The dIANA database – Resource for isotopic paleodietary research in the Baltic Sea area

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ABSTRACT

Paleodietary research is a complex field, which requires large sets of background information. Owing to increasing interest and activity in the field, a substantial amount of archaeological isotope baseline data exist for Northern Europe, consisting mainly of animal bone collagen $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values. However, the data are scattered into dozens of publications written in multiple languages and less-accessible formats, making the data laborious to use. This article presents the first compilation work of this data, the open access dIANA database (Dietary Isotopic baseline for the Ancient North; https://www.oasisnorth.org/diana.html), aimed to support (paleo)dietary research in the Baltic Sea area. The database work is complemented with new analyses of archaeological and (pre-)modern domestic and wild fauna from Finland and Russia broadening the selection of analysed species in the database. We present and discuss data examples, which on one hand show existing spatiotemporal isotope patterns related to diet and differences in the environmental carbon sources and on the other, also visualize the current status of baseline research and the need for further analyses in the circum-Baltic area.

1. Introduction

During the last decades, isotopic analyses of carbon, nitrogen and sulphur in bone collagen have proven to be valuable tools for tracking paleodiet. Accurate knowledge of the isotope values of consumed foods, i.e. the isotopic baseline, is critically important for paleodietary research. Ideally, the isotope baseline for any paleodietary study should consist of a local and contemporary sample set (Casey and Post, 2011; Post, 2002), in archaeological cases deriving preferably from the same find context. This is due to spatial and temporal trends in isotopic values at the base of food webs on a variety of scales. On a continental to global scale, geographical gradients in long-term climatic factors such as sunshine, temperature and precipitation cause systematic patterns in carbon ($\delta^{13}C$) and nitrogen isotope values ($\delta^{15}N$) of soils, plants, and animals (Amundson et al., 2003; Craine et al., 2009; Kohn, 2010; Van

Klinken et al., 2002). Generally, plants (and consumers) show decreasing $\delta^{13}C$ and $\delta^{15}N$ values with decreasing radiation, temperature and increasing precipitation/humidity, but these large-scale systematics are overprinted by regional to local, or even landscape-scale variation influenced by topography, exposure to light, soil drainage etc. (Ambrose, 1991; Sparks and Ehleringer, 1997; Tieszen, 1991).

Besides spatial variability, another important factor affecting isotopic baselines is the temporal variability in climate. For example, the overall transition from the Weichselian glacial period to the Holocene interglacial is known to have accompanied a ca. 1.5–3‰ decline in animal and plant $\delta^{13}C$ values (Drucker et al., 2008, 2011a; Hatté et al., 1998). Since the late glacial, several widely recognized warming and cooling phases have taken place, all of which may have impacted isotopic baseline levels. In Europe, conditions have varied from the Bølling/Allerød warm period (ca. 14,640–12,850 cal yr BP[1]) to the cold

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[1] "Cal yr BP" refers to "calendar years before present" where the term "present" refers to the year 1950 CE. For example, a date of 1000 cal yr BP corresponds to the year 950 CE.

Younger Dryas period (ca. 12,850 cal yr BP) (Rasmussen et al., 2014) and to the Holocene Thermal Maximum (HTM), dating to ca. 8000–4800 cal yr BP (Seppä et al., 2009). In the Late Holocene, considerable climatic events have been the Dark Ages Cold Period (DACP, ca. 400–800 CE; e.g. Büntgen et al., 2016; Helama et al., 2017) and the Medieval Warm Period (MWP, in Scandinavia ca. 900–1100 CE; Lamb, 1977, 1982). Two of the most recent significant stages have been the Little Ice Age (LIA, ca. 1500–1900 CE in northern Europe; Seppä et al., 2009) and the ongoing Modern Warm Period (MoWP; e.g. Kabel et al., 2012). The past few centuries have also seen a decrease in the atmospheric $\delta^{13}C$ values, mostly related to burning of fossil fuels, which has caused plant and animal carbon isotopic values to decline ca. 2‰ since the 1850s; the most intensive drop has happened after 1955 (Graven et al., 2017).

Apart from the above global or continent-wide patterns, smaller scale patterns may be significant in characterizing spatial and temporal variability in isotopic baselines within certain regions. In northeastern Europe, the interplay of the melting Fennoscandian ice sheet, postglacial land uplift and eustatic sea level changes have resulted in a unique development of the environment, most importantly the complex Holocene history of the Baltic Sea. Since the melt waters of the ice sheet created the freshwater Baltic Ice Lake (BIL, 15,000–11,600 cal yr BP; Björck, 1995; Björck et al., 1996), conditions in the Baltic Sea basin have varied from the short and saline Yoldia Sea stage (11,600–10,700 cal yr BP) to the freshwater Ancylus Lake (10,700–8500 cal yr BP) and finally to the present Littorina stage (from ca. 8500 cal BP; Björck, 2008), which experienced its' peak salinities at ca. 6000–4000 cal yr BP (e.g. Ning et al., 2017). In formerly glaciated areas, especially the shores of the Bothnian Bay, postglacial land uplift has also significantly changed the distance to the sea. In addition, for much of its Holocene history the waters of the Baltic Sea have displayed a southwest-northeast salinity gradient due to the influx of saline North Sea and riverine fresh waters, reflected also as distinct trends in the distribution of isotopic values in the basin (Torniainen et al., 2017).

This regional spatiotemporal complexity underlines the importance of applying accurate isotopic baselines, preferentially local and contemporaneous. This notion is widely recognized but still proper baseline information is available only for restricted areas and periods. In many cases, archaeological isotope analyses have been directed in such way that human remains have been prioritized over animals. This has led to situations where no or only few representatives of the dietary items have been analysed. One important factor limiting archaeological baselines is bone preservation which is highly variable in northern Europe. To build more robust baselines, researchers have had to compromise and use data from multiple locations and time periods, with some of the newer studies including also modern data (e.g. Bownes et al., 2017; Fernandes et al., 2015; Katzenberg et al., 2010).

While a thorough sampling of the assumed consumed resources, combined with well-founded, comprehensive understanding of the archaeological context of the study subjects can never be replaced, in circumstances where this type of ideal baseline is not attainable, databases can facilitate paleodietary investigations. Large datasets have many benefits. They can save precious samples from being over-sampled. They also enable the calculation of better means and variability statistics for different dietary resources facilitating the evaluation of appropriate groupings of dietary items and of the minimum sampling numbers needed for representative input values. Having a large amount of background information enables researchers to select species suitable for the particular study and explore possibilities for using substitutes sharing a similar ecology. Databases also help to recognize possible geographical or temporal trends, enable extrapolation of values into areas lacking data and help consider the validity of using modern values for areas lacking archaeological data. Recent efforts such as the IsoMemo initiative (Fernandes et al., 2017) and IsoBank (Pauli et al., 2015), testify to the growing recognition of the importance of large datasets for isotopic research.

This article has two main aims. The first is to introduce dIANA (Dietary Isotopic baseline for the Ancient North) – an open access database compiled to help defining isoscapes to inform isotopic baselines for different times and geographic regions, especially in the Baltic Sea area. Our second aim is to significantly increase the amount of terrestrial isotope baseline data from Finland, where published (pre-)modern stable isotope data have been extremely scarce until very recently. To this end, we have analysed a set of Medieval/(pre-)modern domestic fauna and specimens from the zoological collections of the Finnish Museum of Natural History (FMNH) and compared these results with faunal isotope analyses from Finland and from the neighboring countries.

2. dIANA database in short

The first version of the dIANA database was launched in October 2015 and is accessible without login at https://www.oasisnorth.org/diana.html. dIANA is maintained by the FMNH (Finnish Museum of Natural History) of the University of Helsinki as a part of the Oasis-databases (Open-Access Storage for Northern Isotopic Data; oasisnorth.org). The dIANA database is also a partner in the IsoMemo initiative (Fernandes et al., 2017).

Database users can make queries using various filters (site, country, material, or time period) and use advanced search criteria for ^{14}C-dates, filter by isotopic value (currently $\delta^{13}C$, $\delta^{15}N$, or $\delta^{34}S$) or by literature reference. It is also possible to combine different filters. Search results can be viewed in the online application or downloaded in *.xml* format. By leaving all search options empty, users can download the whole database.

Users can submit data by downloading and filling sample data into an MSExcel template file, which is then submitted via the homepage or by email. A confirmation email is sent to the submitter when the data has been checked and entered into the database. When using data from dIANA, users are asked to acknowledge the database by referencing this publication, always the original source publications for the extracted data, the URL of the dIANA user interface, and the latest update of the database. Additionally, we ask authors to notify us for new publications using or referring to dIANA.

3. The data in dIANA

Carbon, nitrogen and sulphur isotope values and elemental concentrations of various animal and plant tissues, deriving from archaeological and ecological studies, were gathered from the literature to form the body of the dIANA database. For those collagen samples where both carbon and nitrogen isotope compositions had been analysed, data with C/N ratios in the generally accepted range from 2.9 to 3.6 indicating appropriate preservation of collagen (Ambrose, 1990; DeNiro, 1985), were accepted. The use of collagen carbon and nitrogen content as a quality indicator is not as straightforward (e.g. Ambrose, 1990; Van der Plicht and Palstra, 2016; Van Klinken, 1999) and as a general rule samples which were considered acceptable in the original research publications were included. For sulphur, we used the approved quality criteria for different animal groups. For mammal and bird collagen, %S values from 0.12% to 0.35%, a C:S ratio of 600 ± 300 and an N:S ratio of 200 ± 100 have been recommended (Bocherens et al., 2011; Nehlich and Richards, 2009). For fish bone collagen %S range from 0.4% to 0.8%, C:S ratio from 175 ± 50 and N:S ratio from 60 ± 20 has been considered acceptable (Nehlich and Richards, 2009). Most of the values in the dIANA database fall inside this range but there are also samples exceeding the limit because the research concerning these quality criteria is still in progress.

In addition to the values of isotopic composition and elemental content, information on the find location, taxon, sample type and dating of the specimens were included. All associated sample IDs mentioned in the original research were listed. In cases where sample

name was lacking, the taxon has been used as a sample code. Any special commentary by the original authors concerning the samples was included. All data were entered "as is", that is, in the form presented in the original publication without further harmonization or corrections, e.g. for the Suess effect (Keeling, 1979), charring effect (Fraser et al., 2013), lipids (Lidén et al., 1995) or between different pretreatment methods (Pestle et al., 2014).

The temporal range of the collected data spans from Marine Isotope Stage 3 (ca. 60,000–25,000 cal yr BP) to present day. Altogether 229 samples in the database have been directly radiocarbon-dated, currently representing 12% of the data. Because most of the samples have only relative dating we included the cultural affinity to each sample by the original research. Taking notice of the need in some regions to rely on modern materials to define baseline levels, and the potential systematic differences in environmental isotope levels that may result from glacial versus interglacial climatic regimes, we also assigned each data entry to a time period to facilitate data filtering: pre-Holocene (> ca. 11,700 cal yr BP), Holocene, or Post–1950 CE.

At the time of submitting this paper, the dIANA database contains > 1700 isotope entries (archaeological > 1300, modern > 350) from 11 countries, the majority of which were extracted from > 50 studies published between 2003 and 2018 (Fig. 1). The database includes also data from publicly available, but still unpublished thesis works, data received directly from researchers, and previously unpublished data on Finnish (pre-)modern and archaeological faunal specimens (see below). Currently, the total number of baseline data is highest for Sweden ($n = 750$), Finland ($n = 447$), and for Denmark ($n = 325$).

Archaeological mammal and fish samples represent 56% and 26% of the data, respectively. Of the mammals ca. 65% are wild species and 35% domesticates. A majority of the archaeological fish samples derive from marine or brackish contexts. Most modern fish (> 110 specimens) and all invertebrate samples (> 50) derive from two Finnish freshwater lakes. Plant data (> 40) derives from archaeological crops and legumes, and from modern Finnish aquatic plants. The database contains information on over 100 bird samples. The largest sample groups are Medieval birds (> 40) originating from Germany, Sweden and Poland and the (pre-)modern samples from Finland (40).

The dIANA data focuses on certain food groups representing only a small portion of ancient dietary components and is also temporally skewed; isotope values from domesticated animals dominate in the terrestrial record since the Neolithic and the only available plant values belong to this same period. Therefore the database users should carefully consider the environmental and the temporal suitability of the selected data to their specific research questions.
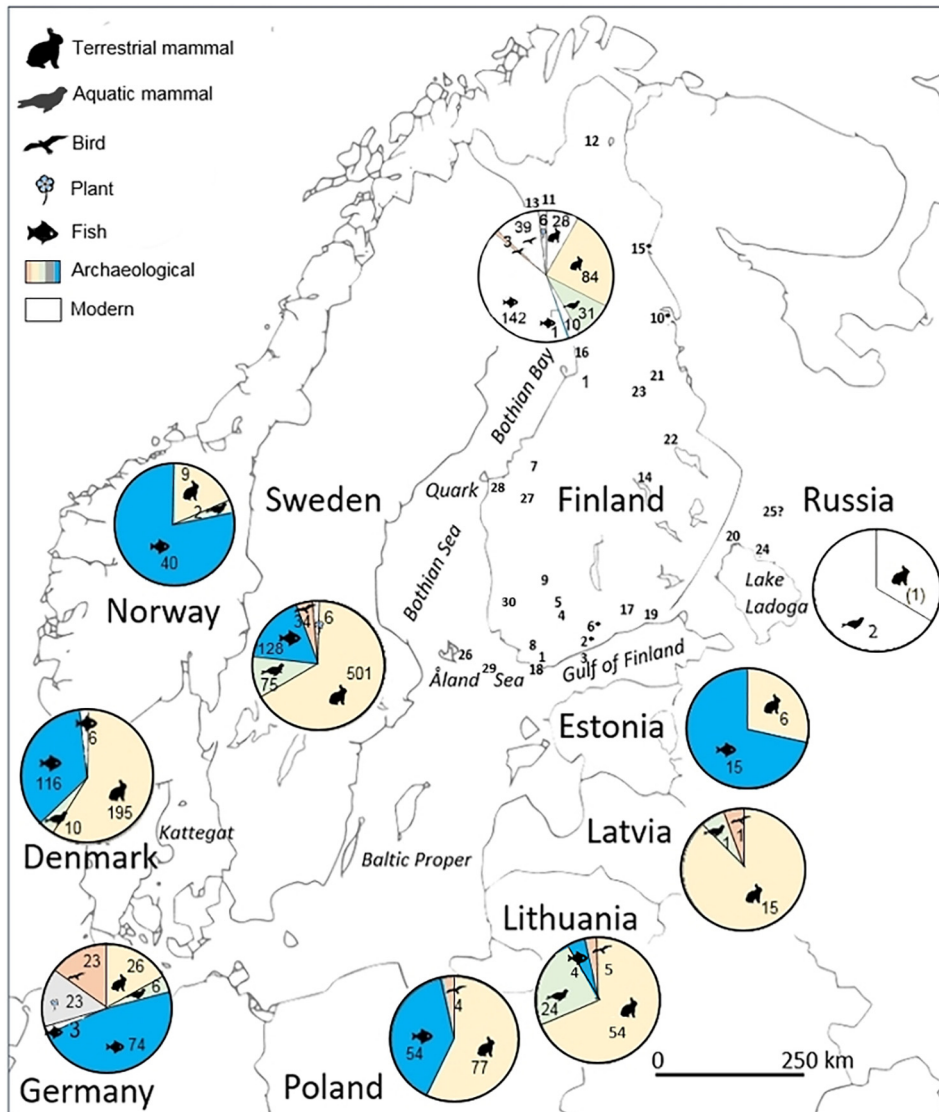

Fig. 1.

3.1. New Finnish baseline material

Prior to the dIANA initiative started in 2015, a total of 16 stable isotope values for terrestrial archaeofauna, all from a single prehistoric cattle tooth (Bläuer et al., 2013), and data from 24ancient seals (Ukkonen, 2002; Ukkonen et al., 2014) were published from Finland. Isotopic data for wild terrestrial animals and birds, known to have played a significant part in prehistoric diets, had not been published at all. During the recent years, the number of publications has started to increase (Bläuer et al., 2016; Lahtinen and Salmi, 2018; Pääkkönen et al., 2016, 2018), but remains low.

In order to improve the faunal isotopic baseline for Finland, altogether 81 specimens from the vertebrate collections of the FMNH were sampled and measured for their δ^{13}C, δ^{15}N, and δ^{34}S values (Table 1; Appendix A). The samples consist of wild mammals and birds which, based on archaeofaunal remains, were available for human diet in the Finnish late prehistory (e.g. Ukkonen and Mannermaa, 2017). Specimens from different parts of Finland were selected in order to get maximal geographical coverage and a preliminary idea of possible systematic geospatial variation in isotope values. Whenever possible, five individuals per species were sampled. The specimens were originally added to the collections of FMNH during years 1867–1944, thus predating the rapid decrease in atmospheric δ^{13}C values since the mid-1950s. In addition to the (pre-)modern museum samples, archaeological faunal remains ($n = 18$) from the extensive medieval burial site Luistari in Eura (Lehtosalo-Hilander, 1982a,b,c, 2000), southwestern Finland, were sampled and analysed for their isotopic composition (Table 1; Appendix A). As of yet, none of the archaeological animal bones have been AMS-dated, so their contemporaneity with the medieval human burials is not certain. However, further chronological research is in progress (Mannermaa, 2018).

Collagen was extracted following Bocherens et al. (1997) and measured for δ^{13}C and δ^{15}N values in the Laboratory of Chronology, FMNH, University of Helsinki, and for δ^{34}S in the University of Tübingen, Germany. A more detailed methodological description is presented in Appendix B and the calibrated measurement data in Appendix A.

The ranges of δ^{13}C and δ^{15}N values of the Finnish wild animals are plotted in Fig. 2b. Terrestrial herbivores had low δ^{15}N values (+0.5 to +6.4‰) due to their low trophic-level diet. Wild forest reindeer (*Rangifer tarandus fennicus*) and the omnivorous bears (*Ursus arctos*) differed from other terrestrial fauna with their higher δ^{13}C values (−21.1 to −19.0‰). In the case of reindeer, this is possibly due to wintertime consumption of lichen (Fizet et al., 1995; Drucker et al., 2001). Seals (*Halichoerus grypus*, *Pusa hispida botnica*, *Pusa hispida ladogensis*) had the highest δ^{15}N values (+12.7 to +14.6‰) and generally high δ^{13}C values (−19.6 to −14.5‰), reflecting their position at the top of aquatic food chains and the level of water salinity in their habitat (Baltic Proper/ Gulf of Bothnia/ freshwater Lake Ladoga), respectively. The δ^{13}C and δ^{15}N values of the FMNH birds distinguished them into three groups related to their preferred habitats and diets (Fig. 2b). The "terrestrial" group of birds showed low δ^{15}N values (+0.5 to +7.7‰), very similar to those of moose, and a narrow range of variation for δ^{13}C (−22.6 to −20.2‰). In contrast, "aquatic" birds had high δ^{15}N (+8.3 to +14.1‰) and more variable δ^{13}C values (−28.4 to −17.3‰). The "semiaquatic" group lies in between, with δ^{15}N values (+3.4 to +11.2‰) reflecting consumption of aquatic organisms, which, based on the relatively low δ^{13}C (−23.4 to −19.8‰) and δ^{34}S values (+0.4 to +9.7‰) (Fig. 2c), were mostly of freshwater origin.

With the intriguing exception of the FMNH grouse (+5.5 to +19.1‰) the δ^{34}S values can generally be used to distinguish the terrestrial/freshwater fauna from the species inhabiting the Baltic Sea (Fig. 2a and c). High δ^{34}S values of seals (+18.3 to +19.9‰) and certain aquatic birds like the common eider (*Somateria mollissima*) (+16.2 to +17.7‰) likely reflect the influence of Baltic Sea sulphate (δ^{34}S ~ +20.5‰; Böttcher and Huckriede, 1997). Another of the two Ladoga seal samples has higher δ^{34}S (+19.9‰; LUO-77) as would be

Table 1
Summary of mean δ^{13}C, δ^{15}N, and δ^{34}S values, their 1σ standard deviation (sd.) and standard error of the mean (SEM) for new Finnish baseline samples with acceptable C/N ratios.

|	Habitat	Taxon	Common name	n	δ^{13}C (‰)			δ^{15}N (‰)			δ^{34}S (‰)			
					Average	sd.	SEM	Average	sd.	SEM	Average	sd.	SEM	
FMNH Birds	Aquatic	*Clangula hyemalis*	Long-tailed duck	4	−19.6	3.7	1.8	11.7	1.9	1.0	10.1	4.1	2.0	
	Aquatic	*Somateria mollissima*	Common eider	2	−17.8	0.4	0.3	8.7	0.5	0.4	16.9	0.9	0.4	
	Aquatic	*Mergus merganser*	Common merganser	1	−17.9			14.2						
	Semiaquatic	*Mergus serrator*	Red-breasted merganser	2	−22.4	0.5	0.3	10.9	0.5	0.3	2.9	0.4	0.3	
	Semiaquatic	*Mergus albellus*	Smew	2	−22.5	0.4	0.2	7.2	5.4	3.8	8.7	0.2	0.1	
	Aquatic	*Melanitta fusca*	Velvet scoter	2	−18.0	1.3	0.9	11.1	0.8	0.5	14.1	1.3	0.9	
	Semiaquatic	*Anas penelope*	Eurasian wigeon	2	−21.2	1.6	1.2	7.9	0.1	0.0	3.1	0.2	0.1	
	Semiaquatic	*Bucephala clangula*	Common goldeneye	1	−23.2			10.4			8.0			
	Semiaquatic	*Anser anser*	Greylag goose	3	−22.6	1.6	0.9	9.0	0.8	0.5	4.6	1.8	1.0	
	Semiaquatic	*Anser fabalis*	Bean goose	3	−22.6	0.6	0.3	7.8	1.6	0.9	7.6	1.8	1.1	
	Semiaquatic	*Branta bernicla*	Brent goose	2	−21.6	1.5	1.0	6.9	1.4	1.0	5.1	6.5	4.6	
	Semiaquatic	*Branta leucopsis*	Barnacle goose	1	−22.2			8.1			4.6			
	Terrestrial	*Tetrao tetrix*	Black grouse	3	−22.4	0.6	0.3	3.1	0.3	0.2	9.4	5.5	3.9	(δ^{34}S n = 2)
	Terrestrial	*Tetrao urogallus*	Western capergaille	5	−22.0	0.2	0.1	3.9	2.5	1.1	10.9	1.8	0.8	
	Terrestrial	*Lagopus muta*	Rock ptarmigan	3	−21.3	0.8	0.5	2.0	1.6	0.9	11.2	3.8	2.2	
	Terrestrial	*Lagopus lagopus*	Willow grouse	3	−21.8	0.4	0.2	1.9	0.7	0.4	13.9	4.7	2.7	
FMNH Mammals	Terrestrial	*Lepus timidus*	Mountain hare	9	−23.9	0.5	0.2	3.4	1.4	0.5	6.8	2.2	1.5	
	Terrestrial/aquatic	*Castor fiber*	Eurasian beaver	3	−22.9	0.5	0.3	2.1	1.6	1.7	6.9	3.0	1.7	
	Terrestrial	*Rangifer tarandus fennicus*	Wild forest reindeer	5	−19.7	0.7	0.3	4.8	1.3	0.6	12.5	5.3	2.4	
	Terrestrial	*Alces alces*	Eurasian elk	5	−22.1	0.8	0.4	3.6	2.1	0.9	7.5	2.0	0.9	
	Terrestrial	*Ursus arctos*	Brown bear	5	−20.4	0.9	0.4	5.3	2.0	0.9	8.8	2.3	1.0	
	Brackish	*Halichoerus grypus*	Grey seal	5	−16.2	1.1	0.5	14.1	0.3	0.1	17.9	0.7	0.3	
	Brackish	*Pusa hispida botnica*	Ringed-seal	5	−17.8	1.7	0.8	13.4	0.5	0.8	16.0	8.6	3.5	
	Freshwater	*Pusa hispida ladogensis*	Ladoga ringed-seal	2	−19.9	0.0	0.0	13.6	0.9	0.7				
Eura Luistari	Terrestrial	*Bos taurus*	Cattle	6	−22.5	0.3	0.1	5.0	0.7	0.3	10.0	0.0	0.0	(δ^{34}S n = 2)
Eura Luistari	Terrestrial	*Equus caballus*	Horse	3	−23.1	0.3	0.2	4.4	1.0	0.7				
Eura Luistari	Terrestrial	*Ovis aries/Capra hircus*	Sheep/Goat	1	−21.6			3.2						
Eura Luistari	Terrestrial/mixed	*Sus domesticus*	Pig	1	−22.8			11.9						
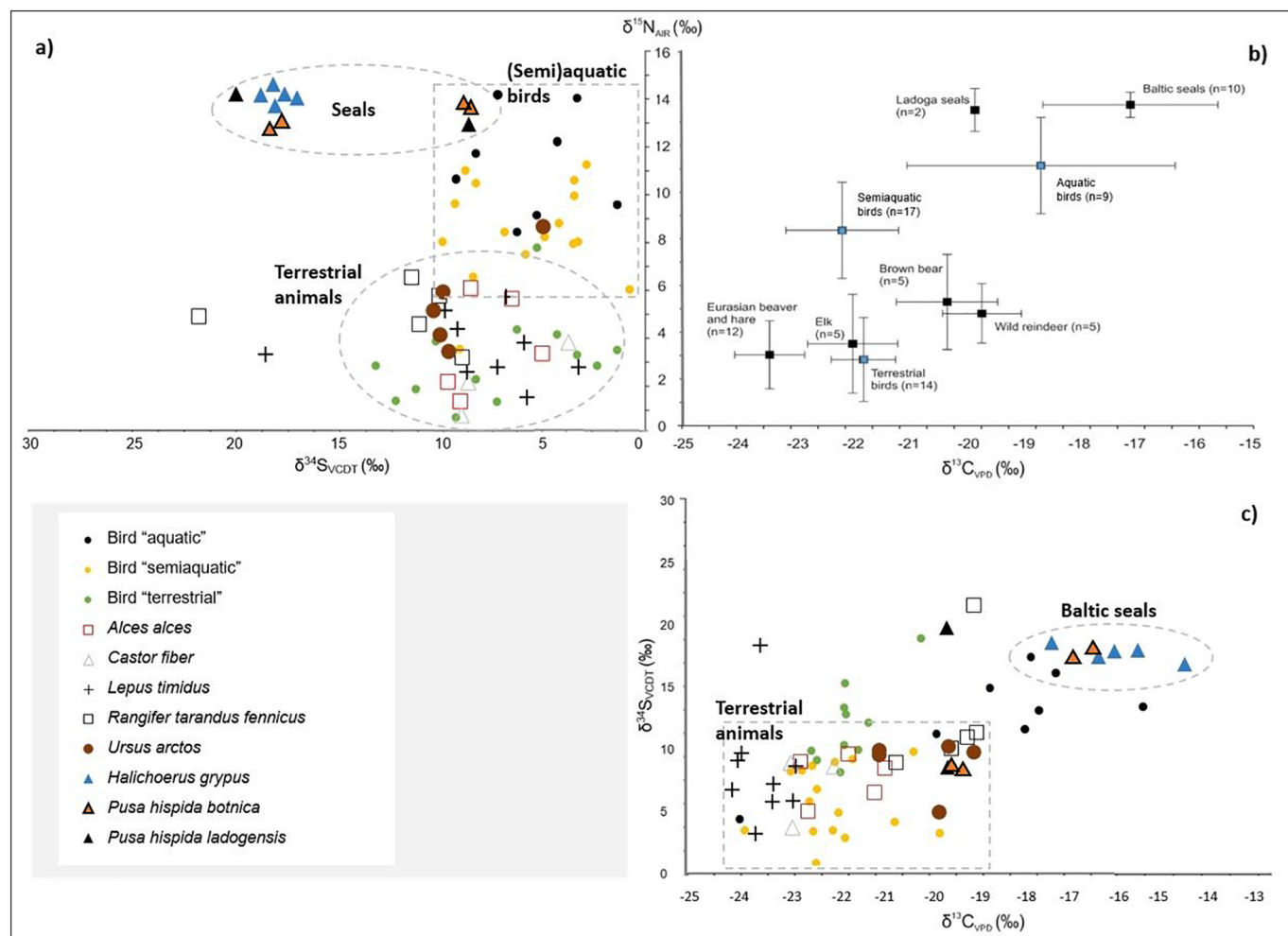
Fig. 2. New Finnish museum specimen data in a) $\delta^{15}N$–$\delta^{34}S$ space; highlighted are ranges for terrestrial animals, seals, and for "semiaquatic" and "aquatic" birds b) $\delta^{13}C$–$\delta^{15}N$ space, and c) $\delta^{13}C$–$\delta^{34}S$ space; highlighted are the ranges for most of the terrestrial fauna and for clearly marine seals. Panel b shows the mean and 68% distribution of isotope values.

expected concerning its habitat.

The range for $\delta^{13}C$ (−22.9 to −21.6‰) and $\delta^{15}N$ values (+3.2 to +6.6‰) for the specimens of domestic animals from the Luistari site was very similar to previously reported values for archaeological and historical period Finnish cattle and sheep (Bläuer et al., 2016), horses ($\delta^{13}C$ from −23.3 to −22.9‰; $\delta^{15}N$ from +3.1 to +5.7‰) from medieval Norwegian and Swedish contexts (Linderholm et al., 2008b; Naumann et al., 2014) and a pig ($\delta^{13}C$ = −22.8‰, $\delta^{15}N$ = +11.9‰) from Sweden (Fornander, 2011).

4. Discussion – patterns emerging from the dIANA data

In the following discussion, we use examples drawn from the data in dIANA to highlight topics worth consideration when conducting paleodietary studies in the circum-Baltic region. An overview of the distribution of the dIANA bone, dentine, and antler collagen, flesh and plant data in $\delta^{13}C/\delta^{15}N$-space is presented in Fig. 3. The total range of isotope values is large – $\delta^{13}C$ values vary from −37.5 to −6.9‰, and $\delta^{15}N$ values from +0.7 to +18.1‰. The large range represents the vast variety of different sample matrices and environments covered by the data, including temporal and geographical variation.

4.1. Aquatic extremes

Much of the variation in aquatic samples is due to the high degree of

variability in ecological conditions and foodwebs in aquatic environments. This is illustrated by the high standard deviations of both modern ($\delta^{13}C_{mean}$ = −28.6‰, SD = 5.4; $\delta^{15}N_{mean}$ = +14.0‰, SD = 2.3; mostly freshwater) and archaeological ($\delta^{13}C_{mean}$ = −16.2‰, SD = 4.6; $\delta^{15}N_{mean}$ = +11.5‰ and SD = 2.9; mostly marine) fish data currently in the database. Highlighted in Fig. 3 are the data ranges for modern freshwater fish flesh from a) Finland and b) Germany. Finnish fish originate from Lakes Kernaalanjärvi and Kuutsjärvi (Figueiredo et al., 2014; Milardi et al., 2016) and show very low $\delta^{13}C$ values (mean = −29.1‰, SD = 4.5), while fish from lakes Schwerin and Ostorf in Germany (Fernandes et al., 2013, 2015), have $\delta^{13}C$ values that are ca. 10‰ higher, indicating significant differences in lake carbon sources. The Finnish lakes also display a large range of $\delta^{15}N$ values, from +7.3‰ for brown trout in Lake Kuutsjärvi to +17.3‰ for asp in Lake Kernaalanjärvi. The unusually low carbon isotope values of Lake Kuutsjärvi brown trout (Milardi et al., 2016), generally a top predator, further highlight the variable ecology of lakes.

Fish have been an important year-round dietary resource for the people of northernmost Europe. This is especially true for Finland with its' thousands of lakes. Thus, for accurate paleodietary reconstructions in this region, it is critically important to have better constraints on isotopic compositions of fish. Furthermore, the isotopic compositions play a role in estimating reservoir effects in establishing radiocarbon chronologies of archaeological sites (Philippsen and Heinemeier, 2013). The extremely high level of isotopic variability displayed by aquatic
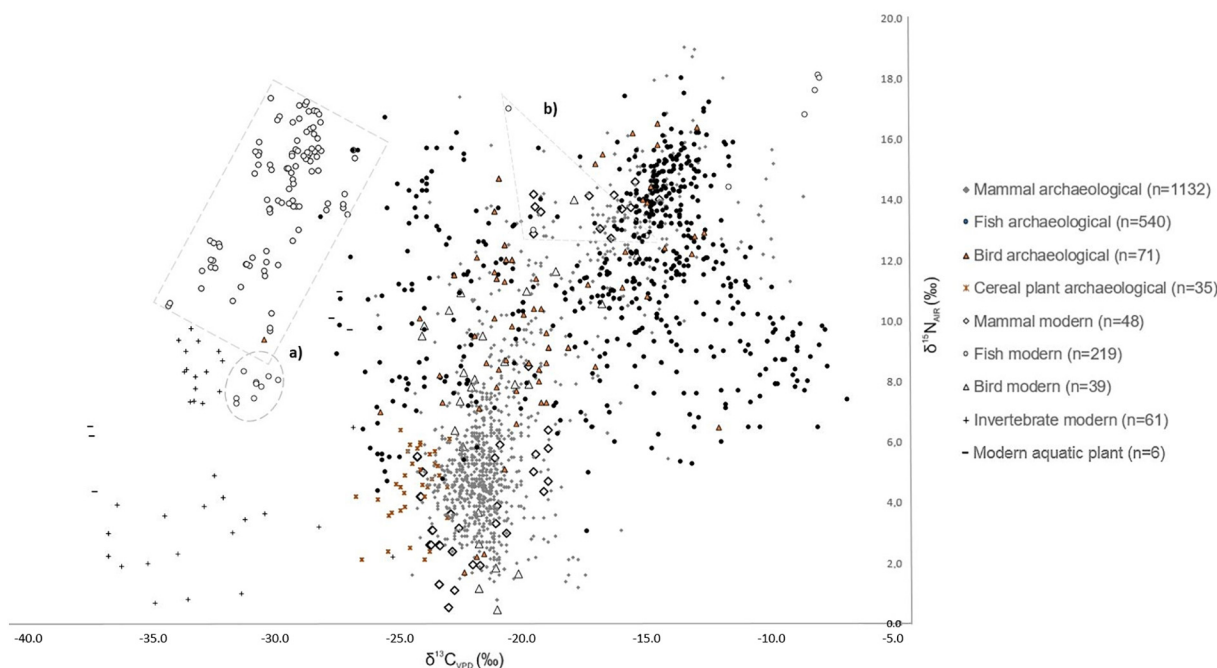
Fig. 3. Distribution of the archaeological (closed dots) and modern sample data in the dIANA baseline database in $\delta^{13}C$–$\delta^{15}N$ space. Highlighted: ranges of modern fish data from a) two Finnish lakes (Figueiredo et al., 2014; Milardi et al., 2016); b) Lakes Schwerin and Ostorf in Northern Germany (Fernandes et al., 2013, 2015).

environments suggests that aquatic isotope baselines, especially freshwater, are very "case-specific". Making assumptions based on non-local or non-contemporaneous (especially for the Baltic Sea) fish data comes with much uncertainty and can lead to significant misinterpretations of past diets. This presents a challenge, however, as freshwater fish are still underrepresented in archaeological isotope records. Therefore, very conservative error margins should be used in cases where a local isoscape is not available.

4.2. Birds

The dIANA dataset shows a considerably wide spread also for (pre-)modern bird data. The $\delta^{13}C$ values range from -24.1 to $-15.4‰$ (mean $= -21.1‰$ and SD $= 2.0$) and $\delta^{15}N$ values range from $+0.5$ to $+14.1‰$ (mean $= +7.0‰$ and SD $= 3.9$). For ancient bird samples the range is even larger; the $\delta^{13}C$ values range from -30.5 to $-12.1‰$ (mean $= -19.3‰$ and SD $= 4.1$) and $\delta^{15}N$ value range from $+2.2$ to $+16.5‰$ (mean $= +10.0‰$, SD $= 3.1$).

Most of the archaeological bird data in dIANA are from aquatic or semiaquatic species. Their large isotopic variability may reflect migratory behavior, their bone collagen isotopic values likely representing a dietary mixture of the wintering and summertime residence areas (Hobson et al., 1994), possibly separated by hundreds of kilometers, and opportunistic selection of food in various habitats.

The (pre-)modern semiaquatic FMNH birds analysed in this study derive partly from the same or closely-related species, and show a similar, large variation especially in the $\delta^{13}C$ values. The total number of bird data is still relatively low, but the existing variation indicates heterogeneous diets and implicates that a reliable estimation of isotopic values for birds as part of the dietary isotopic baseline requires large sample sets. Using data from only a few specimens may give a biased, too narrow picture of the mean and variation of isotope values in birds. To supplement low sampling numbers, it is recommendable to query the dIANA database for isotope values of species with a similar ecology, which can be used to evaluate possible isotopic ranges. Based on the FMNH "terrestrial bird" isotope values which increase the amount of sedentary bird data significantly we note, that in contrast to (semi)aquatic birds, whose tissue isotope values depending on the time of the

hunt, reflect also their wintering area, grouse display a higher level of consistency in their isotopic values and might represent a special group of birds whose $\delta^{13}C$ and $\delta^{15}N$ values can possibly be estimated with a higher degree of reliability even based on lower sample numbers.

4.3. Terrestrial mammals

Compared to the (semi)aquatic fauna, terrestrial herbivore/omnivore mammals have a much smaller range in $\delta^{13}C$ values ranging from -26.9 to $-16.1‰$ ($\delta^{13}C_{mean} = -21.7‰$, SD $= 1.2$). Their $\delta^{15}N$ values range from $+0.5$ to $+17.4‰$ ($\delta^{15}N_{mean} = +5.1‰$, SD $= 2.1$), the highest values deriving from pig and rat specimens. The majority of the terrestrial animal data in dIANA are from low trophic-level herbivores, whose $\delta^{13}C$ values echo the relatively minor variability at the base of the food web. North European terrestrial mammals predominantly consume C3 plants which have a relatively narrow range in $\delta^{13}C$ values due to the homogenous, atmospheric source of carbon – in contrast to aquatic environments – and largely similar climatic conditions over the covered area with little differences in photosynthetic fractionation. Terrestrial animals dwelling in coastal areas may however show sea-spray effect in their collagen isotope values (Richards et al., 2006).

The distribution of $\delta^{13}C$ and $\delta^{15}N$ values in cervids and the most abundant domesticates in the database – cattle and sheep/goat – is presented in Fig. 4 to demonstrate, on the one hand, the unique isotopic signature of reindeer (*Rangifer tarandus*), and on the other, the mutual similarity of isotope values for the other three cervids roe deer (*Capreolus capreolus*), red deer (*Cervus elaphus*), and moose (*Alces alces*), and their relationship to the domestic animal data. Cervids were chosen as representatives of "wild" species due to their relatively high numbers in the database.

While reindeer $\delta^{15}N$ values (mean $= +3.7‰$, SD $= 1.5$) are similar with those of other cervids, their $\delta^{13}C$ values are significantly higher (mean $= -19.0‰$, SD $= 0.9$; Student's two-tailed test; Table 2). Due to their special carbon isotope character, including reindeer into paleo-dietary studies has to be considered site-specifically, especially if statistical modeling is used.

As for the other cervids, there is a statistical difference between *Capreolus* ($\delta^{13}C_{mean} = -22.8‰$, SD $= 0.9$) and *Cervus* sp.

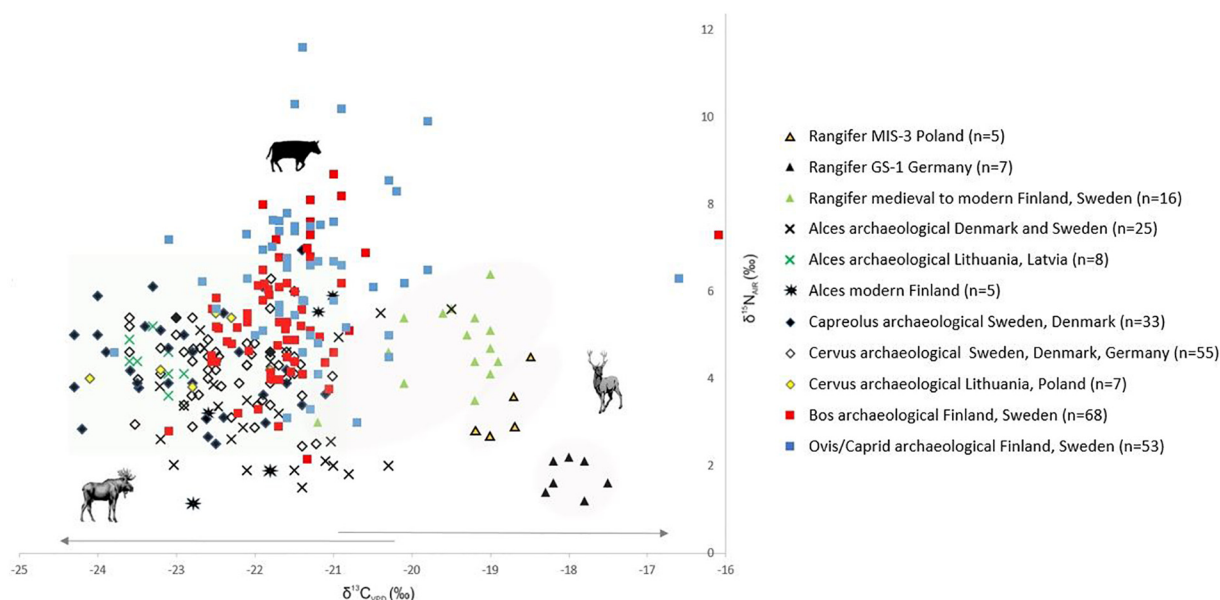**Fig. 4.** Distribution of $\delta^{13}C$ and $\delta^{15}N$ values for cervids, and for the Swedish and Finnish cattle and sheep/goats in the dIANA database. *Rangifer* MIS-3 (Krajcarz et al., 2016); GS-1 (Drucker et al., 2011b); Medieval to (pre-)modern Sweden and Finland (Lahtinen and Salmi, 2018; Salmi et al., 2015; this study); *Alces* Denmark and Sweden (Bocherens et al., 2015; Boethius and Ahlström, 2018; Eriksson et al., 2008, 2016; Fornander et al., 2008; Lidén et al., 2004); Latvia and Lithuania (Antanaitis-Jacobs et al., 2009; Meadows et al., 2016; Piličiauskas et al., 2017a,b); (pre-)modern Finland (this study); *Capreolus* Sweden and Denmark (Boethius and Ahlström, 2018; Craig et al., 2006; Eriksson et al., 2016; Fischer et al., 2007; Gron and Rowley-Conwy, 2017); *Cervus* Sweden, Denmark, and Germany (Boethius and Ahlström, 2018; Eriksson et al., 2016; Fernandes et al., 2015; Fischer et al., 2007; Gron and Rowley-Conwy, 2017; Lidén et al., 2004); Lithuania and Poland (Antanaitis-Jacobs et al., 2009; Piličiauskas et al., 2017a; Reitsema et al., 2017); *Bos* Sweden (Arcini et al., 2012; Eriksson, 2003; Eriksson et al., 2008; Fornander, 2011; Gron and Rowley-Conwy, 2017; Kjellström et al., 2009; Kosiba et al., 2007; Linderholm et al., 2008a,b; Linderholm and Kjellström, 2011; Sjögren, 2017; Finland: Bläuer et al., 2016; Lahtinen and Salmi, 2018; this study); *Ovis/Caprid* Sweden (Eriksson, 2003; Eriksson et al., 2008; Fornander, 2011; Gron and Rowley-Conwy, 2017; Kosiba et al., 2007; Linderholm et al., 2008b, 2014; Sjögren, 2017); Finland (Bläuer et al., 2016; Lahtinen and Salmi, 2018; this study).

($\delta^{13}C_{mean} = -22.3‰$, SD = 0.7) $\delta^{13}C$ values, and their $\delta^{13}C$ values are also lower than those for moose ($\delta^{13}C_{mean} = -22.1‰$, SD = 1.0), although visually inspecting (Fig. 4) the three species seem to have comparable isotope values. However, these inter-species differences are not large enough to warrant separating these species into different dietary groups in paleodietary modeling.

Compared to domestic herbivores ($\delta^{13}C_{mean} = -21.8‰$, SD = 0.7; excluding two specimens with anomalously high values from Kosiba et al. (2007), the group of three cervids ($\delta^{13}C_{mean} = -22.4‰$, SD = 0.9; $\delta^{15}N_{mean} = +4.1‰$, SD = 1.1) shows lower $\delta^{13}C$ values, possibly reflecting more closed habitats for the wild cervids (Drucker et al., 2003, 2008). The $\delta^{15}N$ values of domesticates ($\delta^{15}N_{mean} = +5.7‰$, SD = 1.6) exceeding those measured for wild species are likely related to human influence such as manuring (Bogaard et al., 2007). These differences in domestic vs. wild animal isotope, especially $\delta^{15}N$, values call for attention when prescribing the isotopic values designed to represent terrestrial animal meat.

Moose $\delta^{13}C$ and $\delta^{15}N$ values from mainland of Sweden ($n = 20$) and from Finnish (pre-)modern specimens ($n = 5$) are statistically indistinguishable ($\delta^{13}C_{mean} = -22.0‰$, SD = 1.0; $\delta^{15}N_{mean} = +3.3‰$, SD = 1.2) from each other, but significantly different from Neolithic moose from Latvia and Lithuania ($\delta^{13}C_{mean} = -23.2‰$, SD = 0.3; $\delta^{15}N_{mean} = +4.4‰$, SD = 0.5; $n = 8$), demonstrating that while as a whole the terrestrial mammals appear relatively homogenous, differences can exist. Geographical and/or temporal differences are further illustrated in reindeer samples dating to three climatically contrasting periods. Warm MIS-3 period specimens from Poland ($n = 5$) and cold Younger Dryas period samples from Germany ($n = 7$) form separate clusters. Compared to these, medieval to (pre-)modern Fennoscandian reindeer have lower $\delta^{13}C$ and higher $\delta^{15}N$ values.

Small sample populations as well as the current scarcity of radiocarbon dates limit a more rigorous examination of possible temporal (climate–related) patterns in dIANA data. Besides the clearly separated

Younger Dryas reindeer, temporal variation patterns, such as the HTM and LIA are yet challenging to recognize in the cervid, or in the terrestrial herbivore record in general.

4.4. Patterns of the Baltic Sea

Based on all seal and porpoise collagen records in dIANA, their $\delta^{13}C$ and $\delta^{15}N$ values show a clearly lower level of variability compared to the other (semi)aquatic organisms ($\delta^{13}C_{mean} = -16.3‰$, SD = 2.2; $n = 127$ and $\delta^{15}N_{mean} = +13.7‰$, SD = 2.3; $n = 111$). The variability is further reduced when only samples from the Baltic Sea brackish phase, ca. 8500 cal BP until today ($\delta^{13}C_{mean} = -16.4‰$, SD = 1.4; $n = 77$) and $\delta^{15}N_{mean} = +12.9‰$, SD = 1.3; $n = 72$), are considered.

A spatiotemporal analysis of marine mammal collagen $\delta^{13}C$ values ($n = 114$), presented in Fig. 5, illustrates the source of the total variability, relating to the strength of marine influence over the Baltic Sea basin during its postglacial evolution (Emeis et al., 2003; Ukkonen et al., 2014). The majority of the age estimates are based on relative ages of the find contexts, except the radiocarbon-dated data from Ukkonen (2002), and Ukkonen et al. (2014). The lowest $\delta^{13}C$ values derive from the Baltic Ice Lake samples and from the Bothnian Bay basin. Both represent freshwater conditions with absence of ^{13}C enriched marine carbon. The values are also similar with those of the freshwater Ladoga Lake seal specimens. Seals may, however, migrate several hundreds of kilometers (Martinez-Bakker et al., 2013) and the presumably large habitat shows as a relatively large within-basin standard deviation of samples. The data show that while differences between sub-basins tend to persist (Fig. 5: Mesolithic C vs. D to Neolithic E vs. F), samples deriving from the Kattegat/Baltic Proper area display a relatively stable temporal behavior in $\delta^{13}C$ values from the Mesolithic (Fig. 5C) and Neolithic (Fig. 5E) periods until the (pre-)modern period (Fig. 5G), including the data from FMNH samples.

The database contains far less $\delta^{34}S$ data compared to the $\delta^{13}C$ and

Table 2

Results of Student's two-tailed test comparing a) reindeer and other cervids, b) *Capreolus* and *Cervus* sp., c) moose and other cervids, excluding reindeer, d) domestics and cervids, excluding reindeer, e) archaeological Swedish moose and (pre-)modern Finnish moose and f) Swedish/Finnish moose and Latvian/Lithuanian moose. See Fig. 4 caption for data references. Domestic herbivore data (panel D.) were compiled including data also from the following papers: cattle (Fischer et al., 2007; Noe-Nygaard et al., 2005; Jørkov et al., 2010; Lightfoot et al., 2016; Naumann et al., 2014; Reitsema et al., 2010, 2017; Antanaitis-Jacobs et al., 2009; Piličiauskas et al., 2017a); sheep/goat (Craig et al., 2006; Fischer et al., 2007; Fornander, 2011; Jørkov et al., 2010; Lightfoot et al., 2016; Naumann et al., 2014; Reitsema et al., 2010, 2017; Salmi et al., 2015).

	$\delta^{13}C$ (‰)				$\delta^{15}N$ (‰)			
	n	Mean	SD	SEM	Mean	SD	SEM	
A.								
Reindeer	28	−19.0	0.9	0.17	3.7	1.5	0.28	
Other cervids	133	−22.4	0.9	0.08	4.1	1.1	0.10	
Difference		3.3			−0.4			
p-value for the difference			0.000			0.101		
B.								
Capreolus sp.	33	−22.8	0.9	0.16	4.4	1.9	0.19	
Cervus sp.	62	−22.4	0.7	0.09	4.3	0.8	0.10	
Difference		−0.4			0.1			
p-value for the difference			0.010			0.718		
C.								
Moose	38	−22.1	1.0	0.17	3.5	1.4	0.22	
Capreolus and Cervus sp.	95	−22.5	0.8	0.08	4.3	0.9	0.09	
		0.4			−0.8			
p-value for the difference			0.020			0.000		
D.								
Domestics	189	−21.7	0.7	0.05	5.7	1.6	0.11	$\delta^{15}N$ (n = 188)
Cervids	133	−22.4	0.9	0.08	4.1	1.1	0.10	
Difference		0.7			1.6			
p-value for the difference			0.000			0.000		
E.								
Sweden mainland	20	−22.0	1.0	0.21	3.3	1.22	0.27	
Finland	5	−21.9	0.8	0.36	3.5	2.1	0.95	
Difference		−0.1			−0.2			
p-value for the difference			0.831			0.712		
F.								
Sweden and Finland	26	−21.9	1.0	0.19	3.4	1.4	0.28	
Latvia and Lithuania	8	−23.3	0.3	0.09	4.4	0.5	0.18	
Difference		1.4			−1.0	0.34	0.52	
p-value for the difference			0.000			0.059		

SEM – standard error of the mean.

$\delta^{15}N$ values discussed above, and thus there are only limited possibilities to evaluate generally applicable patterns in $\delta^{34}S$ values in the Baltic Sea area. The new (pre-)modern animal data represent a significant addition to the amount of existing faunal $\delta^{34}S$ analyses in the Baltic Sea area. The major emerging - unsurprising - trend in the dIANA data is the clear difference between the brackish water environment of the Baltic Sea and the terrestrial animals. Eliminating three outlier values, all for seals, two of which are from the Bothnian Bay and also heavily influenced by ^{13}C-depleted carbon of terrestrial origin, the Baltic fauna (seals, fish, and birds) show high $\delta^{34}S$ values and constrained variability (mean = +16.2‰, SD = 1.9), while terrestrial
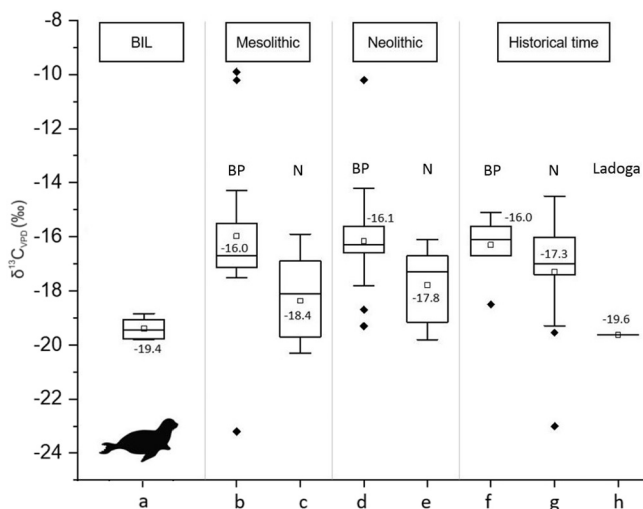

Fig. 5. Spatiotemporal differences in Baltic seal and porpoise finds over the Holocene epoch. Samples represent following identified species (*H. grypus*, *P. phocoena*, *P. groenlandica*, *P. hispida bothniensis* and *ladogensis*, *P. vitulina* and partly undefined species). Species name is given in cases where single species has been analysed for the plotted time-period. Mean value is represented by square symbol and numerical value, box edges represent the 25th and 75th percentiles, and horizontal line is the median. Whiskers represent minimum and maximum values, solid diamonds are outliers. "BIL" = Baltic Ice Lake phase, ca. 15,000–11,600 cal BP (see text); "Historical time" covers time span ca. 500–1915 CE. "BP" refers to Baltic Proper and "N" to the northern parts of the Baltic Sea. a) BIL/freshwater (*n* = 6; Boethius and Ahlström, 2018); b) Mesolithic Danish straits and Baltic Proper (*Halichoerus grypus*; *n* = 13; Boethius and Ahlström, 2018; Craig et al., 2006); c) Mesolithic Bothnia/Quark (*Pusa hispida bothniensis*; *n* = 9; Ukkonen, 2002; Ukkonen et al., 2014); d) Neolithic Baltic Proper and Kattegat (*n* = 53; Antanaitis-Jacobs et al., 2009; Craig et al., 2006; Fischer et al., 2007; Heron et al., 2015; Eriksson, 2004; Eriksson et al., 2008; Lidén et al., 2004; Linderholm et al., 2014; Meadows et al., 2016; Piličiauskas et al., 2017b); e) Neolithic Bothnian Bay (*n* = 8; Lõugas et al., 1996; Ukkonen, 2002; Ukkonen et al., 2014); f) Medieval Baltic Proper and Kattegat (*n* = 7; Grupe et al., 2009; Kosiba et al., 2007; Linderholm et al., 2008b); g) (pre-)modern Gulf of Bothnia and Åland (*n* = 16; Lahtinen and Salmi, 2018; this study); i) (pre-)modern Lake Ladoga (*Pusa hispida ladogensis*; *n* = 2; this study).

animals have lower and much more variable $\delta^{34}S$ values (mean = +9.3‰, SD = 3.1). Interestingly, there is a difference between the mean $\delta^{34}S$ values for seals from Swedish archaeological contexts (Eriksson et al., 2008; Linderholm et al., 2014) and the new Finnish (pre-)modern seal data. Archaeological seal finds show $\delta^{34}S$ values that are distinctly lower (mean = +13.4‰, SD = 1.4; *n* = 11) than their (pre-)modern counterparts ($\delta^{34}S_{mean}$ = +15.9‰, SD = 0.6, *n* = 12), perhaps reflecting a temporal evolution of the $\delta^{34}S$ value of the basin. For example, it has been suggested that during times of more intense bottom hypoxia in the basin, sulfides with typically lower $\delta^{34}S$ values influence the food chain (e.g. Limburg et al., 2015). Acid rain can also have raised the $\delta^{34}S$ values of the Baltic Sea (Krouse et al., 1991).

5. Conclusion

The amount of terrestrial animal isotope analyses in dIANA already offers possibilities to help in the estimation of realistic ranges for bone collagen isotopic values to be used as baseline information in paleo-dietary studies, but more data are needed to cover different types of environments in northern Europe. Our new analyses, especially on birds and sulphur, are highly valuable for the future research. The (pre-)modern data as a whole offer new resources for comparison between modern and archaeological samples, useful for researchers working on contexts where archaeological baseline materials are not available. The

significant diversity in the isotopic character of aquatic habitats, clearly visible in the examples drawn from the dIANA seal, bird, and fish data and discussed above, is essential to acknowledge in baseline work, and, in absence of robust local baseline data, conservative error margins should be used when conducting paleodietary research in the Baltic Sea area. Climatic patterns, such as the HTM and LIA are yet challenging to recognize in the dIANA terrestrial herbivore records due to low data numbers with exact dating, but climate induced isotopic shifts are plausible and should be taken into account.

As discussed earlier, the current database is built upon isotopic data judged reliable by the respective original authors, and no data harmonization has been done largely due to restricted personnel resources available for database upkeep. However, the applied methods have been and will be reviewed at the time of data entry. Any suspicion on inadequate data quality will result in omission of said data from the database. Nevertheless, this leaves the users of the database with the ultimate responsibility to check the original publication for contextual details and for data quality criteria. The dIANA data may for example include samples with carbon and nitrogen content not accepted by all scientists, or this data may be missing. Furthermore, we encourage data users to pay heed also to interlaboratory differences in pretreatment and extraction methods, or analysis and calibration procedures.

Future development of the dIANA database includes possibility to add description of used extraction and analytical methods. It is also possible to import additional isotope systems such as strontium isotope ratios ($^{87}Sr/^{86}Sr$), oxygen and carbon isotope data of bioapatite and compound-specific data, and possibly also to include the omitted analysis data. Currently, dIANA does not contain coordinate (lat, long) information for data sites but georeferencing the find locations is a long-term goal, which will require input from researchers familiar with the sites.

As database developers we wish to see even more diversity in the analysed species; plant isotopic values would highly value and in addition to archaeological primary data, the utilization of zoological collections, modern ecological analogies, and other suitable proxies will ultimately lead to better understanding of (paleo)diets, us humans included.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2019.03.005.

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