3
GrA-56662	Eurogully	43910	450	550	43.4	–21.8	15.9	6.5	3.2	45310	47570	*Mammuthus primigenius*	Ulna		a
GrA-20134	Eurogully	43800	550	600	39.7	–22.4				45100	47600	*Mammuthus primigenius*	Fibula		3
GrA-22585	Eurogully	43550	1050	1200	44.5	–22.0	16.5	2.3	3.1	44410	48700	*Equus* species	Ulna		a
GrN-28547	Southern Bight	>43500			40.1	–15.0				>45900		*Pagophilus groenlandica*	Humerus	Reservoir effect	3
GrA-64453	Zuid-Holland, Hoek van Holland	43290	380	400	39.9	–14.9	14.5	17.6	3.2	44890	46460	*Pinguinus impennis*	Humerus	Reservoir effect	a
GrA-39964	Great Yarmouth	42960	420	500	38.2	–21.4	14.1	4.1	3.2	44650	46180	*Equus* species	Metacarpal	Soxhlet	a
GrN-28549	Southern Bight	42800	2700	4100	42.3	–15.4				42630	54970	*Eschrichtius robustus*	Vertebra	Res. effect	3
GrA-50866	Brown Bank	42690	470	550	39.1	–21.4	14.8	6.6	3.1	44520	46060	*Mammuthus primigenius*	Tooth		a

(*Continued*)

Table 1 (*Continued*)

Lab code	Locality	Age BP	σ(–)	σ(+)	C%	δ^{13}C (‰)	N%	δ^{15}N (‰)	C/N ratio	calBP low	calBP high	Species	Skeletal element	Remarks	Quality
GrA-40013	Zeeland, Westerschelde	42400	800	1100	36.6	–20.5	13.1	11.1	3.3	43360	47060	*Elephas antiquus*	Mandible	Soxhlet	a
GrA-20259	Brown Bank	42300	900	1000	36.3	–18.9	13.8	3.2	3.1	43300	46940	*Rangifer tarandus*	Astragalus		a
GrA-21327	Brown Bank	41970	700	920	44.3	–19.0				43240	46120	*Rangifer tarandus*	Radius	Duplo 20260	3
GrA-50858	Brown Bank	41450	420	490	44.7	–22.4	13.7	8.8	3.8	43330	45050	*Mammuthus primigenius*	Tooth		2
GrM-24067	Terneuzen	>41400			38.3	–20.5	14.1	5.5	3.2	>44100		*Coelodonta antiquitatis*			a
GrM-24068	Terneuzen	>41400			40.1	–21.6	14.9	3.2	3.1	>44100		*Coelodonta antiquitatis*			a
GrM-24070	Terneuzen	>41400			43.0	–21.4	15.6	7.5	3.2	>44100		*Equus* species			a
GrM-24073	Terneuzen	>41400			41.5	–20.4	15.3	3.2	3.2	>44100		*Mammuthus primigenius*			a
GrM-24074	Terneuzen	>41400			40.6	–21.9	14.9	5.3	3.2	>44100		*Mammuthus primigenius*			a
GrM-24188	Terneuzen	>41400			33.9	–22.2	12.4	8.1	3.2	>44100		*Mammuthus primigenius*			a
GrM-24189	Terneuzen	>41400			41.0	–21.8	15.0	7.0	3.2	>44100		*Mammuthus primigenius*			a
GrA-20260	Brown Bank	41200	800	900	39.8	–19.1	14.4	5.1	3.2	42880	45530	*Rangifer tarandus*	Radius		a
AA-17634	Brown Bank	>41100								>44190		*Mammuthus primigenius*	Tooth		1
GrA-56655	North Sea	41090	350	400	36.4	–22.1	13.3	6.1	3.2	43240	44640	*Mammuthus primigenius*	Unknown		a
GrA-32599	Eurogully	40750	380	440	38.7	–20.1	14.2	5.5	3.2	43060	44470	*Megaloceros giganteus*	Antler		a
GrA-11643	Brown Bank	40660	350	350	39.3	–20.1				43070	44380	*Crocuta crocuta spelaea*	Ulna		3
GrA-34337	Zeeland, Yerseke	40550	350	400	40.5	–16.4	14.7	15.1	3.1	43000	44340	*Delphinapterus leucas*	Mandible		a

Table 1 (*Continued*)

Lab code	Locality	Age BP	σ(–)	σ(+)	C%	δ^{13}C (‰)	N%	δ^{15}N (‰)	C/N ratio	calBP low	calBP high	Species	Skeletal element	Remarks	Quality
GrA-64644	Denmark, Holmgren	40360	230	240	39.1	–13.9	15.3	12.0	3.0	42980	44110	*Odobenus rosmarus*	Atlas	Reservoir effect	a
GrM-24066	Terneuzen	40100	1200	1400	40.1	–21.4	14.7	5.7	3.2	42070	46220	*Mammuthus primigenius*			a
AA-17635	Brown Bank	>40000								>43070		*Mammuthus primigenius*	Vertebra		1
GrA-50864	North Sea	39970	380	440	34.9	–21.7	13.3	7.9	3.1	42690	44100	*Mammuthus primigenius*	Tooth		a
GrA-31471	North Sea	39970	320	360	41.5	–19.4	13.9	8.2	3.5	42730	44020	*Panthera spelaea*	Scapula		a
GrN-27411	Eurogully	39910	950	1070	45.8	–20.8				42290	44870	*Coelodonta antiquitatis*	Pelvis		3
GrA-39518	Great Yarmouth	39900	650	850	35.6	–20.9				42460	44420	*Bison* species	Metacarpale	Soxhlet	3
GrA-56658	Brown Bank	39860	310	350	41.2	–21.5	15.1	7.2	3.2	42660	43960	*Mammuthus primigenius*	Femur	SIRI	a
AA-17637	Brown Bank	39800	3400	3400						40620	55500	*Mammuthus primigenius*	Vertebra		1
GrA-21326	Eurogully/Brown Bank	39770	650	700	41.1	–19.2				42450	44290	*Rangifer tarandus*	Calcaneum	Duplo 20254	3
GrA-21419	Brown Bank	39700	1700	2100	42.2	–19.1	14.7	4.4	3.3	41140	48720	*Rangifer tarandus*	Metacarpal	Duplo 20255	a
AA-17639	Brown Bank	>39300								>42750		*Mammuthus primigenius*	Carpal bones		1
GrA-20257	Eurogully	39200	650	700	35.9	–21.2	13.7	6.8	3.1	42230	44020	*Rangifer tarandus*	Phalanx		a
GrA-20255	Brown Bank	39150	650	700	40.9	–19.1	17.6	4.3	2.7	42210	43990	*Rangifer tarandus*	Metacarpal		2
GrA-34349	Eurogullly	39100	320	360	41.6	–14.0	13.3	12.2	3.6	42380	43010	*Eschrichtius robustus*	Atlas	Reservoir effect	a
GrA-20261	Brown Bank	39000	600	700	39.0	–19.2	14.1	4.3	3.2	42150	43880	*Rangifer tarandus*	Epistropheus		a
AA-17636	Brown Bank	>39000								>42620		*Mammuthus primigenius*	Fibula		1

(*Continued*)

Table 1 (*Continued*)

Lab code	Locality	Age BP	σ(–)	σ(+)	C%	$\delta^{13}C$ (‰)	N%	$\delta^{15}N$ (‰)	C/N ratio	calBP low	calBP high	Species	Skeletal element	Remarks	Quality
GrA-50852	Eurogully	38960	350	400	38.6	–22.4	13.8	7.3	3.3	42310	42970	*Mammuthus primigenius*	Vertebra		a
GrA-31284	Brown Bank	38960	355	355	35.1	–19.8	13.2	3.6	3.1	42320	42970	*Rangifer tarandus*	Antler	Artifact	a
AA-17638	Brown Bank	>38900								>42500		*Mammuthus primigenius*	Carpal bones		1
AA-17648	Brown Bank	>38600								>42470		*Mammuthus primigenius*	Tooth		1
UtC-3752	Westhinder	38500	800	800						41770	43900	*Delphinapterus leucas*	Vertebra	Reservoir effect	1
AA-17642	Brown Bank	37900	2800	2800						37730	52520	*Mammuthus primigenius*	Tooth		1
GrA-37558	Stekels	37860	355	355	41.9	–19.9	16.3	4.8	3.0	41910	42510	*Equus caballus*	Metacarpal	Artifact	a
GrN-27410	Eurogully	37580	740	810	45.6	–21.7				41130	42830	*Mammuthus primigenius*	Cranium		3
GrA-25815	Southern Bight	37440	310	310	42.3	–20.3	11.9	15.0	3.5	41660	42360	*Elephas antiquus*	Unknown		1
GrA-39962	Great Yarmouth	37240	260	280	27.5	–22.6				41550	42250	*Mammuthus primigenius*	Vertebra	Soxhlet	3
AA-17647	Brown Bank	36800	2400	2400						36780	49390	*Mammuthus primigenius*	Tooth		1
GrA-11641	Brown Bank	36740	230	230	42.5	–20.1				41270	42010	*Ovibos moschatus*	Metacarpal		3
OxA- 6308	Brown Bank	36300	1100	1100						39460	42580	*Megeloceros giganteus*	Metacarpal		1
AA-17643	Brown Bank	>36200								>41220		*Mammuthus primigenius*	Tooth		1
OxA- 6307	Brown Bank	35600	1200	1200						38150	42490	*Ovibos moschatus*	Metacarpal		1
AA-17645	Brown Bank	35200	2000	2000						36140	44420	*Mammuthus primigenius*	Tooth		1
GrA-25570	Brown Bank	35160	315	315	36.0	–19.3	12.6	2.2	3.3	39660	40980	*Rangifer tarandus*	Antler		a
UtC-3753	Brown Bank	34600	500	400						39230	40480	*Delphinapterus leucas*	Humerus	Reservoir effect	1

Table 1 (*Continued*)

Lab code	Locality	Age BP	σ(–)	σ(+)	C%	$\delta^{13}C$ (‰)	N%	$\delta^{15}N$ (‰)	C/N ratio	calBP low	calBP high	Species	Skeletal element	Remarks	Quality
AA-17634	Brown Bank	33800	1200	1200						36190	41340	*Mammuthus primigenius*	Metacarpal		1
GrA-39966	Great Yarmouth	31460	150	160	42.8	–19.5	14.4	2.5	3.5	35430	36180	*Rangifer tarandus*	Antler	Soxhlet	a
UtC-10999	Brown Bank	31300	400	400		–17.6				34760	36410	*Homotherium latidens*	Tooth	Same animal	1
UtC-10456	Brown Bank	31300	400	400		–18.1				34760	36410	*Homotherium latidens*	Tooth	Same animal	1
GrA-54021	Zuid-Holland, Zandmotor	31140	190	200	32.3	–21.3				35110	36110	*Lepus* species	Mandible		3
K-3726	Denmark	30880	1110	1270						33120	39160	*Odobenus rosmarus*	Cranium	Reservoir effect	1
GrA-69520	Zuid-Holland, Zandmotor	29900	490	550	34.3	–20.7	12.5	8.5	3.2	33240	35450	*Alopex lagopus*	Unknown		a
GrA-20294	Eurogully/Brown Bank	29460	250	250	38.5	–19.4	15.7	4.1	2.9	33380	34470	*Rangifer tarandus*	Astragalus		a
GrA-50454	Eurogully	28740	180	190	45.5	–26.4				32220	33740	*Protophormia terraenovae*	Chitine	Pup blowfly	a
UtC-11000	Brown Bank	28100	220	220		–21.2				31600	32990	*Homotherium latidens*	Tooth	Same animal	1
UtC-11065	Brown Bank	27650	280	280		–17.7				31110	32740	*Homotherium latidens*	Mandible	Same animal	1
GrA-26887	Eurogully	27510	180	190	No data	–14.7				31150	31780	*Pagophilus groenlandica*	Sacrum	Reservoir effect	1
UtC-10908	Brown Bank	26900	400	400		–18.9				30250	31740	*Homotherium latidens*	Mandible	Same animal	1
UtC-11064	Brown Bank	26700	240	240		–15.3				30360	31200	*Homotherium latidens*	Mandible	Same animal	1
GrA-65933	Zuid-Holland, Maasvlakte 2	25130	130	130	26.2	–15.5	9.3	14.5	3.3	29130	29850	*Halichoerus grypus*	Unknown	Reservoir effect	2
GrA-33828	Eurogully	24670	150	160	19.0	–23.4						*Castor fiber*	Femur		r
K-3727	Denmark	24380	620	620						27490	30000	*Odobenus rosmarus*	Cranium	Reservoir effect	1

(*Continued*)

Table 1 (*Continued*)

Lab code	Locality	Age BP	σ(–)	σ(+)	C%	$\delta^{13}C$ (‰)	N%	$\delta^{15}N$ (‰)	C/N ratio	calBP low	calBP high	Species	Skeletal element	Remarks	Quality
K-4473	Denmark	23500	460	460						26960	28820	*Odobenus rosmarus*	Cranium	Reservoir effect	1
GrA-37536	Brown Bank	15360	90	90	38.1	–19.5				18300	18850	Caprinae	Unknown	Same animal	3
GrA-38211	Brown Bank	15190	60	60	37.0	–19.2	14.1	7.5	3.0	18280	18670	Caprinae	Unknown	Same animal	a
GrA-37800	Brown Bank	15120	50	50	38.3	–19.2				18240	18650	Caprinae	Unknown	Same animal	3

Table 2 Data for North Sea fossil animal bones, selected for Holocene age. The table contains a column indicating the quality aspect of the measurement, wherein “a” means accepted, “1” accepted but not all criteria known, “2” not all criteria met but accepted, “3” accepted but only C isotopes measured. The calibrated dates are shown at 95% confidence level (“low” to “high”).

Lab code	Locality	Age BP	1σ	C%	δ^{13}C (‰)	N%	δ^{15}N (‰)	C/N ratio	calBP low	calBP high	Species	Skeletal element	Remarks	Quality
GrA-28364	Brown Bank	11560	50	37.9	–20.6	14.5	3.9	3.1	13315	13575	*Bison* species	Metatarsus	Decorated	a
GrA-34644	Brown Bank	10730	60	33.9	–21.2				12620	12765	*Gulo gulo*	Mandible		3
GrA-36110	Brown Bank	10000	50	44.4	–21.1	14.8	3.7	3.5	11265	11730	*Cervus elaphus*	Antler	Artifact	a
GrA-27206	Brown Bank	9910	50	39.9	–20.9	16.6	1.7	2.8	11210	11610	*Alces alces*	Antler	Artifact	2
GrA-37796	Stekels	9815	40	42.9	–21.2	15.1	3.5	3.3	11175	11310	*Cervus elaphus*	Antler		a
GrA-37795	Stekels	9675	40	43.7	–20.8	16.5	4.1	3.1	10800	11205	*Cervus elaphus*	Antler	Artifact	a
GrA-37004	Brown Bank	9520	50	39.7	–21.7	14.1	3.4	2.8	10595	11090	*Alces alces*	Antler	Artifact	2
GrA-68250	Zuid-Holland	9510	50	44.3	–20.6	16.2	2.2	3.2	10585	11080	*Alces alces*	Antler		a
GrA-25514	North Sea	9500	180	41.5	–21.5				10290	11235	*Cervus elaphus*	Antler		3
UtC-7886	Brown Bank	9450	70						10500	11075	*Sus scrofa*	Humerus		1
GrA-29203	Brown Bank	9350	60	20.4	–22.3						*Capreolus capreolus*	Antler		r
OxA-13425	Southern Bight	9305	70						10275	10690	*Sus scrofa*	Unknown		1
OxA-13426	Southern Bight	9290	65						10255	10655	*Sus scrofa*	Unknown		1
GrA-51667	North Sea	9220	40	38.6	–22.7	14.7	4.9	3.1	10250	10500	Bovidae	Metacarpal	Artifact	a
GrA-30732	Brown Bank	9070	50	40.6	–21.9	14.5	5.0	3.3	10155	10380	*Cervus elaphus*	Tibia	Artifact	a
GrA-40524	Eurogully	9070	45	38.1	–21.6	13.7	3.2	3.2	10170	10375	*Cervus elaphus*	Antler	Artifact	a
GrA-43612	Stekels	8945	45	34.8	–22.8	13.9	5.4	2.9	9905	10225	Unknown	Bone	Artifact	a
GrA-30722	Brown Bank	8910	50	45.1	–21.1	16.5	4.8	3.2	9795	10205	*Castor fiber*	Femur		a
GrA-51668	North Sea	8900	40	44.3	–22.4	15.6	5.2	3.3	9820	10195	*Bos primigenius*	Unknown	Artifact	a
GrA-31283	Brown Bank	8880	40	38.9	–22.2	12.8	2.4	3.6	9780	10185	*Capreolus capreolus*	Tibia		a
GrA-29204	Brown Bank	8870	50	42.4	–22.2				9755	10185	*Cervus elaphus*	Antler	Artifact	3
GrA-34339	Southern Bight	8860	40	39.1	–21.9				9765	10175	*Sus scrofa*	Mandible		3
GrA-37561	Stekels	8830	40	44.2	–21.7	15.2	2.5	3.4	9695	10150	*Cervus elaphus*	Antler	Artifact	a
GrA-52432	Eurogully	8825	45	39.4	–24.8				9685	10155	*Lutra lutra*	Cranium		3
GrA-20256	Brown Bank	8820	60	40.6	–22.7	16.8	4.0	2.8	9625	10170	*Rangifer tarandus*	Phalanx		2
GrA-25569	Brown Bank	8800	50	38.2	–22.3	14.7	5.2	3.0	9560	10150	*Bos primigenius*	Metapodal	Modified	a
GrA-24209	Eurogully	8780	50	47.7	–25.6	16.7	10.2	3.3	9550	10120	*Canis* species	Cranium		a
GrA-22998	Brown Bank	8780	60	36.2	–22.6	15.5	5.5	2.7	9550	10125	*Bos primigenius*	Metacarpal	Artifact	2
GrA-32600	Eurogully	8710	45	41.7	–21.2	15.1	4.0	3.2	9540	9890	*Sus scrofa*	Humerus		a

(Continued)

Table 2 (*Continued*)

Lab code	Locality	Age BP	1σ	C%	δ^{13}C (‰)	N%	δ^{15}N (‰)	C/N ratio	calBP low	calBP high	Species	Skeletal element	Remarks	Quality
GrA-36113	Brown Bank	8710	50	39.7	–22.5	13.4	2.2	3.5	9540	9890	*Cervus elaphus*	Antler	Artifact	a
GrA-59743	Zuid-Holland, Maasvlakte	8680	60	37.8	–19.6	13.9	4.2	3.2	9535	9890	unknown	Unknown	Harpoon	a
GrA-30795	Brown Bank	8660	50	45.7	–21.9	16.1	5.3	3.3	9530	9765	unknown	Metapodal	Artifact	a
GrA-25568	Southern Bight	8600	50	36.6	–21.8	13.9	2.1	3.1	9485	9690	*Cervus elaphus*	Antler	Modified	a
GrA-33949	Eurogully	8405	45	36.8	–21.4	12.5	3.0	3.4	9300	9530	*Capreolus capreolus*	Antler	Artifact	a
GrA-20353	Brown Bank	8350	50	30.6	–23.3				9140	9485	*Rangifer tarandus*	Phalanx		3
GrA-52433	Zuid-Holland, Maasvlakte 2	8300	40	32.0	–26.2	13.3	8.6	2.8	9135	9440	*Lutra lutra*	Mandible		2
GrA-42195	Zuid-Holland, Rockanje	8295	45	42.4	–22.1	13.1	6.3	3.8	9130	9440	unknown	Unknown		2
GrA-30731	Brown Bank	8240	50	45.8	–21.2	16.4	4.2	3.3	9025	9410	*Alces alces*	Antler	Artifact	a
GrA-51786	Eurogully	8175	40	42.8	–22.8	16.6	6.1	3.0	9010	9275	*Bos primigenius*	Horn pit		a
GrA-25851	Southern Bight	8135	45	40.0	–11.4	15.6	15.9	3.0	8990	9270	*Tursiops truncatus*	Mandible	Reservoir effect	a
GrA-22999	Eurogully	8070	50	38.5	–20.4	16.0	3.4	2.8	8720	9195	*Cervus elaphus*	Antler	Modified	2
GrA-23201	Eurogully	7970	60	25.6	–26.9						*Alces alces*	Antler	—	r
GrA-30974	Zeeland, Westerschelde	7900	60	0.5	–23.1						*Odobenus rosmarus*	Unknown	Reservoir effect	r
GrA-30721	Eurogully	7780	50	31.9	–21.9	13.4	6.2	2.8	8420	8645	*Sus scrofa*	Atlas		2
GrA-25850	Southern Bight	7390	50	43.5	–12.4	16.0	14.9	3.2	8035	8345	*Tursiops truncatus*	Mandible	Reservoir effect	a
UtC-7885	Brown Bank	7270	60						7965	8190	*Tursiops truncatus*	Vertebra	Reservoir effect	1
GrN-28551	Southern Bight	7180	60	38.7	–11.7				7865	8170	*Halichoerus grypus*	Bone	Reservoir effect	3
GrA-64384	Zuid-Holland, Zandmotor	6480	40	35.5	–14.3	12.9	17.7	3.2	7585	7780	*Pinguinus impennis*	Humerus	Reservoir effect	a
OxA-13427	Southern Bight	5455	70						6005	6400	*Sus scrofa*	Unknown		1
GrA-34378	North Sea	4815	40	40.4	–14.0	16.2	13.9	2.9	5465	5605	*Eschrichtius robustus*	Cranium		a
GrA-34342	Wadden Sea (G)	4550	35	45.2	–12.3	17.1	15.4	3.1	5050	5435	*Orcinus orca*	Maxila	Reservoir effect	a

Table 2 (*Continued*)

Lab code	Locality	Age BP	1σ	C%	$\delta^{13}C$ (‰)	N%	$\delta^{15}N$ (‰)	C/N ratio	calBP low	calBP high	Species	Skeletal element	Remarks	Quality
GrA-34380	Southern Bight	4230	35	46.8	–15.0	14.6	14.5	3.7	4625	4860	*Eschrichtius robustus*	Vertebra	Reservoir effect	2
GrN-31093	Noord-Holland, Andijk	4130	40	39.1	–14.1				4525	4825	*Eschrichtius robustus*	Unknown	Reservoir effect	3
GrA-34761	Southern Bight	4055	35	46.7	–14.6	13.8	16.0	3.4	4420	4795	*Eschrichtius robustus*	Unknown	Reservoir effect	a
GrA-20280	Zeeland, Roompot	4030	60	32.2	–22.6				4295	4815	*Cervus elaphus*	Antler	Axe	3
GrA-34379	North Sea	3925	35	42.2	–13.1	16.6	14.0	3.0	4240	4510	*Eschrichtius robustus*	Cranium	Reservoir effect	a
GrA-25820	Southern Bight	3900	45	38.7	–11.6	14.4	17.4	3.1	4490	4510	*Orcinus orca*	Unknown	Reservoir effect	a
GrA-34385	Southern Bight	3650	35	47.2	–13.4	17.4	14.6	3.2	3870	4090	*Eschrichtius robustus*	Vertebra	Reservoir effect	a
GrA-50510	North Sea	3540	40	42.5	–22.6	14.6	5.1	3.4	3695	3960	*Cervus elaphus*	Antler	artifact	a
GrA-65546	Zuid-Holland, Zandmotor	3505	35	39.4	–14.2	13.8	16.0	3.3	3645	3880	*Pinguinus impennis*	Unknown	Reservoir effect	a
GrA-26885	Southern Bight	3335	35	No data	–13.1				3465	3685	*Phocaena phocaena*	Atlas	Reservoir effect	1
GrA-25852	Southern Bight	3120	40	39.8	–12.0	14.7	15.6	3.2	3220	3445	*Lagenorhynchus albirostris*	Mandible	Reservoir effect	a
GrA-37555	Stekels	2505	35	43.2	–12.4	15.0	16.2	3.4	2460	2740	*Lagenorhynchus albirostris*	Vertebra	Reservoir effect	a
GrA-34383	Southern Bight	2270	35	45.0	–14.6	16.1	12.5	3.3	2155	2350	*Eschrichtius robustus*	Axis	Reservoir effect	a
GrA-66408	Yerseke	2190	30	39.4	–16.7	13.4	9.3	3.4	2110	2320	*Balaenidae*	Bulla	Reservoir effect	a
GrA-57505	Eurogully	2070	30	43.7	–12.9	16.9	13.6	3.0	1940	2120	*Odobenus rosmarus*	Tooth	Neolithic axe; reservoir effect	a
UtC-7884	White Bank	1921	35						1735	1930	*Eschrichtius robustus*	Mandible	Reservoir effect	1
GrA-34369	White Bank	1870	35	43.6	–15.1	17.0	16.1	3.0	1705	1875	*Eschrichtius robustus*	Mandible	Reservoir effect	a

(*Continued*)

Table 2 (*Continued*)

Lab code	Locality	Age BP	1σ	C%	δ13C (‰)	N%	δ15N (‰)	C/N ratio	calBP low	calBP high	Species	Skeletal element	Remarks	Quality
GrA-34368	North Sea	1865	30	42.8	–14.9	15.6	15.9	3.2	1705	1865	*Eschrichtius robustus*	Vertebra	Reservoir effect	a
KIA-25282	Wadden Sea, Terschelling	1645	25						1410	1685	*Eschrichtius robustus*	Mandible	Reservoir effect	1
GrA-22093	Zeeland, Roompot	1370	40	37.1	–20.9				1175	1350	*Cervus elaphus*	Unknown	Duplo 20291	3
GrA-20291	Zeeland, Roompot	1310	60	36.9	–20.5				1070	1340	*Cervus elaphus*	Antler	Carved face	3
GrA-34526	Brown Bank	110	50	45.2	–21.8	15.9	5.1	3.3	5	280	Bovidae	Unknown		a

Table 3 Overview of analyzed species, environment and average values of the stable isotope ratios $\delta^{13}C$ and $\delta^{15}N$.

Species (English)	Species (Latin)	Environment & diet	n	$\delta^{13}C$ (‰)	n	$\delta^{15}N$ (‰)
Straight tusked elephant	*Elephas antiquus*	Terrestrial herbivore	7	–20.7	7	9.9
Woolly mammoth	*Mammuthus primigenius*/sp.	Terrestrial herbivore	29	–22.0	25	6.9
Cave lion	*Panthera spelaea*	Terrestrial carnivore	2	–19.3	2	8.5
Arctic fox	*Alopex lagopus*	Terrestrial carnivore	1	–20.7	1	8.5
Hyena	*Crocuta crocuta spelaea*	Terrestrial carnivore	1	–20.1	0	
Dog/wolf	*Canis lupus*/sp.	Terrestrial carnivore	2	–22.5	2	9.0
Bear	*Ursus arctos*/sp.	Terrestrial omnivore	2	–21.3	2	5.6
Otter	*Lutra lutra*	Freshwater carnivore	2	–25.5	1	8.6
Wolverine	*Gulo gulo*	Terrestrial carnivore	1	–21.2	0	
Woolly rhinoceros	*Coelodonta antiquitatis*	Terrestrial herbivore	5	–20.7	3	4.4
Horse	*Equus caballus*/sp.	Terrestrial herbivore	7	–21.2	7	4.8
Roe deer	*Capreolus capreolus*	Terrestrial herbivore	2	–21.8	2	2.7
Moose	*Alces alces*	Terrestrial herbivore	5	–21.0	5	3.2
Red deer	*Cervus elaphus*	Terrestrial herbivore	14	–21.6	9	3.5
Giant deer	*Megaloceros giganteus*	Terrestrial herbivore	4	–20.0	3	4.9
Reindeer	*Rangifer tarandus*	Terrestrial herbivore	16	–19.9	12	3.8
Balaenidae	Balaenidae	Marine carnivore	1	–16.7	1	9.3
Bowhead whale	*Balaena mysticetus*	Marine carnivore	1	–14.8	1	14.3
Common rorqual	*Balaenoptera physalus*	Marine carnivore	1	–12.6	0	
Beluga whale	*Delphinapterus leucas*	Marine carnivore	4	–15.5	3	15.2
White-beaked dolphin	*Lagenorhynchus albirostris*	Marine carnivore	2	–12.2	2	15.9
Grey whale	*Eschrichtius robustus*	Marine carnivore	14	–14.3	12	14.2
Killer whale	*Orcinus orca*	Marine carnivore	2	–12.0	2	16.4
Grey seal	*Halichoerus grypus*	Marine carnivore	2	–13.6	1	14.5
Walrus	*Odobenus rosmarus*	Marine carnivore	5	–13.3	4	12.1
Bottlenose dolphin	*Tursiops truncatus*	Marine carnivore	2	–11.9	2	15.4
Harp seal	*Pagophilus groenlandica*	Marine carnivore	2	–15.4	0	
Wild boar	*Sus scrofa*	Terrestrial omnivore	3	–21.7	2	5.1

(Continued)

Table 3 (*Continued*)

Species (English)	Species (Latin)	Environment & diet	n	δ^{13}C (‰)	n	δ^{15}N (‰)
Musk ox	*Ovibos moschatus*	Terrestrial herbivore	1	–20.1	0	
Bison	*Bison priscus*/sp.	Terrestrial herbivore	3	–20.4	1	3.9
Aurochs	*Bos primigenius*	Terrestrial herbivore	5	–22.1	5	5.3
Caprinae	Caprinae	Terrestrial herbivore	1	–19.2	1	7.5
Bovid	Bovidae	Terrestrial herbivore	5	–22.0	5	5.6
Hare	*Lepus* sp.	Terrestrial herbivore	1	–21.3	0	
Beaver	*Castor fiber*	Terrestrial herbivore	1	–22.1	1	4.8
Human	*Homo sapiens*	Terrestrial omnivore	124	–20.0	123	12.1
Great auk	*Pinguinus impennis*	Marine carnivore	3	–14.5	3	17.1
Unknown	Unknown	Unknown	6	–21.7	6	5.2