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ASSESSING THE RADIOCARBON FRESHWATER RESERVOIR EFFECT FOR A NORTHWEST-EUROPEAN RIVER SYSTEM (THE SCHELDE BASIN, BELGIUM)

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ABSTRACT. The freshwater reservoir effect (FRE) for the Schelde basin (Belgium) is assessed for the Roman, Medieval and early Post-medieval periods by comparing historical and archaeological dates from individual archaeological deposits with radiocarbon dates on the remains of freshwater fish and terrestrial mammals from those same deposits. This is the first time such an assessment has been attempted for the Schelde basin. The FRE offsets prove to be substantial for the historical periods considered. They also differ markedly between fish species and between size classes of a single species. These observations have implications for the evaluation of radiocarbon dates obtained on archaeological remains of humans (and animals) with a substantial amount of freshwater fish into their diet. The data obtained in this study suggest that it will not be easy to correct for any FRE.

KEYWORDS: radiocarbon dating, freshwater reservoir effect, freshwater fish, Belgium, historical periods.

INTRODUCTION

Any interpretations of radiocarbon dates obtained on the remains of organisms from aquatic biotopes need to take into account that a restricted exchange in CO_2 between water and the atmosphere maintains a depletion of ^{14}C in water bodies compared to the atmosphere (Lanting and van der Plicht 1998), a phenomenon known as the reservoir effect. This effect operates in both marine and freshwater environments. The marine reservoir effect (MRE) is roughly similar throughout the world's surface oceans, amounting to about 400 years (Stuiver and Braziunas 1993), while the local variations that are known to exist are mostly moderate (see http://calib.org/marine/). The freshwater reservoir effect (FRE) is more complicated. In freshwater bodies, the depletion of ^{14}C is the result of groundwater input into an aquatic biotope. This groundwater can have a significant residence time and can have undergone an input of ^{14}C-depleted sources (Drucker et al. 2016), such as fossil inorganic carbonates (Geyh et al. 1998) or fossil organic carbon (Boaretto et al. 1998). Additionally, some rivers are characterized by a high FRE through the input of ancient glacial meltwater (Hall and Henderson 2001). This input of carbon from many different organic and inorganic sources, which is then dissolved into the water, is highly variable, making it nearly impossible in hydrogeological studies to radiocarbon date the age of the groundwater, in the sense of establishing the amount of time that has elapsed between the precipitation of water in a recharge area and its arrival in a discharge area (Fontes 1992; Mook 1992; International Atomic Energy Agency 2013).

Data on the FRE are lacking for many river systems and lakes, and where data are available, they show that values can differ markedly between water bodies (see Fernandes et al. 2016, for Germany) or even within the same freshwater aquatic system; that the FRE differs between species in an aquatic system (Svyatko et al. 2017), possibly as a function of the organism's position in the foodweb (see Fernandes et al. 2013; Philippsen 2013); and, finally, that due to changes in climate, hydrogeography, etc., at a given location, the FRE can—and will—fluctuate through time (e.g. Zhou et al. 2015). It has been stated that the FRE generally does not exceed several hundred years (Keaveney and Reimer 2012), but exceptions are known, e.g. from Iceland (Ascough et al. 2007; see also further).

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Reservoir effects have a dramatic impact on the interpretation of radiocarbon dates obtained on aquatic organisms, including when these dates are used to date cultural deposits (e.g., Culleton 2006; Motuzaite-Matuzeviciute et al. 2015). Reservoir effects also have a marked impact on radiocarbon dates obtained on the archaeological remains of humans (or other organisms) having consumed aquatic organisms as part of their diet. In the case of human remains, interpretations are further complicated because any interpretation of the radiocarbon dates has to take into account the relative contributions of marine and freshwater organisms to the diet, as each are characterized by their own reservoir ages.

In the case of the Schelde basin (Belgium, northwestern Europe), this archaeological problem still prevails, especially because the FRE remained unstudied for the river system. The archaeological record of this part of the world is rich and varied, and is characterized by a long prehistoric occupation, four centuries of Roman domination, and early (and dense) urbanization in Medieval and early Post-medieval times. Archaeozoological and historical data indicate that the consumption of freshwater and marine fish was important and that it fluctuated significantly through time and among groups within society (Van Neer and Ervynck 2004; 2016), making the absolute dating of human remains especially challenging.

This study aims to assess the FRE within the river Schelde and its affluents, and to document the inter- and intra-species variability for a number of fish taxa, by evaluating the radiocarbon dates obtained on archaeological freshwater fish remains. The study involves (1) radiocarbon analysis of freshwater fish and terrestrial mammal bones from a single archaeological context of which the historical date is known, (2) radiocarbon analysis of freshwater fish and terrestrial mammal bones from a context lacking a historical date but having a cultural-archaeological date, again allowing for the comparison of radiocarbon dates between terrestrial and freshwater organisms from a single deposit, (3) radiocarbon analysis of freshwater fish bones from two contexts having cultural-archaeological dates but lacking radiocarbon data from terrestrial organisms (due to options taken during the analysis of the former excavations), and (4) N and C stable isotope analysis for most of the samples that have been radiocarbon dated, to interpret the ecology and diet of the specimens sampled. This stable isotope dataset is enlarged with the results of a previous study on archaeological fish remains from the Schelde basin (Fuller et al. 2012).

In what follows, first the study area will be introduced, after which the analysis of the archaeological animal remains, the radiocarbon and stable isotope results, and possible interpretations will be presented.

THE SCHELDE RIVER BASIN

The general hydrogeography of the Schelde basin (Figure 1) has been described in different publications (e.g., Bayens et al. 1998; Breine et al. 2007; 2010; Deforce 2014; Meire et al. 2005; 2015; Van Strydonck and De Mulder 2000). The basin covers an area of about 22,000 km² and drains water from most of Flanders (northern Belgium). While the source of the river Schelde is located in northern France (near Saint-Quentin), most of its basin is located in Flanders. The Schelde basin is a typical slow-moving lowland river system, with the source of the main river (Schelde) located about 100 meters above sea level. This main river has a length of 355 km. The basin sheds its waters into the North Sea and is subject to tidal influence, which nowadays is still observable upstream as far as Gent, where the incoming salt water is blocked by a sluice. Before the construction of sluices, tidal influence extended farther upstream. At any point within the part of the basin under tidal influence, salinity fluctuates seasonally (due to differences in precipitation), but in general, it can be stated that the sites from the study area

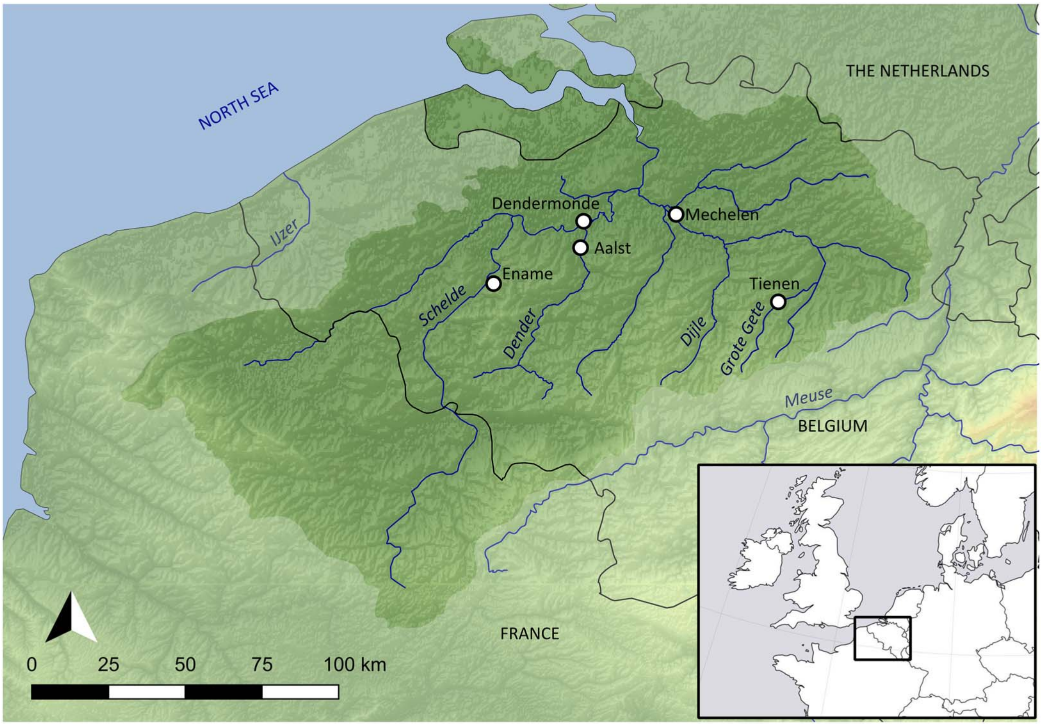

Figure 1 The Schelde basin (Belgium), with the location of the sites mentioned in the text: Aalst, Dendermonde, Ename, Mechelen, Tienen.

(see below) are located in the oligohaline (salinity range 0.5–5‰) and freshwater (salinity <0.5‰) zones of the river.

The direct runoff of surface (i.e. rain) water does not sufficiently explain the volume of discharge of the river system. It is therefore thought that the Schelde and its affluents realize their flow rate mainly through the input of groundwater derived from precipitation. Because it can take a considerable amount of time for groundwater to travel from the recharge areas within the basin to the discharge areas, the presence of so-called old water can be expected in the river. In addition, the groundwater discharging into the Schelde basin will have taken up organic and inorganic carbon from different sources (each with their own radiocarbon date), further increasing the likelihood of a reservoir effect in the river system. Unfortunately, precise data about this “contamination” with old carbon are not available.

In ecological terms, the freshwater fish fauna investigated here mainly belongs to the zone defined by Huet (1954) as the “bream zone”. This zone harbors the fish fauna from slow-moving or still waters (stream velocity 0–10 cm/s), in a broad river bed with a sandy or silty bottom, and water temperatures sometimes exceeding 20°C. Typical species for this zone are bream (*Abramis brama*), roach (*Rutilus rutilus*), carp (*Cyprinus carpio* f. domestica), rudd (*Scardinius erythrophthalmus*), tench (*Tinca tinca*), pike (*Esox lucius*), perch (*Perca fluviatilis*) and eel (*Anguilla anguilla*).

Over the past two millennia, the Schelde river and its basin have experienced significant alterations on Flemish territory, mainly linked to changes in the geography of the Schelde estuary (i.e., the shortening of the distance to the sea) and the construction of dikes (affecting the breadth of the river valley, the depth of the river, its stream velocity and the impact of the tides). The Schelde of Roman times was thus a different river system than that of Medieval and Post-medieval times (Van Strydonck and De Mulder 2000).

MATERIAL AND METHODS

Sites

For this study, radiocarbon dates and stable isotope measurements were obtained from four archaeological sites in the Schelde basin (Figure 1), ranging from the Roman period (1st to 4th century AD) to the early Post-medieval period (16th century AD). A number of stable isotope data previously obtained from the study area (Fuller et al. 2012) has been included in the analysis and interpretations. Because only those species that also appear in the current study have been taken into account, use of the Fuller et al. (2012) data has resulted in the inclusion of only a limited number of additional sites (see below).

Both freshwater fish and domestic mammal bone samples have been analyzed from a cesspit excavated at the Hopmarkt site in the town of Aalst. This deposit has been linked to historical information about the activities of a crossbow maker between 1489 and 1498 AD on the basis of specific archaeological finds (De Groote et al. in press). Aalst is located on the river Dender, an affluent of the Schelde.

Both freshwater fish and domestic mammal bone samples have been analyzed from a ritual deposit from the Roman site known as Grijpenveld, now in the town of Tienen, interpreted as an event representing a single moment in time, associated with the cult within a temple of Mithras (Martens 2004; Lentacker et al. 2004). The context has been dated archaeologically to the third quarter of the 3rd century AD on the basis of the characteristics of the ceramic finds (Martens 2004). Tienen is located on the Grote Gete, a small river in the eastern part of the Schelde basin.

A small number of fish remains were analyzed from a cesspit in the late Medieval prison tower in the town of Mechelen (the *Steen*), of which the fill has been dated archaeologically to the early 14th century based on the ceramic finds (Troubleyn et al. 2009). Mechelen is situated on the river Dijle, which is in the eastern part of the Schelde basin.

The majority of the fish remains in this study derive from a cesspit excavated in a house (*De Cop*) near the market square of the town of Dendermonde, of which the fill has been dated archaeologically to the first half of the 16th century based on cultural artefacts (Beeckman and Van Hecke 2017). Dendermonde is located at the confluence of the rivers Dender and Schelde, ca. 14 km downstream from Aalst.

The stable isotope data included from Fuller et al. (2012) derive from two contexts that are further explored here (Dendermonde–De Cop, Mechelen–Steen), from two additional sites within one of the towns already included in this study (Mechelen–Lamot: 9th–12th century, Mechelen–Veemarkt: 14th–15th century), and from a location that is not covered by the new data from this study, namely, the abbey of Ename, near Oudenaarde (comprising a context dated archaeologically to around 1500 AD and a context dated archaeologically to the 17th century) (Figure 1). References to these additional contexts can be found in Fuller et al. (2012).

Species

The domestic mammals (pig, cattle, sheep) on which radiocarbon dates were obtained need no introduction. It is not expected that the diet of these animals, in the periods and regions considered in this study, was influenced by a significant input of either marine or freshwater organisms. Even for the omnivorous pig, stable isotope studies from Flanders show no significant consumption of aquatic organisms in historical times (Ervynck et al. 2007). In contrast, the ecology and life cycle of the freshwater fish species studied are key to the interpretation of the results obtained. The ten fish taxa that have been included in this study are representative of the freshwater species typically encountered in archaeological sites along the oligohaline and freshwater zones of the Schelde basin (Van Neer and Ervynck 1994). For each of these species, when possible, bones representing different length classes were selected, as it is known that feeding habits change as fish grow larger and that this markedly influences their stable isotope ratios (e.g., Häberle et al. 2016a; 2016b).

In terms of number of finds and species richness, the carp family (Cyprinidae) is the major freshwater fish group in the study area. It should be noted that species identifications of isolated skeletal elements are not always easy to achieve, in particular when these elements are from smaller individuals. At the site of Tienen–Grijpenveld, the few available cyprinid bones (rare finds for the Roman period) were not species diagnostic, but they cannot be carp, as the species had not yet been introduced in Roman times. For the other sites, only bones of cyprinids that were identified to species have been included in the present study. Most of the cyprinid material is from bream (*Abramis brama*; n = 7) and roach (*Rutilus rutilus*; n = 7), while less material was available from carp (*Cyprinus carpio* f. domestica; n = 3), ide (*Leuciscus idus*; n = 2) and silver bream (*Blicca bjoerkna*; n = 1). Most of the bones correspond to fish that were larger than 20 cm SL (standard length, i.e. the length of the fish measured from the tip of the snout to the base of the tail). In the case of roach, it was possible to obtain a single sample of smaller fish (between 8 and 15 cm SL) with sufficient mass to enable analysis, but for the remaining cyprinid species, a sufficient bone mass for length classes below 20 cm SL could not be accumulated.

The second group of fish consists of three carnivorous species, namely, pike (*Esox lucius*; n = 21), perch (*Perca fluviatilis*; n = 5), which inhabit exclusively freshwater environments, and eel (*Anguilla anguilla*; n = 5), which is catadromous. In the case of pike, the length classes varied between 20–30 cm SL and > 50 cm SL, and for the length classes above 30 cm, most samples consisted of a single bone. Similarly, for perch, no samples were available for fish below 20 cm SL. Each of the six samples of eel was made up of numerous bones, mainly vertebrae, that each have a relatively small bone mass. Because estimation of fish length on the basis of isolated eel vertebrae is not always very precise (Thieren et al. 2012), there is a wide range of fish lengths indicated for each of these samples. However, in general, it can be said that the eel remains represent medium-sized individuals.

The third group of fish consists exclusively of flounder (*Platichtys flesus*; n = 11), of which both small individuals, measuring 10–20 cm SL, and larger individuals, measuring 20–30 cm SL and 30–40 cm SL, were available for sampling. All the flounder specimens come from the site of Dendermonde–De Cop, and they appear to represent young fish that may have been captured in local freshwaters, as well as larger, imported fish that typically would have lived in the Schelde estuary and in coastal waters.

Considering the interpretations intended to make use of these data, it should be stressed that in the case of the smallest fish, a number of data points does not represent single individuals, but, rather, a mixture of specimens, albeit still from the same size class (except for eel, see above) and from the same individual archaeological context. It has been assumed that, within the specific archaeological contexts sampled, specimens from these smaller, economically less important size classes derive from the same environment. In the case of the larger specimens, attention has been paid to avoiding the selection of bones from the same individual, either by taking single bone elements from different archaeological units, or by selecting the same skeletal element from within the same unit. In the case of flounder, for instance, the os anale (an unpaired element) and the cleithra (a paired element) were preferentially used for sampling, and the roach is only represented by the highly species-diagnostic pharyngeal plates. Because of this sampling strategy, we are rather confident that the selected bones are from different individuals. However, in the case of the larger pike from Dendermonde it was not possible to follow that procedure as bones of large individuals were rare and derive from only two different archaeological find units within the same cesspit.

Two further confounding factors have to be considered regarding this dataset. First, it is assumed that all of the fish sampled were caught locally, from the main rivers running near or through the sites. However, it must be taken into account that a trade in fish products may have occurred. In general, the historical sources are not very informative about such trade at the site level, making it impossible to exclude sites or assemblages from the analysis based on their involvement in the freshwater fish trade. However, it can be assumed that, because most freshwater fish was consumed fresh and was locally available everywhere, the trading distances cannot have been substantial (see Theurot 2004 for a case study from France), with the exception of eel, which can easily be transported alive and was also traded in a processed form (smoked), and carp, which can also easily be transported alive. Second, there is the possibility in Medieval and later periods of fish having derived from fish farming, and these farmed fish, living in a different environment, often enriched by the anthropogenic input of nutrients, can be expected to have different isotopic signatures than individuals of the same species living in the river system. Again, historical information does not provide enough detail on this economic activity at the site level. Late Medieval texts, for instance from France, mention the species that were most commonly harvested from fish ponds. The major species is carp, but in most cases pike is also mentioned as another highly valued species (Monvoisin 2004; Rouillard 2004). A wide variety of other species, mainly cyprinids, are suspected to also sometimes have been reared in ponds to be marketed (Beck 2004), although, with the exception of bream (Mattéoni 2004), they are usually not named. Sometimes large quantities of bream are mentioned in the accounts (Mattéoni 2004) and there are historical references to ponds stocked with both carp and bream (Berthier 2004).

Sample Pretreatment

Collagen extraction was performed following Longin's (1971) method. Between 100 and 500 mg of fragmented bone was demineralized in 10 ml 8% HCl for 20 minutes at room temperature and subsequently rinsed with milliQ-water. After that, the sample was immersed for 15 minutes in 1% NaOH and again rinsed with milliQ-water. Subsequently, 1% HCl was added for neutralization, after which the sample was again washed with milliQ-water. For all the steps mentioned above, Ezee-filters were used. Gelatinization of the extract was done in a solution of pH = 3, at 90°C for 12 hours. The resulting gelatin was filtered with a Millipore 7 micrometer glass filter and subsequently freeze-dried. ^{14}C, stable isotopes (δ ^{13}C and δ ^{15}N), %C, %N and the atomic C:N ratio were analyzed on the bone collagen.

Stable Isotope Ratios (δ^{13}C and δ^{15}N), %C, %N, and Atomic C:N Ratio Analyses

Carbon and nitrogen stable isotope compositions were measured as the ratios of the heavy isotope to the light isotope (^{13}C/^{12}C or ^{15}N/^{14}N) and are reported in delta (δ) notation as parts per thousand (‰), where δ^{13}C or δ^{15}N = $([R_{sample}/R_{standard}] - 1) \times 1000$, and R is ^{13}C/^{12}C or

$^{15}N/^{14}N$, relative to internationally defined standards for carbon (Vienna Pee Dee Belemnite, VPDB) and nitrogen (Ambient Inhalable Reservoir, AIR).

Analyses were performed in duplicate on a Thermo Flash EA/HT elemental analyzer, coupled to a Thermo DeltaV Advantage Isotope Ratio Mass Spectrometer via ConfloIV interface (ThermoFisher Scientific, Bremen, Germany) at the Department of Earth and Environmental Sciences of the KU Leuven, Belgium. Standards used were IAEA-N1, IAEA-C6, and internally calibrated acetanilide. Analytical precision was 0.25‰ for both $\delta^{13}C$ and $\delta^{15}N$ based on multiple measurements of the standard acetanilide.

Carbon and nitrogen concentrations in bone gelatin in relation to the bulk weight were also determined; these will be referred to as weight percentage of carbon and nitrogen (%C and %N). These two quality indicators provide information on protein degradation. Ambrose (1990) cites a collagen weight %C and %N range for well-preserved collagen of 15.3–47% and 5.5–17.3%, respectively. The atomic C:N ratio of the bone collagen samples was used to classify the collagen samples as uncontaminated or contaminated (DeNiro 1985; Ambrose 1990). Samples providing results outside the 2.9–3.6 range were regarded as being contaminated.

Radiocarbon Analysis

All samples were transformed into graphite using the automatic graphitization device AGE (Němec et al. 2010; Wacker et al. 2010; Boudin et al. in press), and ^{14}C concentrations were measured with accelerated mass spectrometry (AMS) at the Royal Institute for Cultural Heritage (Brussels) (Boudin et al. 2015). ^{14}C results are expressed in pMC (percentage modern carbon) and indicate the percentage of modern (1950) carbon corrected for fractionation using the $\delta^{13}C$ AMS measurement.

Calibration, modeling and statistical analysis of the radiocarbon dates were executed with the Oxcal 3.10 program (Bronk Ramsey 2005), using atmospheric data from Reimer et al. (2009). The same program and calibration curve were also used to transform archaeological and historical calendar dates into radiocarbon data (BP). The FRE offsets (in ^{14}C years) were calculated as "^{14}C freshwater fish – ^{14}C terrestrial material", with the latter measurement being the Oxcal combination (R_Combine function) (Ward and Wilson 1978) of all terrestrial mammal dates obtained for a given archaeological context or the Oxcal transformation of an archaeological or historical date. The uncertainty of a FRE offset was calculated using $\sigma FREO = \sqrt{(\sigma a^2 + \sigma b^2)}$, where σa and σb are ^{14}C age uncertainties for the fish samples and the combined or transformed terrestrial mammal samples.

RESULTS AND INTERPRETATION

Success Rate of the Analysis

All new lab results derived from this study are listed in Table 1. Some samples did not yield enough collagen to enable to conduct both stable isotope and ^{14}C analyses. When there was less than 1mg collagen, only stable isotope analyses were performed.

Of the 95 samples analyzed, 92 yielded results. The terrestrial mammal samples all had a good success rate. Of the 67 fish samples analyzed, 3 samples, from Dendermonde–De Cop, did not yield any collagen; these are not listed in Table 1 and are excluded from the interpretations. One additional sample (lab code RICH-23651) had an atomic C:N ratio (= 5.7) that falls outside the range of 2.9–3.6 proposed by DeNiro (1985) and thus indicates contamination. This sample is listed in Table 1 but was also excluded from the interpretations. All the other fish samples

Table 1 Stable isotope (δ^{13}C and δ^{15}N) and radiocarbon data for four archaeological sites from the Schelde basin (Belgium) (SL: standard length, see text, n.a.: not available, n.r.: not relevant, *: outlier, °: C:N ratio too high).

Lab code	Species	Estimated SL (cm)	δ^{13}C	δ^{15}N	Atomic C:N	%C	%N	^{14}C date (BP)	^{14}C date uncertainty (1σ, BP)	FRE offset (BP)	FRE offset uncertainty (BP)
Mechelen - Steen											
RICH-21593	Eel (*Anguilla anguilla*)	Mix	−16.3	12.9	3.2	40.4	14.8	1362	32	762	44
RICH-21594	Eel (*Anguilla anguilla*)	Mix	−17.6	12.6	3.2	39.9	14.7	1501	35	901	46
n.a.	Pike (*Esox lucius*)	>50	−23.9	15.1	3.5	32.3	10.8	n.a.	n.a.	n.a.	n.a.
Aalst - Hopmarkt											
RICH-21952	Eel (*Anguilla anguilla*)	20–60	−19.2	12.3	3.2	34.4	12.5	1172	30	809	31
RICH-21971	Eel (*Anguilla anguilla*)	30–50	−16.1	12.5	3.2	34.1	12.5	1233	32	870	33
RICH-21927	Carp (*Cyprinus carpio* f. domestica)	25–35	−21	7.8	3.6	31.6	10.3	1300	32	937	33
RICH-21951	Carp (*Cyprinus carpio* f. domestica)	25–35	−22.6	10.5	3.3	15.4	5.4	1192	31	829	32
RICH-21963	Carp (*Cyprinus carpio* f. domestica)	25–35	−23.2	8	3.4	17	5.9	1270	30	907	31
RICH-21972	Roach (*Rutilus rutilus*)	8–15	n.a.	n.a.	3.3	n.a.	n.a.	1316	40	953	41
RICH-21998	Sheep (*Ovis ammon* f. aries)	n.r.	−22.3	8.7	3.1	42.6	15.9	322	28	n.r.	n.r.
RICH-21999	Sheep (*Ovis ammon* f. aries)	n.r.	−21.6	7.2	3.1	40.6	15.1	367	28	n.r.	n.r.
RICH-22000	Sheep (*Ovis ammon* f. aries)	n.r.	−22.5	8.4	3.1	39.9	15	288	28	n.r.	n.r.
RICH-22037	Sheep (*Ovis ammon* f. aries)	n.r.	−22.4	6.9	3.2	39.5	14.3	340	30	n.r.	n.r.
RICH-22038	Sheep (*Ovis ammon* f. aries)	n.r.	−23	8.1	3.2	33.1	12.1	377	30	n.r.	n.r.
RICH-22045	Sheep (*Ovis ammon* f. aries)	n.r.	−22.7	7.6	3.1	33	12.2	380	29	n.r.	n.r.
RICH-22046	Sheep (*Ovis ammon* f. aries)	n.r.	−22.6	8.2	3.2	34.3	12.6	360	29	n.r.	n.r.
RICH-22044	Cattle (*Bos primigenius* f. taurus)	n.r.	−23.1	7.1	3.3	39	13.9	354	31	n.r.	n.r.
RICH-22041	Cattle (*Bos primigenius* f. taurus)	n.r.	−22.7	5.2	3.2	43.2	15.9	413	30	n.r.	n.r.
RICH-22042	Cattle (*Bos primigenius* f. taurus)	n.r.	−22.5	3.8	3.2	37.8	13.8	373	28	n.r.	n.r.
RICH-22043	Pig (*Sus scrofa* f. domestica)	n.r.	−21.7	5.3	3.1	36.7	13.6	371	29	n.r.	n.r.
RICH-22039	Pig (*Sus scrofa* f. domestica)	n.r.	−21.8	7.4	3.2	31.1	11.2	545*	29	n.r.	n.r.
RICH-22040	Pig (*Sus scrofa* f. domestica)	n.r.	−22	7.1	3.2	43.4	15.6	412	29	n.r.	n.r.
RICH-22047	Pig (*Sus scrofa* f. domestica)	n.r.	−22	5.8	3.2	35.4	12.9	370	29	n.r.	n.r.
Tienen - Grijpenveld											
RICH-22051	Eel (*Anguilla anguilla*)	50–80	−24.9	13.5	3.1	39.3	14.6	2588	31	1107	32
RICH-22052	Cyprinid (Cyprinidae indet.)	40–50	−23.5	10.6	3.2	37.3	13.6	3120	32	1639	33
RICH-22053	Cyprinid (Cyprinidae indet.)	40–50	−27.1	11.8	3.2	31.6	11.5	2335	32	854	33
RICH-22070	Sheep (*Ovis ammon* f. aries)	n.r.	−22.8	8.3	3	32.1	12.5	1816	32	n.r.	n.r.

RICH-22071	Sheep (*Ovis ammon* f. aries)	n.r.	−21.8	7.2	3	37.5	14.6	1819	32	n.r.	n.r.
RICH-22112	Sheep (*Ovis ammon* f. aries)	n.r.	−22	10.3	3	31.4	12	1842	31	n.r.	n.r.
RICH-22113	Sheep (*Ovis ammon* f. aries)	n.r.	−21.5	6.7	3	37.8	14.5	1847	31	n.r.	n.r.
RICH-22115	Sheep (*Ovis ammon* f. aries)	n.r.	−21.2	3.9	3.1	36.2	13.8	1855	32	n.r.	n.r.
RICH-22072	Cattle (*Bos primigenius* f. taurus)	n.r.	−23.1	7.4	3	36.9	14.2	1842	32	n.r.	n.r.
RICH-22073	Cattle (*Bos primigenius* f. taurus)	n.r.	−21.3	12.2	3	37	14.3	1809	34	n.r.	n.r.
RICH-22109	Cattle (*Bos primigenius* f. taurus)	n.r.	−22.3	8.1	3.1	32.7	12.4	1834	32	n.r.	n.r.
RICH-22116	Cattle (*Bos primigenius* f. taurus)	n.r.	−22.5	7.5	3.2	24.6	9	1872	31	n.r.	n.r.
RICH-22117	Cattle (*Bos primigenius* f. taurus)	n.r.	−22.7	4.5	3.1	37.7	14	1864	32	n.r.	n.r.
RICH-22108	Pig (*Sus scrofa* f. domestica)	n.r.	−20.2	8.5	3.1	34.3	12.9	1831	31	n.r.	n.r.
RICH-22110	Pig (*Sus scrofa* f. domestica)	n.r.	−21.4	4.7	3.1	30.5	11.5	1858	32	n.r.	n.r.
RICH-22111	Pig (*Sus scrofa* f. domestica)	n.r.	−22.2	9	3.1	40	15.3	1835	32	n.r.	n.r.
RICH-22114	Pig (*Sus scrofa* f. domestica)	n.r.	−20.4	7.2	3.1	29.3	11.2	1838	31	n.r.	n.r.
Dendermonde - De Cop											
RICH-23021	Pike (*Esox lucius*)	20–30	−25.9	13.4	3.5	32.8	10.9	994	32	644	44
RICH-23022	Pike (*Esox lucius*)	20–30	−26.2	8.6	3.4	43.3	15	882	32	532	44
RICH-23024	Pike (*Esox lucius*)	20–30	−26.3	9.9	3.3	41.5	14.6	680	30	330	42
n.a.	Pike (*Esox lucius*)	20–30	−25.5	11.8	3	36.4	12	n.a.	n.a.	n.a.	n.a.
n.a.	Pike (*Esox lucius*)	20–30	−26.2	14.7	3	38.1	12.7	n.a.	n.a.	n.a.	n.a.
RICH-21592	Pike (*Esox lucius*)	30–40	−23.8	10.2	3.3	39.9	14.2	473	34	123	45
RICH-22669	Pike (*Esox lucius*)	30–40	−26.6	11.8	3.2	39.8	14.5	451	29	101	42
RICH-22670	Pike (*Esox lucius*)	30–40	−24.4	15.4	3.3	33.8	12.1	1645	32	1295	44
RICH-22671	Pike (*Esox lucius*)	30–40	−26.1	15.4	3.3	33.9	12.1	1336	34	986	45
n.a.	Pike (*Esox lucius*)	30–40	−23.6	15.9	3.3	34.3	12.3	n.a.	n.a.	n.a.	n.a.
n.a.	Pike (*Esox lucius*)	30–40	−23.6	15.6	3.2	34.7	11.9	n.a.	n.a.	n.a.	n.a.
n.a.	Pike (*Esox lucius*)	30–40	−25.7	9.7	3.5	11.2	3.4	n.a.	n.a.	n.a.	n.a.
RICH-22672	Pike (*Esox lucius*)	40–50	−26.9	16.7	3.2	27.3	10	1030	31	680	43
RICH-22663	Pike (*Esox lucius*)	40–50	−26.8	16.3	3.1	21.6	8.2	999	32	649	44
RICH-22661	Pike (*Esox lucius*)	40–50	−26.9	16.6	3.2	27.5	9.9	947	30	597	42
RICH-22664	Pike (*Esox lucius*)	40–50	−27	16.8	3.2	23.3	8.4	994	31	644	43
RICH-22662	Pike (*Esox lucius*)	40–50	−26.8	16.6	3.2	20	7.4	1054	32	704	44
RICH-22673	Pike (*Esox lucius*)	50–60	−27	16.4	3.2	28.7	10.5	1099	35	749	46
RICH-22674	Pike (*Esox lucius*)	50–60	−25.7	17.2	3.2	31	11.1	1295	32	945	44
RICH-22675	Pike (*Esox lucius*)	50–60	−26.8	16.9	3.3	25.9	9.3	1022	30	672	42
RICH-23030	Perch (*Perca fluviatilis*)	20–30	−24	17	3.2	35.8	12.9	1730	34	1380	45
RICH-22994	Perch (*Perca fluviatilis*)	20–30	n.a.	n.a.	3.1	n.a.	n.a.	1840	30	1490	42
RICH-22995	Perch (*Perca fluviatilis*)	20–30	−24.7	15.4	3.2	35.1	12.7	1348	28	998	41

Table 1 (*Continued*)

Lab code	Species	Estimated SL (cm)	$\delta^{13}C$	$\delta^{15}N$	Atomic C:N	%C	%N	^{14}C date (BP)	^{14}C date uncertainty (1σ, BP)	FRE offset (BP)	FRE offset uncertainty (BP)
RICH-22998	Perch (*Perca fluviatilis*)	20–30	−23.7	17	3.2	38.4	14.1	1604	28	1254	41
RICH-23003	Perch (*Perca fluviatilis*)	30–40	−24.9	15.9	3.1	27.1	10.2	1371	28	1021	41
RICH-23713	Flounder (*Platichthys flesus*)	10–20	−26.1	13.9	3.3	40.7	14.5	1479	26	1129	40
RICH-23722	Flounder (*Platichthys flesus*)	10–20	−24.1	14.9	3.2	37.6	13.7	1662	26	1312	40
RICH-23707	Flounder (*Platichthys flesus*)	20–30	−15.7	12.4	3.3	39.2	14	1320	26	970	40
n.a.	Flounder (*Platichthys flesus*)	20–30	−23.6	15	3.3	27.1	9.5	n.a.	n.a.	n.a.	n.a.
RICH-23715	Flounder (*Platichthys flesus*)	20–30	−23	14.6	3.2	42.8	15.6	1731	30	1381	42
RICH-23651	Flounder (*Platichthys flesus*)	30–40	−23.9	13.9	4.2°	20.2	5.7	986	36	636	47
RICH-23640	Flounder (*Platichthys flesus*)	30–40	−14.6	11.7	3.4	39.4	13.6	937	30	587	42
RICH-23651	Flounder (*Platichthys flesus*)	30–40	−16.2	11.3	3.4	39.5	13.7	1050	30	700	42
RICH-23710	Flounder (*Platichthys flesus*)	30–40	−11.2	11.9	3.2	35.5	13	868	28	518	41
RICH-23718	Flounder (*Platichthys flesus*)	30–40	−12	11.5	3.2	48.8	18	874	26	524	40
RICH-23720	Flounder (*Platichthys flesus*)	30–40	−14	11.9	3.1	40.4	15	928	30	578	42
RICH-23721	Bream (*Abramis brama*)	20–25	−25.8	15.4	3.3	35.2	12.6	1740	28	1390	41
RICH-23716	Bream (*Abramis brama*)	20–25	−25.3	14.5	3.2	40.9	15	1718	29	1368	42
RICH-23723	Bream (*Abramis brama*)	20–25	−24.8	15.6	3.3	38.7	13.8	1698	29	1348	42
RICH-23652	Bream (*Abramis brama*)	20–25	−26.5	12.8	3.4	37.9	13.2	1399	31	1049	43
RICH-23654	Bream (*Abramis brama*)	25–30	−25.4	14.5	3.4	41.2	14.3	1675	31	1325	43
RICH-23711	Bream (*Abramis brama*)	25–30	−24.8	14.7	3.3	45.2	16	1822	27	1472	40
RICH-23714	Bream (*Abramis brama*)	25–30	−24.6	14.7	3.2	42	15.3	1814	26	1464	40
RICH-23727	Roach (*Rutilus rutilus*)	20–25	−22	14.8	3.2	38.1	14.1	2195	28	1845	41
RICH-23653	Roach (*Rutilus rutilus*)	20–25	−27.3	15.1	3.4	38.5	13.4	2014	31	1664	43
n.a.	Roach (*Rutilus rutilus*)	25–30	−25.8	14.3	3.4	24.8	8.5	n.a.	n.a.	n.a.	n.a.
RICH-23712	Roach (*Rutilus rutilus*)	25–30	−25.6	15	3.1	38.1	14.1	2103	26	1753	40
RICH-23717	Roach (*Rutilus rutilus*)	25–30	−28.4	14.6	3.2	33.7	12.5	1911	26	1561	40
RICH-21595	Roach (*Rutilus rutilus*)	30–40	−25.7	14.1	3.2	44.8	16.2	2077	32	1727	44
RICH-23639	Ide (*Leuciscus idus*)	25–30	−22.5	14.5	3.4	35.4	12	1006	31	656	43
RICH-23708	Ide (*Leuciscus idus*)	30–35	−21.7	14	3.3	43.7	15.5	969	26	619	40
RICH-23719	White bream (*Blicca bjoerkna*)	20–25	−23.6	15	3.3	35.3	12.4	1717	27	1367	40

(n = 63) have an acceptable atomic C:N ratio (see Table 1). The %C and %N of all these samples indicate well-preserved collagen.

The success rate of collagen extraction for the fish samples was 94% in this study, while it was only about 40% in the Fuller et al. (2012) study—even though both projects used samples from archaeological contexts that are similar in terms of chronology, taphonomy and preservation conditions. The difference can be explained by the alkaline wash, used in this study between the demineralization and the hydrolysis steps, while Fuller et al. (2012) applied ultrafiltration after the demineralization. Because the failed samples of Fuller et al. (2012) all had atomic C:N ratios that exceeded 3.6, it is likely that the majority of the contamination is the result of the impact of soil components, such as humic and fulvic acids, from the archaeological context. In addition, all the bone material used by Fuller et al. (2012) (and in this study) was excavated from refuse contexts and cesspits rich in organic material, which represent aggressive environments in terms of post-depositional chemical alteration of bone. This could have resulted in humic substances becoming bound or cross-linked to the collagen matrix and thus difficult to eliminate. Adding an alkaline step helps to remove basic soluble organics, such as humic acids (although not completely: Arslanov and Svezehentsev 1993; Van Klinken and Hedges 1995), which explains the high success rate in this study. Ultrafiltration of bone collagen, dissolved as gelatin (molecular weight ~100,000 Dalton), has received considerable attention as a method to obtain more reliable ^{14}C dates and stable isotope signatures (Brown et al. 1988; Bronk Ramsey et al. 2004; Higham et al. 2006; Mellars 2006). It is indeed an effective method for removal of low-molecular weight contaminants from bone collagen. However, it does not remove high-molecular weight contaminants, such as cross-linked humic-collagen complexes (Brock et al. 2007).

Dating the Sites

The date range established from historical documents for the context from Aalst–Hopmarkt was tested through radiocarbon analysis of 14 bones from terrestrial domestic mammals. All radiocarbon dates showed similar values except one (RICH 22039, Table 1). Because this sample was considerably older than the others, it may represent a residual find and it has therefore been excluded from the analysis. The remaining 13 dates could be combined [X^2 test: df = 12, T = 16.4 (5% 21.0)] into one date (363 ± 8 BP), which, after calibration with 95.4% probability, results in an age range of 1460 to 1520 AD (62.7%) or 1590 to 1620 AD (32.7%). The first range coincides perfectly with the historical date range of 1489 to 1498 AD.

The archaeological date range for the ritual deposit excavated at Tienen–Grijpenveld was tested through radiocarbon analysis of 14 terrestrial domestic mammal bones. They could be reliably combined [X^2 test: df = 13, T = 4.2 (5% 22.4)] into the single date of 1841 ± 8 BP, which, after calibration with 95.4% probability, yields a date range of 125–225 AD. This is considerably older than the original archaeological interpretation of the ceramics from the deposit, but new information about the chronological distribution of the pottery types now allows the excavator to accept an older starting date for the assemblage (Martens, pers. comm.).

The fill of the cesspit in the late Medieval prison tower of Mechelen–Steen has only been dated on the basis of the ceramic finds. In order to allow an evaluation of the radiocarbon dates from the freshwater fish remains, the cultural date range has been transformed into a simulated radiocarbon date of 600 ± 30 BP. A similar exercise has been performed for the contents of a cesspit excavated at Dendermonde–De Cop; a date of 350 ± 30 BP will be used to compare the radiocarbon dates of the freshwater fish remains against.

Stable Isotopes of the Freshwater Fish

Figures 2, 3 and 4 depict the 99 stable isotope measurements for the carnivorous fish species, flounder and cyprinids analyzed in this study. To this dataset are added the measurements published by Fuller et al. (2012, see Table S1 in the online Supplementary Material), which allows to increase the sample size for eel and small roach.

The scatter of data for eel suggests the existence of two populations: one with high δ^{15}N and low δ^{13}C values, showing limited variation, and one with less negative δ^{13}C and lower δ^{15}N values, showing more pronounced variation in both parameters (Figure 2). As explained in Fuller et al. (2012), this divergence is due to the fact that the second population derives from more estuarine waters than the first one. The most ^{13}C-depleted specimens are from Tienen–Grijpenveld, Ename and Mechelen–Lamot (Table 1), and these are interpreted as fish that were caught locally, away from the Schelde estuary. One eel from Mechelen–Lamot has a more estuarine signature, however, and that is also the case for the eel remains from the other sites at Mechelen (Steen and Veemarkt), from Aalst–Hopmarkt and from Dendermonde–De Cop. Those will have been imported to the local markets from fishing grounds farther downstream.

The stable isotope signatures of perch and (larger) pike are similar to those of the samples that were argued to be “freshwater eel” (Figure 2). Both size classes of perch show similar values, but in the case of pike, there is a clear shift in the isotope signals in animals that are older (and thus larger), a phenomenon that has recently been discussed in studies on Swiss freshwater species (Häberle et al. 2016a, 2016b). For the smaller size classes of pike, variation is high, with animals showing a range of low to elevated δ^{15}N values. The largest specimens (>40 cm SL), however, show limited variation and consistently high δ^{15}N values. This small variability in isotope value is strking for the larger pike and in retrospect, it cannot be excluded that some of the bones pertained to the same individual. It is possible that perch undergoes a similar shift in isotope signals during its life cycle, but because the smallest size classes are lacking in the dataset, this cannot be evaluated. For pike and perch, the dataset also does not allow to observe differences in isotopic signatures between sites.

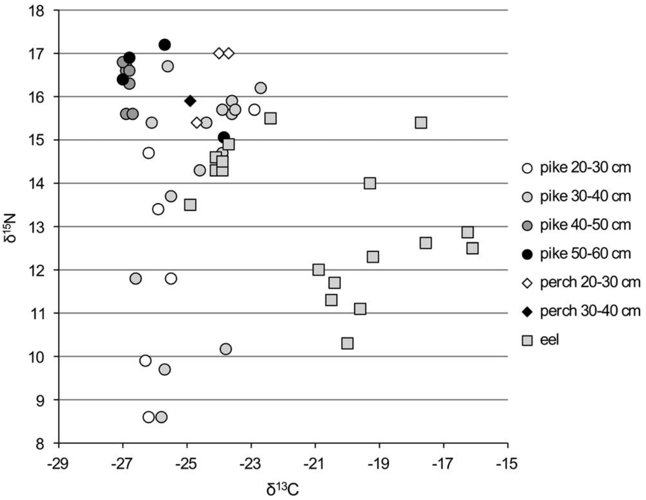

Figure 2 δ^{13}C and δ^{15}N ratios for the carnivorous fish from the Schelde basin (n = 54).

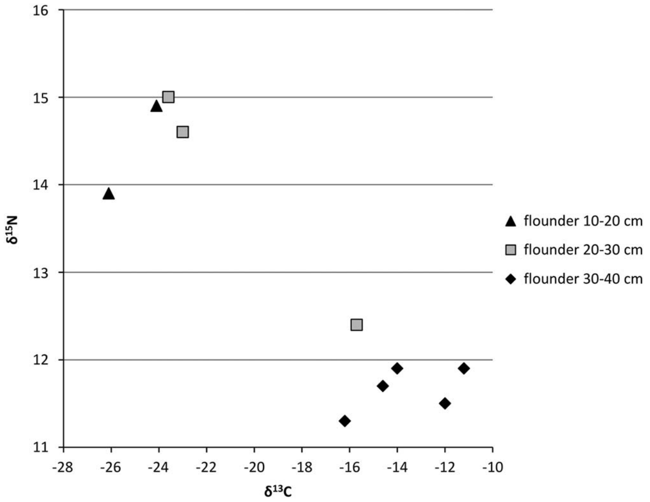

Figure 3 $\delta^{13}C$ and $\delta^{15}N$ ratios for flounder from the Schelde basin (n = 10).

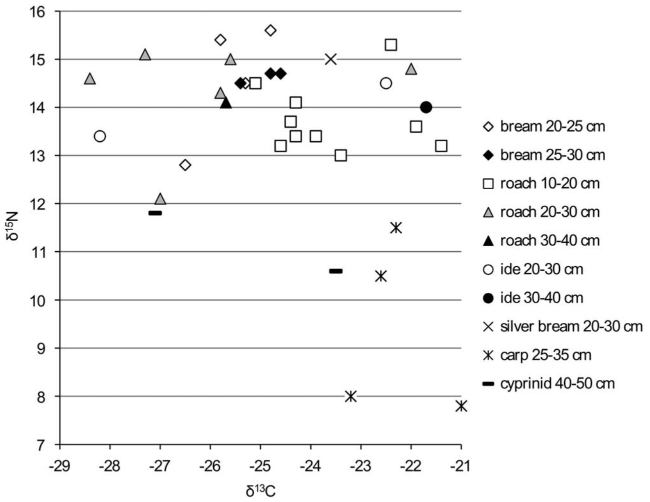

Figure 4 $\delta^{13}C$ and $\delta^{15}N$ ratios for the cyprinids from the Schelde basin (n = 35).

Flounder also appears to undergo a shift in isotope signature during its life cycle (Figure 3). The smaller fish show isotope values that closely resemble those of the "freshwater eel" but do not reach the elevated $\delta^{15}N$ values of perch and large pike (Figure 2). The larger flounder, however, show lower $\delta^{15}N$ and less negative $\delta^{13}C$ values and could, just like the "estuarine eel" population, represent animals living more downstream, in brackish waters. It should be noted that the lower $\delta^{15}N$ values for these "estuarine flounder" most probably are not caused by a lower position in the food chain, but, rather, by a shift to a diet consisting of organisms from the estuary that themselves have low $\delta^{15}N$ values. Early in life, flounder feed on small crustaceans and worms, whereas later on they mainly feed on snails and bivalves and, in freshwater, also insect larvae (Duncker 1960: 328). The shift towards more mollusks in older flounder explains the lower $\delta^{15}N$ values seen in the larger size classes (cf. Riget et al. 2007: fig. 2).

The cyprinids show large variation in $\delta^{13}C$ values and rather high $\delta^{15}N$ values for all size classes (Figure 4) compared with the flatfish and the carnivorous fishes; higher than would be expected from herbivores versus carnivores within the same food chain. The only exceptions are carp and the unidentified (large) cyprinids from Tienen–Grijpenveld (which, as noted above, cannot be carp). No marked shifts in isotope signatures between the size classes of a single species are observed. In the case of the $\delta^{15}N$ values, this is possibly due to the fact that small specimens are virtually lacking in the dataset (cf. Häberle et al. 2016b).

Dating the Fish

When the 56 radiocarbon dates obtained on the freshwater fish remains are evaluated against, on the one hand, the combined dates on the terrestrial mammals and, on the other hand, the simulated radiocarbon dates representing the cultural date of an assemblage, the following marked differences become clear. The minimum FRE offset for the 56 specimens analyzed is 101 ^{14}C years (for a pike from Dendermonde–De Cop), while the maximum offset is 1845 ^{14}C years, for a roach from the same site. The distribution of the FRE offsets is irregular, which must of course be the result of the (uneven) presence of different species, ecological subgroups and size classes. The distribution covers almost all of the histogram classes between the minimum and the maximum (Figure 5). There are no marked differences in the ranges of FRE offsets between carnivorous species, flounder and cyprinids, but there are differences in the end points of the absolute values, with the lowest values being attained by the carnivorous group and the highest by the cyprinids.

In order to facilitate the interpretation of the variation in the FRE offsets, the values are compared against the isotope measurements for each group within the dataset (carnivores, flounder, cyprinids) (Figures 6 to 11). When the "estuarine eel" are left aside, the graph of $\delta^{13}C$ versus FRE offset for the carnivorous fish (Figure 6) suggests a relationship between the two parameters, although this cannot be proven statistically. For the most part, less negative $\delta^{13}C$ values seem to coincide with higher FRE offsets, although the largest pike do not follow the pattern of the smaller pike exactly. In general, the large variation within a single size class of pike is surprising: amongst the animals of 30–40 cm SL, which consists of two specimens from the same assemblage from Dendermonde–De Cop, one has a FRE offset of 101 ^{14}C years, while the other attains 1295 ^{14}C years. The comparison between $\delta^{15}N$ values and FRE offsets for the

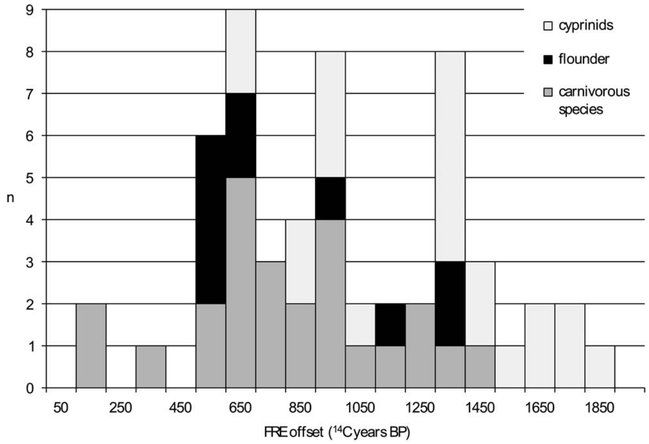

Figure 5 Distribution of the FRE offset for the radiocarbon dated freshwater fish remains from the Schelde basin (n = 56).

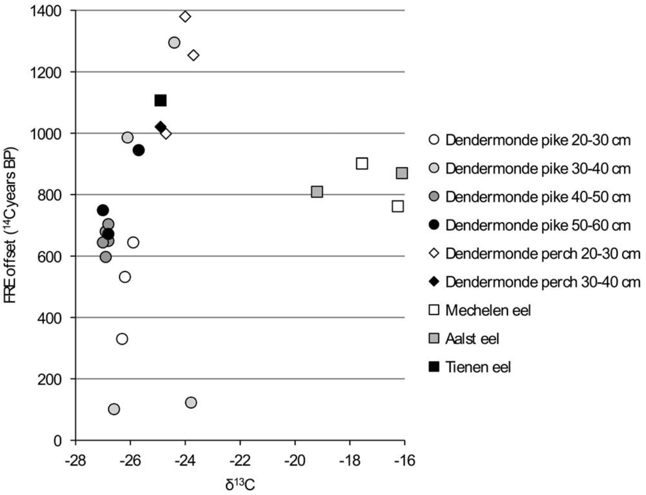

Figure 6 FRE offset versus δ^{13}C ratio for the carnivorous fish from the Schelde basin (n = 25).

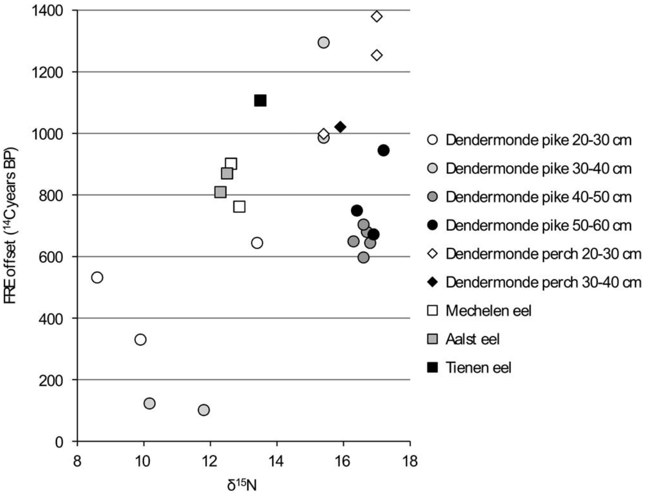

Figure 7 FRE offset versus δ^{15}N ratio for the carnivorous fish from the Schelde basin (n = 25).

carnivorous fish (Figure 7) shows more or less the same pattern as the previous graph, with large pike again forming a distinct group.

The comparison of the isotope values with the reservoir data for flounder (Figures 8 and 9) clearly shows that the larger animals have a lower FRE offset than the smaller ones. This difference can easily be explained by the fact that the larger animals would have lived in an environment with more input of marine water (with a reservoir offset of only 400 ^{14}C years). A shift in diet associated with the change in biotope may also have had an impact, but this is difficult to evaluate.

The graphs for the cyprinids (Figures 10 and 11) show no clear patterns except for carp and ide, which have markedly lower FRE offsets than the other cyprinids, although within that

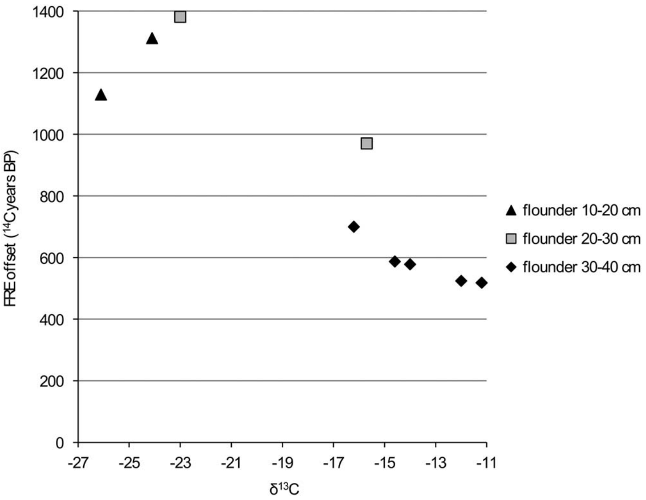

Figure 8 FRE offset versus δ^{13}C ratio for flounder from the Schelde basin (n = 9).

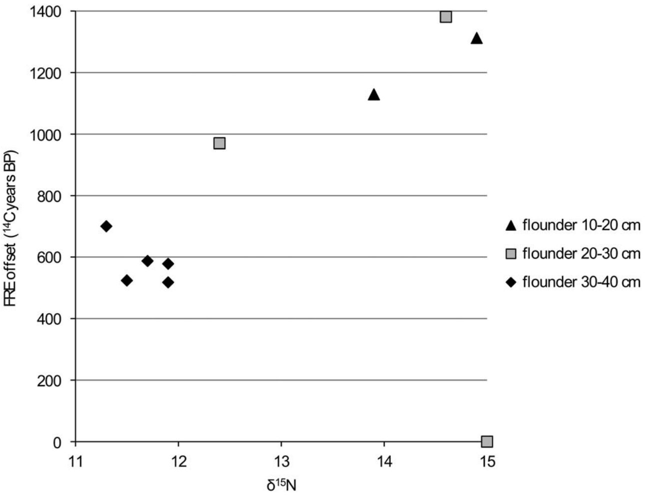

Figure 9 FRE offset versus δ^{15}N ratio for flounder from the Schelde basin (n = 9).

general pattern of lower offsets, the isotopic signatures of the two species are clearly different (see Figure 4).

DISCUSSION

This study has proven useful in several respects. The fact that the ^{14}C dates of the terrestrial animals from Aalst–Hopmarkt and Tienen–Grijpenveld could be statistically combined into a single date, which in the case of Aalst coincided with the date range based on historical sources, proves that none of these species are subject to an FRE offset—not even the omnivorous pig. The stable isotope data for all of the terrestrial animals point to the same conclusion (Table 1).

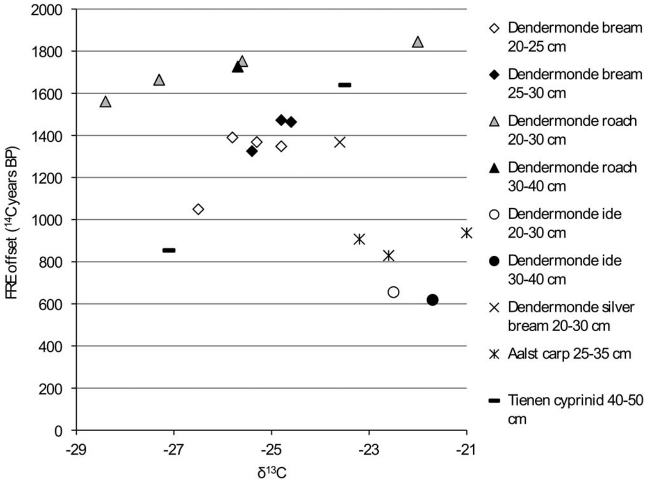

Figure 10 FRE offset versus $\delta^{13}C$ ratio for the cyprinids from the Schelde basin (n = 21).

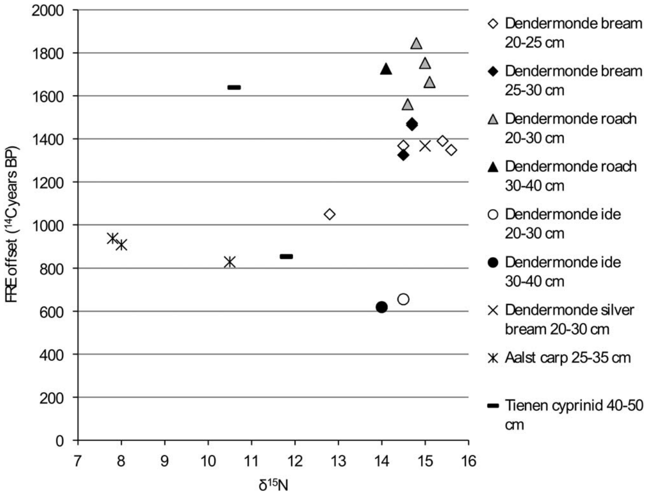

Figure 11 FRE offset versus $\delta^{15}N$ ratio for the cyprinids from the Schelde basin (n = 21).

More importantly, the results obtained in this study confirm the observations made by Fuller et al. (2012) concerning the high variability of $\delta^{13}C$ and $\delta^{15}N$ values within the group of freshwater fishes, and within individual species of fish. They also corroborate the findings of Häberle et al. (2016a, 2016b) that the isotopic signature changes over the lifetime of a freshwater fish. In the case of pike, the same pattern has been found in the population from the Schelde basin, that had been demonstrated in the Swiss specimens studied by Häberle et al. (2016b, fig. 3). A similar comparison for perch could not be made because the dataset from the Schelde basin lacks the smaller size classes (< 20 cm SL) included in the Swiss study.

In general, the $\delta^{15}N$ values of the species examined here are 4–5‰ higher than those of equivalent prehistoric remains from northern Europe (e.g. Fischer et al. 2007; Schmolcke et al. 2016), which may suggest a strong anthropogenic influence, rather than differences in the ecology of the river basins or climatic fluctuations. Most probably, especially the onset of severe soil erosion from the beginning of agriculture (see below) is the cause of a shift in isotope values between fish from prehistoric sites versus those from later sites. Fish farming cannot provide the whole explanation because carp (the cyprinid most likely to have been farmed) has lower $\delta^{15}N$ values than the other cyprinids (Figure 4), a group that was presumably less likely farmed.

From this project, it is clear that the FRE offset of aquatic fish can attain high values in the Schelde basin. Aquatic environments with large FRE offsets were already known, e.g. from Lake Mývatn, northern Iceland (1300 to 1700 ^{14}C years: Ascough et al. 2007), the Caspian lowlands (1477 ± 52 and 1037 ± 52 ^{14}C years: Shishlina 2010), the Lake Baikal region, in the Upper Lena river basin (1981 ± 30 ^{14}C years: Schulting et al. 2015), and the Karachay-Cherkess Republic, on the Podkumok river in Russia (3819 ± 39 ^{14}C years: Higham et al. 2010). Less elevated FREs have been assessed for Łańskie Lake in northeastern Poland (740 ^{14}C years: Pospieszny 2015), for different water bodies in Germany (Fernandes et al. 2016). Studies from the Minusinsk basin, southern Siberia, possibly suggest that for that area the influence of a FRE on archaeological human ^{14}C dates is negligible (Svyatko et al. 2016).

In many of the examples cited, the underlying mechanisms that have resulted in high or low FREs are not completely clear (Ascough et al. 2007), and that is also the case for the Schelde basin. It could be that groundwater reaching the river system had spent a long time travelling from the recharge to the discharge areas, especially when it became part of the system of deep and old geological aquifers that characterize the area (see Borremans 2015). Probably more importantly, it could be that ancient organic material, stored within soils and sediments (Abbott and Stafford 1996; Hall and Henderson 2001; Moreton et al, 2004) was transported into the river via percolating rain and groundwater or directly deposited into the river by erosion, a process that became increasingly important with the deforestation linked with the onset of agriculture (see Butman et al. 2015, for an actualistic study). Or it could be that when the river cut through ancient peat layers, these same oxidation and deposition processes manifested themselves. Today, the Schelde river is characterized by a high amount of dissolved inorganic carbon (Hellings et al. 2001). Of course, the situation will have been quite different prior to modern-day pollution and quite different again in prehistoric times, prior to agriculture and other anthropogenic impacts, yielding the possibility that the FRE may also have been different in those days (see Meylemans et al. 2013 for the evolution of the river system).

This study shows not only that the FRE in the Schelde basin reaches high absolute values, but also that the FRE is highly variable, both between species and between size classes in a single species. Within a single species, it can be assumed that the observed variation is caused by shifts in diet related to the growth of the fish or to a move towards another aquatic biotope. It would be expected to see this pattern replicated in the stable isotope data, but in most cases, the stable isotope dataset does not reveal any clear relationships between FRE offset and $\delta^{13}C$ and $\delta^{15}N$ values, a conclusion that was also reached by a similar study for the Eurasian steppe (Svyatko et al. 2017). Most probably, for the Schelde basin, the unknown origin of the archaeological freshwater fish sampled plays an obscuring role. It seems likely that the archaeological freshwater fish in this study originated from different water sources and that this has complicated the picture, as water from local brooks, ponds or the main rivers is expected to have markedly different chemical composition and ^{14}C age. Fish trade and fish farming would further complicate the picture. The current dataset, unfortunately, does not allow to investigate these complicating factors, but they certainly deserve a future study in their own right. For the same reasons (uncertainty over the fishes' origin, large intra- and inter-species variation), differences in FRE offsets between sites could not be observed, and the evaluation of a possible diachronic evolution will remain out of reach until a much larger dataset is obtained.

The FRE offsets measured here certainly must be taken into account when interpreting radiocarbon dates on archaeological human skeletons. It has been evaluated for the marine reservoir effect in archaeological human material from Belgium (Ervynck et al. 2014) that this phenomenon seems not to influence the radiocarbon dates obtained from human skeletons. However, for the FRE, the issue has been raised in a number of specific case studies, such as the radiocarbon analyses of the relic of Saint Waldetrudis (Van Strydonck et al. 2009) and of the skeletons of two historically known bishops buried in the cathedral of Tournai (Boudin et al. 2014). The FRE offsets measured in this study will also have to be taken into account if and when skeletons from monastic graveyards in the Schelde basin are radiocarbon dated (a type of analysis not yet undertaken in Belgium), since it is known that the food rules followed in abbeys promoted the frequent consumption of both marine and freshwater fish (Ervynck 1997). In general, however, corrections of the dates will be very difficult to make. First of all, the isotopic signature of a human skeleton can be the result of very different combinations of food products (plants versus meat, aquatic versus terrestrial, marine versus freshwater) (Grupe 2014; Phillips et al. 2014), and, within the group of freshwater organisms, of combinations of many different species, size classes and ecological groups, all with their own FRE offset, as this study shows. That these freshwater organisms' wide variety of isotope signals hardly shows a clear relationship with their FRE offset, further complicates any correction of a human radiocarbon date.

CONCLUSION

This study has shown that the FRE offsets of fish from freshwater and brackish biotopes within the Schelde basin can reach high values (up to almost two millennia) and can be very varied. Differences occur between species, between size classes within a species, between eco-groups within a species, and within all of these categories. It is likely that this large variability is responsible for the fact that any clear differences between sites or chronological periods could not be observed on the basis of the current dataset.

The observations in this study serve as a warning against assessing FREs for a particular aquatic system on the basis of only a limited sample size comprising only a limited number of species and size classes, as this may lead to the variability in FRE being significantly underestimated. It is also clear that, at least in the case of the Schelde basin, it will be extremely difficult to establish a correction factor for these FREs when dating archaeological human remains from the area, not only because the FRE offsets themselves are so variable, but also because the high inter- and intra-species variation in the freshwater fish isotope signatures observed will hamper any dietary reconstruction using inferences from the bulk stable isotopes. Even if this problem could be overcome, the lack of statistical relationship between the isotopic values and the FRE offsets will make the correction of ^{14}C ages of human bones with a dietary FRE extremely complex, if not impossible. It should also not be forgotten that these same human bones may also be affected by reservoir effects related to the presence of estuarine or marine organisms in the diet, making the task of correcting radiocarbon dates even more challenging. Of course, all of these considerations will also be relevant when radiocarbon dating certain other categories of finds incorporating aquatic organisms, such as residues of fish remains in pottery (see Boudin et al. 2010; Teetaert et al. 2017).

Finally, the suggestion that there is a significant direct (farming) or indirect (soil erosion) anthropogenic influence on the data (on the isotopes and most probably also on the FRE offsets) should serve as a warning against using data from present-day fish populations to interpret archaeological phenomena during the historic period (i.e. before the Industrial Revolution), and even more so during the prehistoric period.

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SUPPLEMENTARY MATERIAL

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