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ORIGINAL PAPER

Aquatic resources in human diet in the Late Mesolithic in Northern France and Luxembourg: insights from carbon, nitrogen and sulphur isotope ratios

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Abstract We investigated the contribution of freshwater resources to the diet of seven Late Mesolithic hunter-gatherers (ca. 5300–7000 BC) from Northern France and Luxembourg using stable isotope ratios. In addition to the carbon and nitrogen stable isotope ratios ($\delta^{13}C$, $\delta^{15}N$), we explored the potential of the sulphur isotopic ratios ($\delta^{34}S$) to detect and quantify the proportion of protein derived from aquatic foodstuff. In only two sites, animal remains from an associated settlement were available and subsequently examined to decipher the isotopic differential between terrestrial and freshwater resources. The quantification of their relative contribution was simulated using a Bayesian mixing model. The measurements revealed a significant overlap in $\delta^{13}C$ values between freshwater and terrestrial resources and a large range of $\delta^{15}N$ values for each food category. The $\delta^{34}S$ values of the aquatic and terrestrial animals were clearly distinct at the settlement in the Seine valley, while the results on fish from Belgium demonstrated a possible overlap in $\delta^{34}S$ values between freshwater and terrestrial resources. Local freshwater ecosystem likely contributed to ca. 30–40 % of the protein in the diet of the individuals found in the Seine settlement. Out of this context, the isotopic signature and thus contribution of the available aquatic foods was difficult to assess. Another potential source of dietary protein is wild boar. Depending on the local context, collagen $\delta^{34}S$ values may contribute to better assessment of the relative contribution of freshwater and terrestrial resources.

Keywords Mesolithic · Stable isotopes · Freshwater · Northern France · Luxembourg

Introduction

For the last few decades, the application of stable isotope ratio analyses on Late Mesolithic hunter-gatherers in Europe has mainly been considered in the context of the transition to the first farming communities of the Neolithic and their relative use of aquatic resources in this important transitional period (e.g. Lubell et al. 1994; Richards and Mellars 1998; Lillie and Richards 2000; Richards et al. 2003a, c; Bonsall et al. 2004; Bocherens et al. 2007; Fischer et al. 2007; Smits and van der Plicht 2009; Lightfoot et al. 2011; Schulting and Richards 2001; Guiry et al. 2015). Most of the studies quoted above were conducted on sites from coastal environments where the consumption of marine resources was investigated. To date, research on the use of freshwater resources by Mesolithic groups in a continental context has been restricted to relatively few specific geographical areas such as the Danube Gorges (e.g. Bonsall et al. 2004; Borić et al. 2004; Nehlich et al.

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2010), the Dnieper Basin (Lillie et al. 2011), the Meuse Basin (Bocherens et al. 2007) and western Germany (Bollongino et al. 2013).

An increasing number of Late Mesolithic burials have recently been added to the archaeological record of continental Northwestern Europe, notably in Northern France (e.g. Valentin et al. 2008; Meiklejohn et al. 2010; Bosset and Valentin 2013). It contrasts with the poorly represented Late Mesolithic archaeological contexts of Belgium and the yet sole example of Loschbour in Luxembourg (review in Meiklejohn et al. 2014). A large number of the Northern France burials are associated with very few, if any, artefacts and are not associated to settlement context. Based on faunal remains found in Northern France and Luxembourg, animal food resources appear to include the wild boar (*Sus scrofa*), red deer (*Cervus elaphus*), roe deer (*Capreolus capreolus*) and aurochs (*Bos primigenius*) (e.g. Cordy 1982; Bridault 1997; Ducrocq et al. 2008; Leduc et al. 2013; Marinval-Vigne et al. 1989). Evidence for fishing is limited until 8200 ^{14}C BP and confidently attested at only two sites: Noyen-sur-Seine and La Chaussée-Tirancourt in Northern France (Marinval-Vigne et al. 1989; Ducrocq and Ketterer 1995).

Stable isotope ratios and paleodiet

Carbon and nitrogen isotope abundances in bone collagen have proved to be useful tracers of the source of protein, namely terrestrial versus aquatic, in the diet of ancient hunter-gatherers in continental context (e.g. Richards et al. 2001; Bocherens et al. 2007; Drucker et al. 2016). For predators, the collagen δ^{13}C and δ^{15}N values depend on those of their food with a factor of enrichment, which is limited in ^{13}C but significant in ^{15}N (0.8 to 1.3 ‰ compared with 3 to 5 ‰ in the latter; e.g. Bocherens and Drucker 2003). For a comparable trophic position, specimens from aquatic ecosystems deliver higher ^{15}N abundances than specimens from terrestrial context (e.g. Schoeninger and DeNiro 1984; Dufour et al. 1999), a difference that is reflected in their consumers. However, the respective ranges of δ^{15}N values of terrestrial and freshwater resources also depend on environmental factors such as temperature and aridity that may differ significantly geographically and temporally (e.g. Drucker et al. 2003; Bocherens et al. 2014). This can result in a large range of isotopic variation and thus overlapping isotopic values between potential prey species (e.g. Dufour et al. 1999; Katzenberg et al. 2010).

The ^{34}S abundances in collagen have increasingly been investigated on archaeological remains to track aquatic resources consumption (review in Nehlich 2015). Primary producers are characterized by δ^{34}S values around +20 ‰ in oceanic contexts, whereas, in continental ecosystems, they exhibit lower δ^{34}S values except in areas close to coastlines due to the sea spray effect (e.g. Peterson and Fry 1987). The δ^{34}S values of plants are passed on along the food chain with minor fractionation from ca. −1 to +1.5 ‰ (Richards et al. 2003b; Barnes and Jennings 2007; Tanz and Schmidt 2010) if not negligible (McCutchan et al. 2003; Arneson and MacAvoy 2005). Depleted δ^{34}S values are observed as the result of the reduction of sulphate (SO_4^{2-}) to hydrogen sulphide (H_2S) and subsequent reoxidation by bacteria, which are notably present in rivers and aquatic sediments (Fry et al. 1986; Holmer and Storkholm 2001). Hence, a distinction in the abundance of ^{34}S is expected between terrestrial and freshwater ecosystems and has indeed already been explored in ancient contexts (Privat et al. 2007; Nehlich et al. 2010, 2011; Bocherens et al. 2011). Although a clear distinction in the collagen δ^{34}S values was found in most cases between terrestrial and freshwater faunal remains, the observed ranges of values were variable from one case study to the other due to local differences in geology, atmospheric deposition and conditions of sulphur cycling. The pattern of distinction in ^{34}S abundances between terrestrial and freshwater resources is thus unpredictable, and systematic analyses of the local faunal remains are required to establish it.

In this paper, we aim to reconstruct the contribution of freshwater resources to the diet of Late Mesolithic humans from Northern France and Luxembourg (ca. 6300–8000 ^{14}C BP, ca. 5300–7000 BC) using ^{13}C and ^{15}N abundances of their bone collagen. For this purpose, we established the isotopic baseline using as many animal remains as possible from the same region and time span to decipher the specific stable isotope pattern of the associated ecosystems. We considered, in addition, the abundances in ^{34}S in order to explore further quantitative estimation of the different sources of protein, in particular between freshwater and terrestrial and possibly fine-tune the reconstruction of subsistence at an individual level.

Materials and methods

Materials

The studied human remains come from different sites in Northern France and Luxembourg (Fig. 1) and witnessed diverse funerary treatments. The site of Loschbour at Heffingen in the Grand-Duchy of Luxembourg, discovered in 1935, provided a primary inhumation (LSB1) with a cremation (LSB2) (Toussaint et al. 2009). The excavation also revealed evidence of a settlement area with a lithic industry of Montbanian culture and some faunal remains predominantly of not only wild boar but also aurochs, red deer, roe deer and beaver (Gob 1982). The buried individual was a male adult whose skull was partially ochered (Delsate et al. 2009, 2011). Two aurochs ribs in apparent association with the human individual were dated to 7115 ± 45 ^{14}C BP (Gob 1982).

Fig. 1 Geographical location of the sites investigated in this study

Regarding Northern France, Maisons-Alfort at Zac d'Alfort (Val de Marne, France) corresponds to a primary single burial. The individual is a mature adult of unknown sex due to the poor preservation of the remains (Valentin et al. 2008). Similarly, the sites of Cuiry-lès-Chaudardes 'Les Fontinettes' and Berry-au-Bac 'Le Vieux Tordoir' have both provided a single human burial with a necklace made of pike vertebrae in the first case (Ilett 1998) and with ochre and a bone artefact in the latter. In contrast, the human remains at Noyen-sur-Seine 'Hauts des Nachères' were found in a non-funerary context. The site is a riverbank formation located between Nogent-sur-Seine and Montereau. Archaeological remains from the four excavated loci reveal a Mesolithic occupation in palaeochannels of the Seine River in a peat context. Surface erosion led to the exposure of the peat deposit 9sup in locus 3, while the lower peat deposit 9 is visible in the excavated locus 2 (reviewed in Mordant et al. 2013). One radiocarbon date was obtained on the wood fibres of a fish trap (8000 ± 100 ^{14}C BP) recovered at the basis of layer 9. Two more recent dates were retrieved on wood fragments from level 9sup: 7040 ± 80 ^{14}C BP and 6240 ± 70 ^{14}C BP. A preliminary study of a sub-sample of the human remains, found in both level 9sup and level 9, described cranial and postcranial remains of varying degrees of completeness and, in some cases, showing superficial modifications such as traces of burning and cutmarks (Auboire 1991). In this paper, we investigate one adult and one juvenile individual from level 9 and one adult from level 9sup on which further study is currently conducted for age and sex determination. With the exception of the non-adult individual from layer 9 of Noyen-sur-Seine (NO7300), the individuals under consideration were directly radiocarbon dated (Table 1).

The interpretation of the isotopic signature of the human individuals requires the establishment of isotopic baseline provided by local faunal remains. The terrestrial animals we included are red deer (*C. elaphus*) and wild boar (*S. scrofa)* from both Noyen-sur-Seine and Loschbour. In addition, roe deer (*Capreolus capreolus*), aurochs (*B. primigenius*), wild boar (*S. scrofa*), wolf (*Canis lupus*), red fox (*Vulpes vulpes*), lynx (*Lynx lynx*), and wild cat (*Felis silvestris*) were sampled from the faunal assemblage of Noyen-sur-Seine. With the exception of one unfused long bone of aurochs (NO5200), only mature individuals were sampled from the animal remains and, as far as possible, the same anatomical part was selected. Aquatic animals chosen for sampling encompass European pond turtle (*Emys orbicularis*), northern pike (*Esox lucius*) and European eel (*Anguilla anguilla*) as well as one of their predator, the otter (*Lutra lutra*), all specimens coming from Noyen-sur-Seine. One pike and several cyprinids from the Mesolithic occupation of Abri du Pape located along the Meuse river in Belgium, with radiocarbon dates ranging from 8800 to 7850 ^{14}C BP (in Léotard et al. 1999) supplemented the dataset.

Magdalenian fish freshwater species (ca. 12,800 ^{14}C BP) including burbot (*Lota lota*), brown trout (*Salmo trutta fario*), and nase (*Chondrostoma nasus*) from earlier Magdalenian sites of the Meuse valley (Drucker et al. 2016) were also added in the present analysis.

Sample preparation and analysis

Collagen was extracted following a protocol based on Longin (1971) and modified by Bocherens et al. (1997). The extraction process includes a step of soaking in 0.125 M NaOH between the demineralization and solubilization steps to achieve the elimination of lipids. Elemental analysis (C, N, S) and isotopic analysis ($\delta^{13}C$, δ15N, $\delta\ ^{34}S$) were conducted at the Department of Geosciences of Tübingen University using a NC2500 CHN-elemental analyser coupled to a Thermo Quest Delta + XL mass spectrometer. Sample $\delta^{13}C$ and $\delta^{15}N$ values are reported relative to the international reference scales V-PDB for carbon and AIR for nitrogen isotopes. Analytical error, based on within-run replicate measurement of laboratory standards (albumen, modern collagen, USGS 24, IAEA 305A), was ±0.1 ‰ for $\delta^{13}C$ values and ±0.2 ‰ for $\delta^{15}N$ values. Samples were calibrated to $\delta^{34}S$ values relative to V-CDT of NBS 123 ($\delta^{34}S = 17.1$ ‰), NBS 127 ($\delta^{34}S = 20.3$ ‰), IAEA-S-1 ($\delta^{34}S = -0.3$ ‰) and IAEA-S-3 ($\delta^{34}S = 21.7$ ‰). The reproducibility is ±0.4 ‰ for $\delta^{34}S$ measurements, and the error on S measurement is 5 %. Reliability of the $\delta^{13}C$ and $\delta^{15}N$ values can be established by measuring collagen chemical composition, with atomic C:N ranging from 2.9 to 3.6 (DeNiro 1985) and the percentage of C and N above 8 and 3 %, respectively (Ambrose 1990). We retained $\delta^{34}S$ values of samples whose atomic C:S and N:S fit into the range of 300–900 and 100–300, respectively (Nehlich and Richards 2009) and whose percentage of S ranged between 0.14 and 0.26 %, determined through the results of modern mammalian collagen (Aldrich collagen, modern elk and modern camel) measured in the same sets. The ^{34}S amounts and the $\delta^{34}S$ values in animal species from level 9 of Noyen-sur-Seine published in Bocherens et al. (2011) were normalised based on Sigma collagen (0.22 ± 0.003 % and 4.2 ± 0.2 ‰) and Aldrich collagen (0.18 ± 0.01 % and 1.8 ± 0.6 ‰) measurements used in Drucker et al. (2011).

Direct AMS radiocarbon dates have been performed on most of the considered human remains and some faunal specimens (Table 1). The results were then calibrated with a 95.4 % confidence level and rounded to the nearest 5 based on the OxCal 4.2 programme (Bronk Ramsey and Lee 2013) using the IntCal13 calibration curve (Reimer et al. 2013).

Table 1 List of the radiocarbon dates obtained on the sites from Northern France and Luxembourg investigated in this study

Site	Location	Excavation reference	Description	Lab no.	^{14}C dating BP	^{14}C age BC 95.4 % prob.	^{14}C source
Loschbour 1	Heffingen	Burial LSB1	Human, adult male	LSB-1	7205 ± 50 OxA-7338	6215–5995	2
Loschbour 1	Heffingen	Burial LSB1	Aurochs, ribs		7115 ± 45 GrN-7177	6065–5900	2
Zac d'Alfort	Maisons-Alfort	Burial 7	Human, adult	ZMA-1	8030 ± 50 Ly-9817	7085–6705	3
Les Fontinettes	Cuiry-lès-Chaudardes		Human, adult	CRC-1	7400 ± 60 GrA-28268	6415–6095	4
Le Vieux Tordoir	Berry-au-Bac	Burial 353	Human, adult	BRB-1	6325 ± 35 SacA-5455	5375–5215	4
Haut-des-Nachères	Noyen-sur-Seine	Locus 3, layer 9sup	Wood		6240 ± 70 Gif-6991	5360–5010	1
Haut-des-Nachères	Noyen-sur-Seine	Locus 3,layer 9sup basis	Wood		7040 ± 80 Gif-7125	6050–5745	1
Haut-des-Nachères	Noyen-sur-Seine	Locus 3, layer 9sup	Human, adult	NO7200	7490 ± 45 GrA-50237	6440–6250	This work
Haut-des-Nachères	Noyen-sur-Seine	Locus 1, layer 9	Human, adult	NO6800	7915 ± 45 GrA-50239	7030–6650	This work
Haut-des-Nachères	Noyen-sur-Seine	Locus 1, layer 9	Red deer, bone	NO5000	7810 ± 45 GrA-45303	6770–6505	This work
Haut-des-Nachères	Noyen-sur-Seine	Locus 1, layer 9	Otter, bone	NO6500	8070 ± 45 GrA-45301	7175–6825	This work
Haut-des-Nachères	Noyen-sur-Seine	Locus 1, layer 9 basis	Fish trap		8000 ± 100 Gif-6633	7245–6635	1

1: Mordant and Mordant 1992, 2: Higham et al. 2007, 3: Valentin et al. 2008, 4: Posth et al. 2016

Calculation of the proportions of consumed preys

The relative contribution of the different preys to the average diet of the human individuals was simulated using a Bayesian mixing model approach performed in the Stable Isotope Analysis in R (SIAR) package (Parnell et al. 2010), using the R software, version 3.0.2 (Team R Core 2013). SIAR offers the possibility to incorporate uncertainty in input data and yields not only a range of possible dietary proportions but also provides also their relative probability distribution (Parnell et al. 2010). We considered a trophic enrichment factor (TEF) of +1.1 ± 0.2 and +3.8 ± 1.1 ‰ for δ^{13}C and δ^{15}N values, respectively, based on a review comparing the δ^{13}C and δ^{15}N values of the bone collagen of predators and that of their prey in modern and ancient terrestrial ecosystems (reviewed in Bocherens et al. 2015). There are however few controlled feeding experiments on mammals to enlighten TEF between consumer body tissues and their diet for δ^{34}S (Richards et al. 2003b; Tanz and Schmidt 2010). In this study, we used a TEF of 0.5 ± 2.4 ‰ for δ^{34}S corresponding to an average of published TEF data for modern fauna (reviewed in Nehlich 2015).

Results and discussion

δ^{13}C and δ^{15}N values of the preys

The δ^{13}C values of the collagen of the terrestrial fauna of the Mesolithic occupation of Noyen-sur-Seine and Loschbour revealed some inter-species differences (Table 2, Fig. 2). Among the terrestrial ungulates, the wild boar showed δ^{13}C values varying from −21.5 to −18.8 ‰, while a range of lower values were observed for aurochs, red deer and roe deer (−23.8 to −22.3 ‰). The latter are similar to collagen values reported for herbivores consuming plants that developed under a dense canopy (see review in Drucker et al. 2008). Several studies in boreal and temperate forest confirmed the occurrence of a ‘canopy effect’ on understory plants (Broadmeadow et al. 1992; Brooks et al. 1997; Bonafini et al. 2013) due to the accumulation of ^{13}C-depleted CO_2 produced by leaf litter recycling and the change in photosynthetic activity and stomatal conductance linked to the specific conditions of light and humidity (e.g. Francey et al. 1985; van der Merwe and Medina 1991; Broadmeadow et al. 1992). Thus, a closed forest habitat can be deduced for the aurochs and roe deer of Noyen-sur-Seine and the red deer at both Noyen-sur-Seine and Loschbour as both show very similar δ^{13}C values range (−23.1 to −22.3 and −23.1 to −22.5 ‰, respectively). In contrast, the relatively high δ^{13}C values of the wild boar of Noyen-sur-Seine and Loschbour could be due to their specific consumption of fruits, acorns and underground tubers (e.g. Ballari and Barrios García 2014). No canopy effect is expected for these food items since they come from the top of the canopy or develop underground. It would be thus premature to conclude that the habitat of the wild boar was not overlapping that of the deer and large bovine. Hence, the temperate forest can be considered as the permanent habitat of a large variety of the terrestrial preys hunted by the Mesolithic groups around Noyen-sur-Seine and Loschbour.

Most of the δ^{15}N values of the ungulates clustered between 3.7 and 7.4 ‰ with comparable range from one species to another (Table 2, Fig. 2). However, two specimens from Noyen-sur-Seine, roe deer NO5500 and wild boar NO1100, showed a higher δ^{15}N value of 10.0 and 9.2 ‰, respectively, and so did a wild boar sample from Loschbour as well. The high ^{15}N abundance of the Loschbour specimen can be explained by the nursing effect since the collagen was extracted from a canine root. The enriched ^{15}N collagen from the two samples of Noyen-sur-Seine could be explained by the consumption of a specific enriched ^{15}N plant, such as mushrooms (e.g. Drucker et al. 2012), locally specific conditions of temperature and/or aridity (e.g. Amundson et al. 2003; Craine et al. 2009) or a forage quality significantly under the animal’s requirement (e.g. Robbins et al. 2010; Poupin et al. 2011). An alternative reason for the case of the wild boar could be the access to animal protein since this species can be omnivorous (e.g. Ballari and Barrios García 2014). Such a hypothesis was confirmed through the ^{15}N analysis of single amino acids (Naito et al. 2013). Even though the number of these high ^{15}N ungulates was limited, they might have introduced variability in the δ^{15}N values of the terrestrial predators.

δ^{13}C and δ^{15}N values of the animal predators

Within the terrestrial carnivores, among which considerable variation in isotopic composition was observed, two groups can be considered on the basis of their δ^{15}N values. The first group corresponded to a δ^{15}N value of 9.3 ‰ and included the wild cat and the wolf (δ^{13}C value of −19.8 and −21.3 ‰, respectively). The red fox and the lynx both yielded δ^{15}N values around 12 ‰, but δ^{13}C in the same range as the wild cat and the wolf. These last predators presented the expected enrichment of 3 to 5 ‰ in δ^{15}N and about 1 ‰ in the δ^{13}C (Bocherens and Drucker 2003) in relation to the averaged values of most of the terrestrial ungulates. The more enriched ^{15}N predators can be explained by a consumption of ungulates with high δ^{15}N values such as the wild boar NO1100 and the roe deer NO5500 or young animals since they constitute a source of ^{15}N-enriched meat due to the nursing effect. An opportunistic behaviour can be hypothesised for the red fox, suggesting the scavenging of dietary remains of human groups, including larger preys than those normally hunted by it (Drucker 2001) or some aquatic resources in this context. Indeed, the consumption of large ungulates and aquatic animals through scavenging has been documented for red fox in modern temperate ecosystems (e.g. Jędrzejewski and Jędrzejewska 1992; Lanszki 2005). In

Table 2 Results of stable isotope analyses of collagen ($\delta^{13}C$, $\delta^{15}N$, $\delta^{34}S$) from animal remains from French, Luxembourgian and Belgian sites. The carbon, nitrogen and sulphur composition of the collagen is given through elemental composition (C, N, S) and atomic ratio (C:N, C:S, N:S). The values considered for the calculation of the SIAR averages and standard deviations (in italics) are framed. Details about the selection of the samples for these calculations are given in the main text

Site	Lab n°	Species	Sample	Reference	C (%)	N (%)	C:N	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	S (%)	$\delta^{34}S$ (‰)	C:S (%)	N:S (%)	^{13}C,^{15}N source	^{34}S source
Loschbour 1	LSB2	Red deer	antler		37.4	13.4	3.3	-22.5	6.3	0.15	3.8	677	208	this work	this work
Loschbour 1	LSB5	Red deer	mandible	1886-1943	41.0	13.8	3.5	-23.1	7.1	0.17	6.8	628	181	this work	this work
Noyen/Seine	NO100	Red deer	radius R	84 XVI C150-8 9	41.6	15.1	3.2	-22.8	6.8	0.19	1.9	581	180	1	1, this work
Noyen/Seine	NO400	Red deer	humerus L	84 XVI H140-6 9	42.0	15.8	3.0	-22.3	6.8	0.19	2.0	604	195	1	1, this work
Noyen/Seine	NO600	Red deer	radius L	84 XVI D144-6 9	41.6	14.8	3.3	-23.1	3.7					1	
Noyen/Seine	NO4800	Red deer	metacarpal L	84 XVI E137-12 9	41.8	15.1	3.2	-22.5	4.1						
Noyen/Seine	NO5000	Red deer	metacarpal L	84 XVI D143-15 9	42.5	15.6	3.2	-22.5	6.8	0.14	1.8	812	256	1	1, this work
Noyen/Seine	NO2100	Roe deer	phalanx 1	83 XVI E140 9	42.0	15.5	3.2	-22.7	5.1	0.17	4.1	658	208	1	1, this work
Noyen/Seine	NO2200	Roe deer	phalanx 1	83 XVI E140 9	42.3	15.5	3.2	-22.4	5.5	0.19	4.7	593	186	1	1, this work
Noyen/Seine	NO2400	Roe deer	phalanx 1	84 XVI Y151-36 9	41.9	15.2	3.3	-23.1	3.8					1	
Noyen/Seine	NO5300	Roe deer	femur L	84 XV Z151-36 9	41.6	15.1	3.2	-22.9	3.7					1	
Noyen/Seine	NO5400	Roe deer	tibia L	84 XVI G142-6 9	42.2	15.5	3.2	-22.8	6.3	0.19	0.2	579	182	1	1, this work
Noyen/Seine	NO5500	Roe deer	tibia L	84 XVI E141-2 9	42.7	15.7	3.2	-23.8	10.0					2	
Noyen/Seine	NO5600	Roe deer	phalanx 1	84 XVI H132-38 9	42.8	15.8	3.2	-23.2	6.3					1	
Noyen/Seine	NO1600	Aurochs	phalanx 3	84 XVI C150-8 9	41.4	14.8	3.3	-23.5	5.2					1	
Noyen/Seine	NO1900	Aurochs	metapodial L	84 XVI C149-6 9	41.7	15.2	3.2	-23.4	6.0	0.19	2.7	601	188	1	1, this work
Noyen/Seine	NO2000	Aurochs	metatarsus	84 XV TZ153-9 9	41.5	15.1	3.2	-22.8	5.2					1	
Noyen/Seine	NO5100	Aurochs	metatarsal L	84 XVI G144-4 9	42.5	15.4	3.2	-22.9	4.9	0.15	2.1	757	235	1	1, this work
Noyen/Seine	NO5200	Aurochs	tibia L	84 XVI B148-14 9	41.7	15.2	3.2	-22.6	5.8					1	
							SIAR Average	*-22.9*	*5.8*		*3.0*				

Table 2 (continued)

							SD	*0.4*	*1.5*		*1.9*				
Loschbour 1	LSB3	Wild boar	canine root		41.5	14.8	3.3	-20.4	8.5	0.16	-1.0	692	211	this work	this work
Loschbour 1	LSB6	Wild boar	mandible	2880-1943	40.1	12.9	3.6	-18.8	7.4	0.18	6.6	586	162	this work	this work
Noyen/Seine	NO900	Wild boar	ulna L	84 XVI G148-8 9	41.9	15.2	3.2	-21.5	6.5					1	
Noyen/Seine	NO1100	Wild boar	radius L	84 XVI D148-2 9	41.1	14.9	3.2	-19.7	9.2	0.18	2.1	609	189	1	1, this work
Noyen/Seine	NO1300	Wild boar	humerus L	84 XVI A151-21 9	41.6	15.2	3.2	-20.6	5.4					1	
Noyen/Seine	NO1500	Wild boar	humerus R	83 XVI C148-5 9	40.8	14.5	3.3	-20.1	6.3					1	
Noyen/Seine	NO5900	Wild boar	phalanx 3	84 XVI E147 9	42.7	15.5	3.2	-20.9	5.7					1	
							SIAR Average	*-20.3*	*6.7*		*2.6*				
							SD	*1.0*	*1.4*		*3.8*				
Noyen/Seine	NO4000	Wolf	ulna	84 XVI A153-7 9	41.5	15.3	3.2	-21.3	9.3	0.20	-1.9	563	178	1	1, this work
Noyen/Seine	NO6700	Red fox	metacarpal	84 XVI G178 9	42.4	15.6	3.2	-21.2	12.4	0.17	4.4	670	211	1	1, this work
Noyen/Seine	NO3700	Lynx	tibia	84 XVI D142-5 9	40.3	14.9	3.2	-19.1	11.9	0.24	-1.1	444	140	1	1, this work
Noyen/Seine	NO3500	Wild cat	femur R	85 XVI H206-1 9	40.0	14.5	3.2	-19.8	9.3	0.20	5.1	522	162	1	1, this work
Noyen/Seine															
Noyen/Seine	NO7600	Eel	vertebrae	84 XVI D141	40.7	14.5	3.3	-23.8	8.3					this work	
Abri du Pape	BP-16	Pike	vertebra		40.3	14.3	3.3	-22.5	10.9					this work	
Abri du Pape	BP-20	Cyprinidae	vertebra		34.8	12.5	3.2	-21.2	8.0	0.59	4.0	156	48	this work	this work
Abri du Pape	BP-21	Cyprinidae	epihyal		30.5	11.1	3.2	-22.3	9.5					this work	
Trou du Sureau	Vert-72/74	Burbot	vertebra		26.2	9.5	3.2	-23.2	6.6					3	
Trou du Frontal	Vert-91/-94	Burbot	vertebra		33.3	12.4	3.1	-21.8	10.5					3	
Bois Laiterie	BP 3/11	Burbot	bones		32.5	12.1	3.1	-24.1	9.8					3	
Bois Laiterie	BP 8	Burbot	vertebra		14.8	5.6	3.1	-23.8	7.7					3	
Trou de Chaleux	Vert-84/85	Brown trout	vertebra		37.0	12.2	3.5	-18.7	8.7					3	
Bois Laiterie	BP-5	Brown trout	vertebra		36.9	13.1	3.3	-20.5	9.2	0.47	-4.6	209	64	3	this work
Bois Laiterie	BP6/7/15	Brown trout	vertebra		38.6	13.6	3.3	-19.8	9.4	0.64	-0.5	161	49	3	this work
Bois Laiterie	BP-13	Brown trout	vertebra		35.6	12.8	3.2	-20.5	8.9	0.56	-0.5	169	52	3	this work
Bois Laiterie	BP-14	Brown trout	vertebra		27.0	9.9	3.2	-19.8	8.7					3	
Trou du Frontal	Vert-110	Pike	bone piece		39.5	13.5	3.4	-20.5	10.6					3	
Trou du Frontal	Vert-111	Pike	bone pieces		40.3	14.2	3.3	-23.7	8.1					3	

Table 2 (continued)

Trou de Chaleux	Vert-90	Pike	vertebra		31.1	11.1	3.3	-21.7	10.3					3	
Trou de Chaleux	Vert-82	Nase	bones		40.5	15.4	3.1	-20.1	8.7	0.49	-0.6	222	72	3	this work
Trou du Frontal	Vert-112	Cyprinidae	bone piece		43.3	15.8	3.2	-21.9	11.7					3	
Trou du Frontal	Vert-113	Cyprinidae	vertebra		42.1	15.2	3.2	-21.7	10.6					3	
Trou du Frontal	Vert-114	Cyprinidae	vertebra		41.5	14.2	3.4	-21.8	10.5					3	
							SIAR Average	*-21.6*	*9.4*		*-0.4*				
							SD	*1.5*	*1.3*		*3.0*				
Noyen/Seine	NO4600	Pond turtle	shell	84 XVI G141-8	37.6	13.7	3.2	-25.7	7.6					1	
Noyen/Seine	NO4700	Pond turtle	shell	84 XVI G145-8	39.9	14.4	3.2	-25.3	7.7					1	
Noyen/Seine	NO6100	Pond turtle	L hypoplastron	84 XVI Z151-23	39.7	14.3	3.2	-26.7	7.8					1	
Noyen/Seine	NO6200	Pond turtle	L hypoplastron	84 XVI D141-48	41.4	15.1	3.2	-25.0	7.3					1	
Noyen/Seine	NO6300	Pond turtle	L hypoplastron	84 XVI D146-8	40.5	14.7	3.2	-25.7	8.2	0.24	-19.0	453	141	1	1, this work
Noyen/Seine	NO6400	Pond turtle	R hypoplastron	84 XVI E147	40.1	14.4	3.2	-25.9	8.0					1	
							SIAR Average	*-25.7*	*7.8*						
							SD	*0.6*	*0.3*						
Noyen/Seine	NO3200	Otter	femur	84 XV Z151-49	42.6	15.2	3.3	-19.3	12.3					1	
Noyen/Seine	NO6500	Otter	scapula	84 XVI D142-12	41.2	15.1	3.2	-24.2	10.7	0.21	-14.5	513	161	1	1, this work
Noyen/Seine	NO6600	Otter	fibula	84 XV B147	41.9	15.4	3.2	-23.9	11.1	0.16	-12.7	680	214	1	1, this work
							SIAR Average				*-15.4*				
							SD				*3.2*				

1: Bocherens et al. 2011; 2: Naito et al. 2013; 3: Drucker et al. 2016

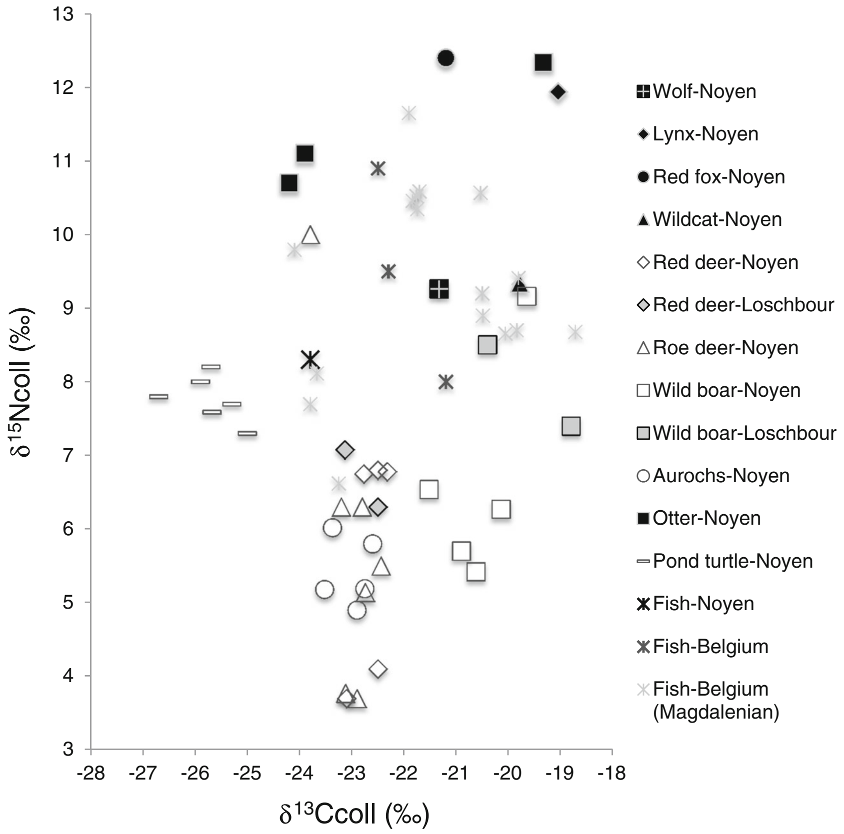


Fig. 2 δ^{13}C and δ^{15}N values of bone collagen of the red deer ($n = 7$), roe deer ($n = 7$), wild boar ($n = 7$), aurochs ($n = 5$), fish ($n = 20$), pond turtle ($n = 6$), wolf ($n = 1$), red fox ($n = 1$), lynx ($n = 1$), wild cat ($n = 1$) and otter ($n = 3$)

conclusion, the contrasted isotopic signatures of the terrestrial carnivores reflect the isotopic diversity of the accessible preys.

The Mesolithic fish from Noyen-sur-Seine and the Abri du Pape clustered between −23.7 and −21.2 ‰ for the δ^{13}C values and between 8.0 and 10.9‰ for the δ^{15}N values (Table 2, Fig. 2). These values fall within the wide range found for fish of the Belgian Magdalenian (−24.1 to −18.7 ‰ in δ^{13}C, 6.6 to 11.7 ‰ in δ^{15}N; Drucker et al. 2016). While the δ^{13}C values of the fish largely overlapped those of the terrestrial fauna, the δ^{15}N values were generally higher as it could be expected based on studies on past and modern ecosystems (e.g. Dufour et al. 1999; Drucker et al. 2016). The pond turtle at Noyen-sur-Seine represents another potential source of aquatic food. Although its δ^{15}N values were comparable to the low values found in freshwater fish (7.3 to 8.2 ‰), its δ^{13}C values were drastically lower, ranging from −26.7 to −25.0 ‰. Recent studies have shown that the pond turtle is neither strictly carnivorous nor a pure aquatic animal (Ottonello et al. 2005) and that it favours a woodland environment for its terrestrial movements during nesting (Ficetola et al. 2014).

The otter specimens show a high variability in their δ^{13}C and to a smaller extent in their δ^{15}N values (Table 2, Fig. 2) than was previously observed in Late Mesolithic contexts from the Netherlands (Smits and van der Plicht 2009). This is probably

Table 3 Results of stable isotope analyses of collagen (δ^{13}C, δ^{15}N, δ^{34}S) from human remains from French and Luxembourgian sites. The carbon, nitrogen and sulphur composition of the collagen is given through elemental composition (C, N, S) and atomic ratio (C:N, C:S, N:S$_c$)

Site	Lab no.	Sample	Reference	C (%)	N (%)	C:N	δ^{13}C (‰)	δ^{15}N (‰)	S (%)	δ^{34}S (‰)	C:S (%)	N:S (%)	^{13}C/^{15}N Source	^{34}S Source
Heffingen	LSB-1	Femur L	LSB1, 20.5.1943	38.5	13.7	3.3	−20.3	11.9	0.14	4.6	735	224	This work	This work
Maisons-Alfort	ZMA-1	Tibia R	ALFIII St7	35.4	12.9	3.2	−21.1	12.6	0.15	6.6	632	197	This work	This work
Cuiry-lès-Chaudardes	CRC-1	Tibia L		40.9	14.6	3.3	−20.1	11.2	0.17	4.9	634	194	This work	This work
Berry-au-Bac	BRB-1	Fibula R	BVT89 353	39.2	14.4	3.2	−20.3	11.6	0.13	2.5	785	242	This work	This work
Noyen-sur-Seine	NO7200	Femur R	85 XVI B212-20	42.8	15.4	3.2	−21.5	12.1	0.23	−8.3	496	153	2	This work
Noyen-sur-Seine	NO6800	Humerus	84 XVI C145-28	42.5	14.6	3.4	−20.1	11.2	0.26	−9.9	436	128	This work	This work
Noyen-sur-Seine	NO7300	Skull	83 XVI E142-8	40.7	14.5	3.3	−21.3	12.3	0.23	−5.0	464	142	2	This work

1: Bocherens et al. 2011; 2: Naito et al. 2013

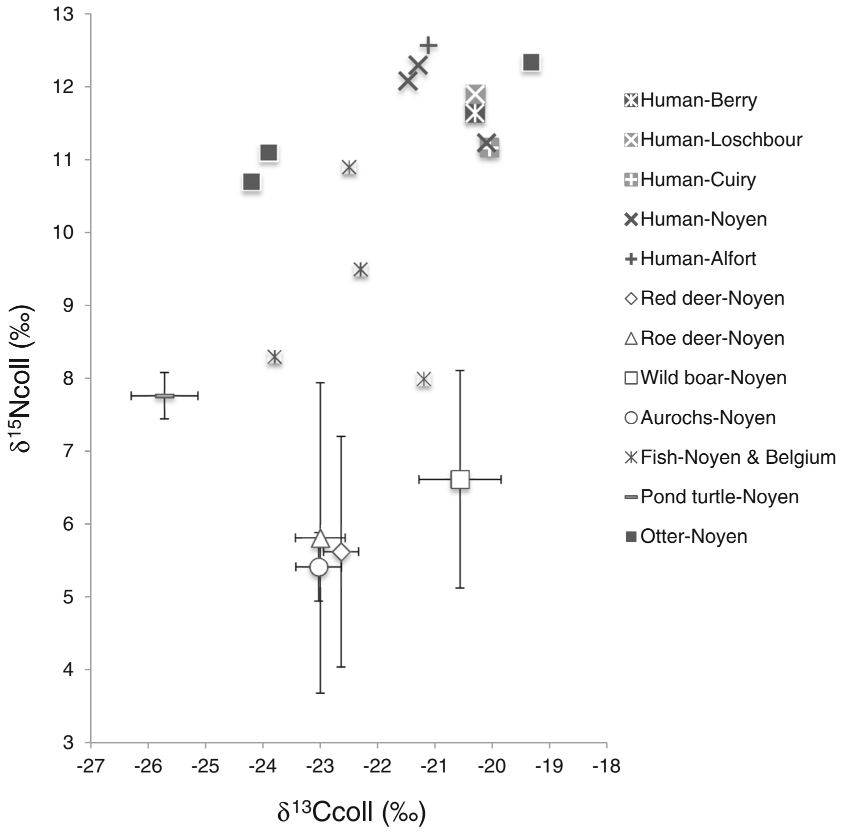


Fig. 3 δ^{13}C and δ^{15}N values of bone collagen of the human individuals compared with the terrestrial herbivores represented in mean and standard deviations (red deer, roe deer, wild boar, aurochs), fish and water-dependent animals (turtle, otter), carnivores (wolf, red fox, lynx, wild cat, otter)

due to a difference in proportion of freshwater and terrestrial resources in their diet. Otters feed not only mainly on fish but consume also amphibians, reptiles (including pond turtles), birds, mammals, and aquatic invertebrates (e.g. Clavero et al. 2003; Lanszki et al. 2006). The species appears thus as a flexible predator that exploited both the terrestrial and freshwater ecosystems as has also been observed in modern ecological studies. Analysis of otter droppings conducted in riverine ecosystems show that fish contributes between ca. 55 and 80 % of the diet (e.g. Lanszki and Molnár 2003; Reid et al. 2013).

δ^{13}C and δ^{15}N values of the human individuals

The human individuals showed δ^{13}C and δ^{15}N values ranging from −21.5 to −20.1 and 11.2 to 12.6 ‰, respectively (Table 3, Fig. 3). The δ^{13}C values collected in two clusters: one around −21.4 ‰ including the individual of Maisons-Alfort, the Noyen-sur-Seine juvenile of layer 9 and the adult of layer 9sup, and another group around −20.2 ‰ including Berry-au-Bac, Cuiry-lès-Chaudardes, Loschbour 1 and the adult of layer 9 of Noyen-sur-Seine. The relatively low ^{13}C cluster showed higher δ^{15}N values (12.1 to 12.6 ‰) than the second one (11.2 to 11.9 ‰), the within-group variability of the δ^{15}N values being less than 0.8 ‰. The two groups can be interpreted as reflecting two different dietary profiles, the lower ^{13}C group having access to aquatic resources since its δ^{15}N values is 6 to 7 ‰ higher in average than the terrestrial animal species. The second cluster possibly incorporated more terrestrial resources leading to lower δ^{15}N values. The large difference in ^{13}C abundances (>3‰) between the human individuals and the pond turtle indicates that this specific animal species was probably not a significant source of food in all of the cases. It is tempting to see a high diet similarity between the individuals of each cluster due to the homogeneity in their isotopic signature. However, the high variability in ^{13}C and ^{15}N abundances displayed by each of the main food groups, namely terrestrial and aquatic, could lead to similar isotopic results despite different diet compositions.

δ^{34}S values of preys and the animal predators

The ^{34}S can provide higher resolution of the relative contribution of terrestrial versus freshwater food resources (e.g. Bocherens et al. 2011). However, the number of samples is then reduced since such a measurement requires the combustion of additional collagen material, of which there are not always remainder due to combustion for prior analyses, as well as an excellent preservation of the amino acid containing the element sulphur, namely methionine (Nielsen et al. 1991).

The δ^{34}S values of the terrestrial ungulates plotted between −1.0 and 6.8 ‰, without clear correlation with species (Table 2, Fig. 4). The range of values exhibited by the large

Fig. 4 δ^{34}S and δ^{15}N values of bone collagen of the red deer (*n* = 5), roe deer (*n* = 3), wild boar (*n* = 3), aurochs (*n* = 2), fish (*n* = 5), pond turtle (*n* = 1), wolf (*n* = 1), red fox (*n* = 1), lynx (*n* = 1), wild cat (*n* = 1) and otter (*n* = 2)

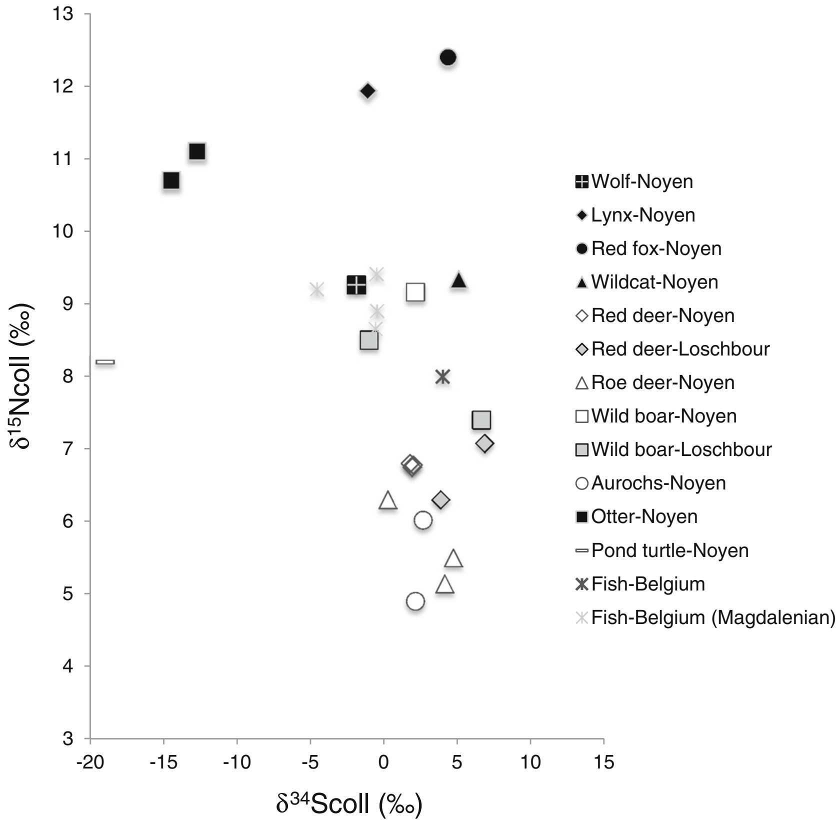
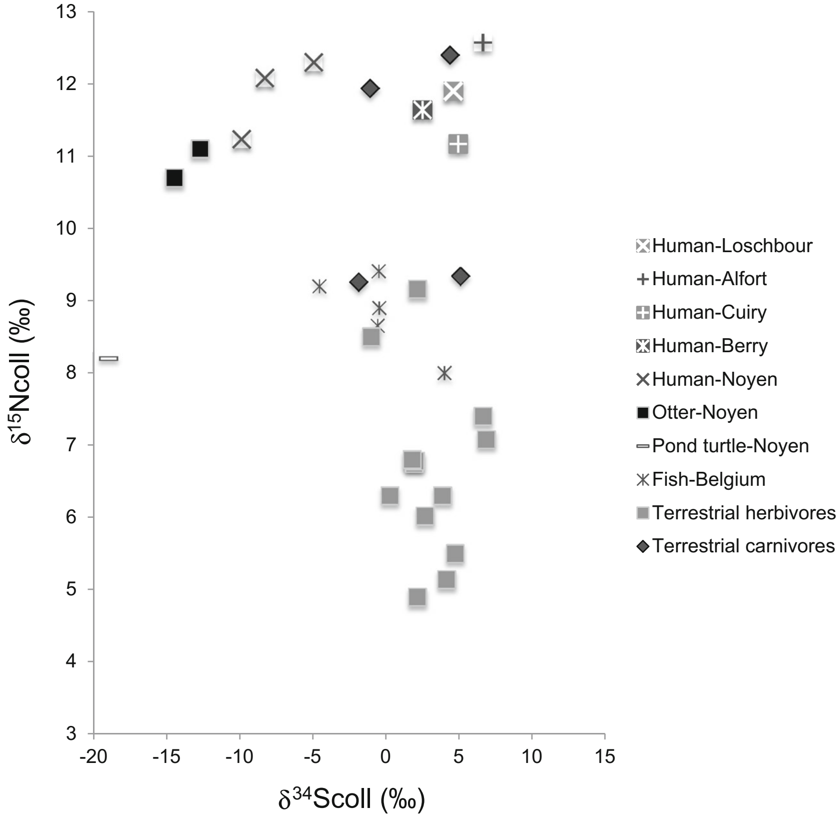


Fig. 5 δ^{34}S and δ^{15}N values of bone collagen of the human individuals (*n* = 7) compared with the terrestrial herbivores including red deer (*n* = 5), roe deer (*n* = 3), wild boar (*n* = 3), aurochs (*n* = 2) to the terrestrial carnivores including wolf (*n* = 1), red fox (*n* = 1), lynx (*n* = 1), wild cat (*n* = 1), and the aquatic-dependent animals including Belgian fish (*n* = 5) and pond turtle (*n* = 1) and otter (*n* = 2) from Noyen-sur-Seine



ungulates was comparable between the site of Loschbour and Noyen-sur-Seine, which suggests these values are representative of the terrestrial resources for the considered geographical region. This is confirmed by the results obtained on the carnivores, averaging the contribution of prey species, with δ^{34}S values clustering in a similar range as the ungulates of both Noyen-sur-Seine and Loschbour (−1.9 to 9.3 ‰).

In contrast, the species of the aquatic ecosystem displayed quite different δ^{34}S values according to their location. At Noyen-sur-Seine, the pond turtle and the two water-dependent otters provide values ranging from −19.0 to −12.7 ‰, while the Belgian fish clustered between −4.6 and 4.0 ‰ (Table 2, Fig. 4). The δ^{34}S values of the latter were thus overlapping with the terrestrial values provided by the sites of Loschbour 1 and Noyen-sur-Seine. Interestingly, the water-dependent animals of Noyen-sur-Seine were significantly distinct from the terrestrial species of the same site in their lower abundances in ^{34}S. The relatively low δ^{34}S of the otters and pond turtle from Noyen-sur-Seine could reflect the anaeorobic bottom water conditions (reduced sulphur) of the local aquatic ecosystem where they mainly fed, while the higher δ^{34}S values of the Belgian fish may correspond to more oxygenated water conditions (sulphate) (see review in Nehlich 2015). Despite a possible terrestrial contribution to their diet, turtle and otter depend significantly on the riverine environment for food and habitat, and the riparian ecosystem they reflect is very distinct in ^{34}S from the terrestrial forested ecosystem represented by the large hunted ungulates. The Belgian fish shows relatively high ^{34}S abundances, which makes them difficult to distinguish from the terrestrial resources. Two distinct groups of aquatic food are identifiable here and should thus be considered separately as far as the ^{34}S tracking is concerned.

δ^{34}S values of preys and the human individuals

The human δ^{34}S values ranged between −9.9 and 6.6 ‰ (Table 3, Fig. 5). All the humans from Noyen-sur-Seine linked to negative values, ranging from −9.9 to −5.0 ‰, while the other individuals displayed a different range varying from 2.5 to 6.6 ‰. The latter aligned with the terrestrial animal range and partly overlapped with the range of the Belgian fish. The relatively lower δ^{34}S values of the humans from Noyen-sur-Seine placed them in an intermediate position between the terrestrial animals and Belgian fish on the one hand and the riparian animals of the same site on the other. In this last case, the consumption of the local aquatic resources is clearly reflected in the ^{34}S abundances of the human individuals. Outside of Noyen-sur-Seine, the interpretation of the human δ^{34}S values may be hindered by potential insufficient discrimination between the local aquatic and terrestrial resources.

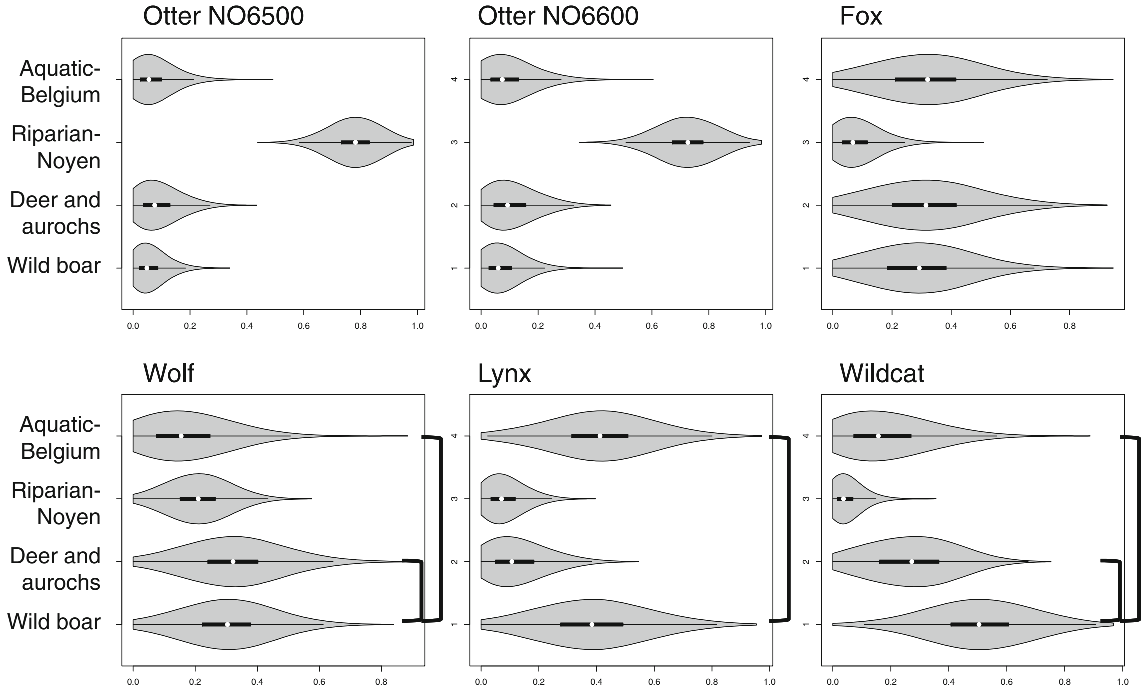


Fig. 6 Proportional contribution of freshwater fish, riparian resources and terrestrial animals consumed by animal predators as estimated by SIAR using the following assumptions: terrestrial foods were estimated from wild boar and other large herbivores separately, freshwater foods were estimated from Magdalenian and Mesolithic Belgian fish, riparian resources were estimated from pond turtle and otter of Noyen-sur-Seine. *Black boxes* and *whiskers* show the median with first and third quartiles and ranges with 1.5 times length of the interquartile range above the third quartile or below the first quartile, respectively. The *shaded area* indicates the Kernel density plot of the probability density of prey proportions. The *brackets* link the resources with a significant negative correlation in their posterior distribution

Proportions of consumed prey calculated using SIAR

For each human individual, the possible contribution of each food source was evaluated using SIAR and considered the combined δ^{13}C, δ^{15}N and δ^{34}S values. The food categories were separated between the wild boar, the ruminant ungulates (red deer, roe deer and aurochs), the aquatic-dependent species of the site of Noyen-sur-Seine and the fish from Belgium, since these four groups differ from each other based on at least one of the isotopic systems. The averaged isotopic values of the wild boars and of the ruminant herbivores were calculated from all the available data from Noyen-sur-Seine and Loschbour. The wild boar canine root was excluded from the calculation for δ^{13}C and δ^{15}N values since they may have been affected by a nursing effect, but it was included in the averaged δ^{34}S value due to the lack of trophic effect (e.g. Tanz and Schmidt 2010; Nehlich et al. 2011). Pond turtles were used to calculate the mean δ^{13}C and δ^{15}N values of the riparian resources of the Seine River, and values of the water-dependent otter (NO6500 and NO6600) were also included to estimate the averaged δ^{34}S values, again because of the lack of significant fractionation effect.

The application of the SIAR model allows for the testing of possible combinations of food groups providing dietary protein to animal and human predators over several years. Some difficulties can be foreseen in the overlapping range of δ^{13}C and δ^{34}S values between the Belgian fish and the terrestrial ungulates. It results in a lack of good discrimination between some food groups, namely wild boar and Belgian fish, testified by a significant negative correlation in their posterior distribution for all the tested predators, except for the fox and the otters (Fig. 6). Such a negative correlation was also found between the ruminant herbivores and the wild boar when testing the diet of the wolf and the wild cat. Among the animal predators, the water-dependent otters with relatively low δ^{13}C values displayed a significant consumption of

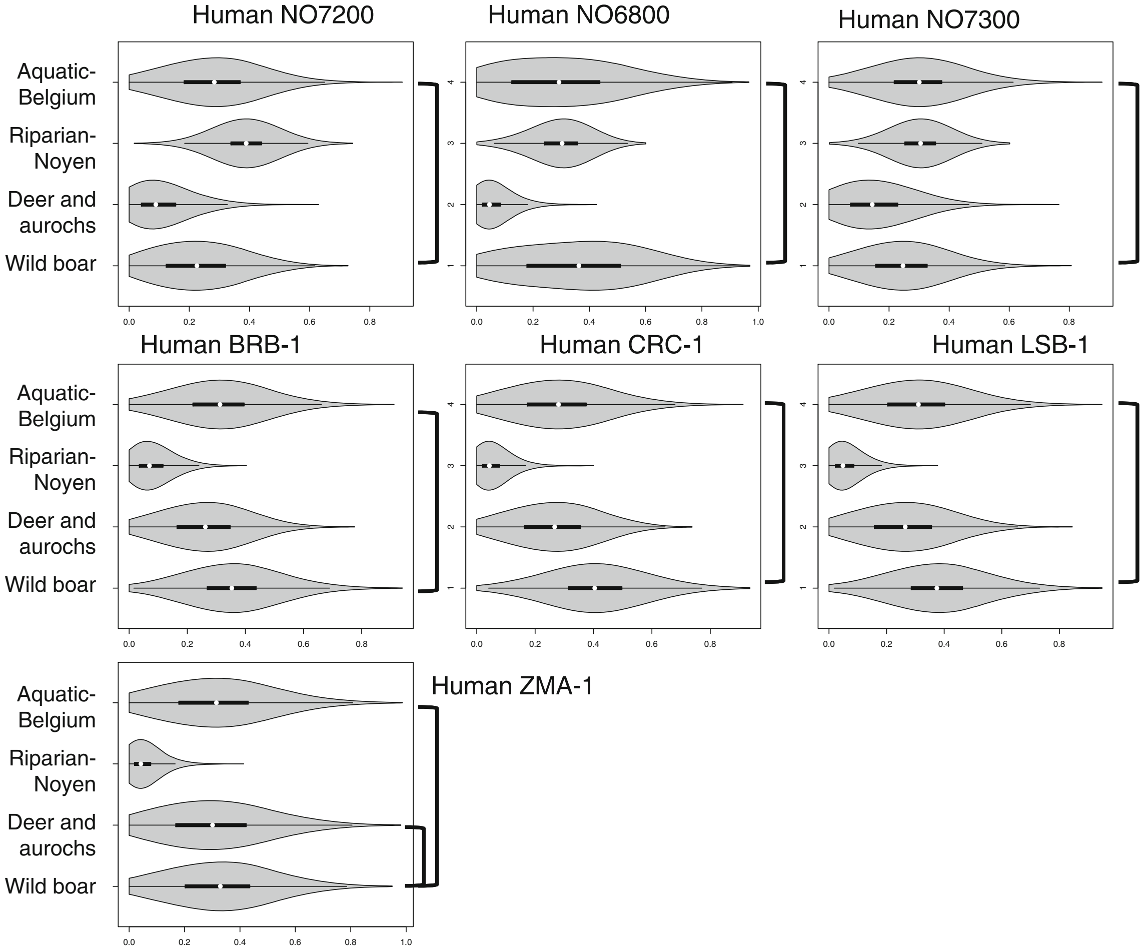


Fig. 7 Proportional contribution of freshwater fish, riparian resources and terrestrial animals consumed by humans as estimated by SIAR using the following assumptions: terrestrial foods were estimated from wild boar and other large herbivores separately, freshwater foods were estimated from Magdalenian and Mesolithic Belgian fish, riparian resources were estimated from pond turtle and otter of Noyen-sur-Seine. *Black boxes* and *whiskers* show the median with first and third quartiles and ranges with 1.5 times length of the interquartile range above the third quartile or below the first quartile, respectively. The *shaded area* indicates the Kernel density plot of the probability density of prey proportions. The *brackets* link the resources with a significant negative correlation in their posterior distribution

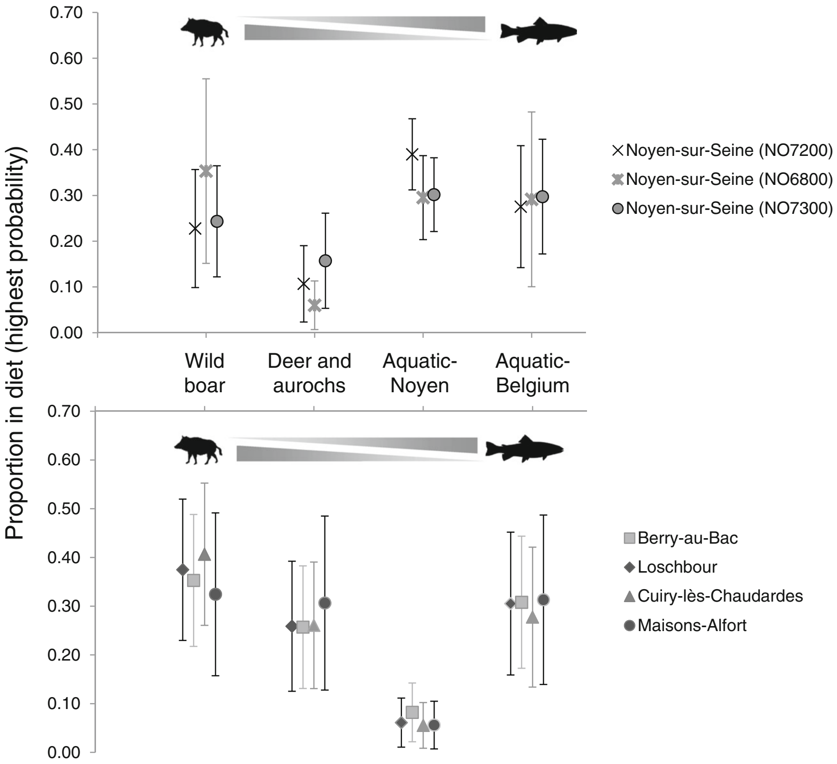


Fig. 8 Percentage of prey contribution with the highest probability for the different human individuals. In every case, the wild boar and the Belgian fish are negatively correlated, meaning that a higher proportion of one involves a lower proportion of the other

local aquatic resources of Noyen-sur-Seine with ca. 80 % of aquatic-derived protein as the highest likely scenario, while the contribution of the Belgian fish type of resources was very limited in probability. It is consistent with the context-dependent isotopic signature of the freshwater resources and fits the expected maximum contribution of aquatic food observed in ecological studies (e.g. Lanszki and Molnár 2003; Reid et al. 2013). Testing the respective probable contributions of the food resources to the diet of the fox did not provide clear results, especially because none of them were expected to be natural preys of this small predator that is more reliant on small rodents and lagomorphs, unless it has access to the carcasses of larger preys (e.g. Jędrzejewski et al. 1989, 2002; Delibes-Mateos et al. 2007; Helldin and Danielsson 2007). Small preys can be expected to yield lower δ^{15}N values than large ungulates based on the results of previous studies (e.g. Bocherens et al. 2011), and their consumption can thus explain the relatively low δ^{15}N values of the wild cat, which is even more specialized on rodents than the red fox (e.g. Carvalho and Gomez 2001). Interestingly, the wolf is the other animal predator with a low δ^{15}N value, which may also reflect the consumption of ungulates with depleted ^{15}N abundances that can be found among the deer specimens. In the temperate Białowieża forest in Poland, red deer is indeed the most hunted prey of the wolf (e.g. Jędrzejewski et al. 2002). In the same ecosystem, the lynx is specialized on medium-sized preys, such as roe deer (e.g. Okarma et al. 1997). The result of the SIAR simulation for the lynx of Noyen-sur-Seine indicated a diet more oriented towards wild boar, perhaps as a consequence of the high availability of this prey and the inter-specific competition with wolf on deer (e.g. Jędrzejewski et al. 1989). In all cases, the contribution of the local riparian resources to the diet of canids and cats of Noyen-sur-Seine was negligible.

The human individuals of Noyen-sur-Seine were the only ones displaying an unambiguous consumption of local aquatic resources. The local riparian resources were potentially contributing to ca. 30 to 40 % of their dietary protein based on their combined δ^{13}C, δ^{15}N and δ^{34}S values (Figs. 7 and 8). These proportions are in accordance with other estimations based on the amino acid ^{15}N composition (Naito et al. 2013). This implies a significant contribution over a large time span that could fit the hypothesis of Marinval-Vigne et al. (1989) of possible food preservation for a delayed consumption along with fishing activities conducted mainly in summer. On another hand, the contribution of the aquatic resources as based on the Belgian fish appears possible, but with a strong negative correlation with the contribution of wild boar. It means that a higher proportion of one involves a lower proportion of the other. The δ^{34}S values supports the dominant input of the local riparian resources as aquatic-based food, leading to the low probability of the Belgian fish-like resource contribution and then a significant consumption of the wild boar as terrestrial resource.

When aquatic resource consumption is attested, its possible impact on the conventional age has to be considered since the freshwater ecosystem can be a reservoir of older ^{14}C that differs from the ^{14}C of the contemporary atmosphere (e.g. Lanting and van der Plicht 1998). The ^{14}C depletion in freshwater-dissolved inorganic carbon is caused by a restricted exchange in CO_2 between water and atmosphere and the input of ^{14}C-depleted sources such as fossil carbonates (Geyh et al. 1998; Lanting and van der Plicht 1998), fossil organic carbon (Boaretto et al. 1998) and ancient glacial melted water (Hall and Henderson 2001). As a result, the offset introduced by the freshwater reservoir effect (FRE) is highly variable and depends on the local causes of the reservoir effect, but does not exceed several hundred years (Keaveney and Reimer 2012; but see exception in Iceland in Ascough et al. 2007). At Noyen-sur-Seine, a difference of 260 ± 63 years was found between the conventional date of one of the aquatic influenced otters (8070 ± 45, NO6500) and a red deer of the same layer (7810 ± 45, NO5000) (Table 1). If the diet accounts for this offset, we can speculate that the consumption of freshwater resources shifted the radiocarbon date of the human remains of no more than ca. 130 years. Indeed, the proportion of the freshwater resources in the human diet was about half of the one estimated in the otter diet. This can thus not explain differences in conventional age as the one observed between the human from layer 9 and the one from layer 9sup at Noyen-sur-Seine.

The consumption of freshwater resources appeared difficult to decipher for the individuals of Berry-au-Bac, Cuiry-lès-Chaudardes, Maison-Alfort and Loschbour 1 using the SIAR model (Fig. 7 and 8). The dietary use of the riparian environment, such as along the Seine bank at Noyen-sur-Seine, can be excluded. However, the non-discriminant results between the Belgian fish and the wild boar as protein providers are a source of uncertainty. In the case of Loschbour 1, the hypothesis of a high consumption of wild boar would fit the archaeological evidences, albeit resulting from old excavations (Cordy 1982) where fish remains may not have been adequately recovered. On the other hand, a necklace made of pike vertebrae found in association with the burial of Cuiry-lès-Chaudardes (Ilett 1998) illustrates the access to aquatic resources, but is certainly not sufficient to provide a clear evidence for fish consumption. If a limited intake of freshwater food could be demonstrated, it would in turn highlight the importance of wild boar in the subsistence pattern of the Loschbour, Cuiry-lès-Chaudardes and Berry-au-Bac individuals, perhaps to a lesser extent for the individual of Maison-Alfort. In this last case, the isotopic discrimination between the different ungulate groups was low, not allowing the determination of the main terrestrial contributor to the human diet. If the dependence on aquatic resources could be established, it would demonstrate that the aquatic environment exploited by humans out of Noyen-sur-Seine was isotopically different from the anoxic riparian context found along the Seine river at that time.

Conclusions

The examined human individuals of the Late Mesolithic from northern France and Luxembourg are all characterized by relatively high $\delta^{15}N$ values of their collagen. Due to the complexity of the $\delta^{13}C$ and $\delta^{15}N$ pattern revealed by the terrestrial as well as the freshwater ecosystem, the interpretation of such values appears difficult at this point. The analysis of the $\delta^{34}S$ values in the same collagen allows for a clear distinction between the local riparian and terrestrial resources at Noyen-sur-Seine, and a SIAR model points to a most likely aquatic contribution around 30 to 40 % of the dietary protein. In contrast, the aquatic $\delta^{34}S$ values determined on fish specimens of the Mesolithic and older periods of the Magdalenian in Belgium point to a possible isotopic overlap between aquatic and terrestrial ecosystems. As a result, the SIAR model fails to discriminate between this potential aquatic resource and the wild boar contribution for the other studied human individuals. However, the delivered probability reconstruction underlines a difference in protein sources compared with the individuals of Noyen-sur-Seine, despite very comparable results in $\delta^{13}C$ and $\delta^{15}N$ values that could have been thought to reflect very similar subsistence strategies. This difference could be linked either to the type of aquatic ecosystem exploited for food or to the higher consumption of terrestrial resources, mainly based on wild boar. In contrast, the diet of the human of Maisons-Alfort may have comprised more comparable proportions of the different large ungulates preys.

The analysis of more collagen from local animals could help to constrain the ambiguity introduced by the overlapping $\delta^{34}S$ values between aquatic and terrestrial resources. However, the Late Mesolithic burials from Northern France and Luxembourg are generally characterized by a lack of association with animal remains and settlement structures with the notable exception of the extra-funerary remains of the site of Noyen-sur-Seine. The potential of the ^{34}S in bulk collagen as a tracer of aquatic consumption in continental environments should not be neglected, though, but needs a thorough case-by-case preliminary evaluation.

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