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The influence of religious identity and socio-economic status on diet over time, an example from medieval France

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Abstract

In Southern France as in other parts of Europe, significant changes occurred in settlement patterns between the end of Antiquity and the beginning of the Middle Ages. Small communities gathered to form, by the tenth century, villages organized around a church. This development was the result of a new social and agrarian organization. Its impact on lifestyles and, more precisely, on diet is still poorly understood. The analysis of carbon and nitrogen isotopes in bone collagen from the inhabitants of the well-preserved medieval rural site Missignac-Saint Gilles le Vieux (fifth to thirteenth centuries, Gard, France) provides insight into their dietary practices and enables a discussion about its transformation over time. A sample of 152 adult individuals dated from 675 to 1175 AD (75 females, 77 males) and 75 specimens from 16 non-human species were analyzed. Results show the exploitation of freshwater, marine, and terrestrial ecosystems as well as various breeding practices specific to each species. The use of both C_4 and halophyte plants for feeding domestic animals was also observed. Concerning human dietary practices, a change seemed to occur at the beginning of the tenth century with an increase of $\delta^{15}N$ values and a decrease of $\delta^{13}C$ values. This corresponds to the introduction of a significant amount of freshwater resources into the diet and could be related to the evolution of the Catholic doctrine. A concomitant diversification of access to individual food resources was also observed, probably linked to the increased diversity of practice inside a population otherwise perceived as one community.

Keywords High Middle Ages · Christianity · Carbon isotopes · Nitrogen isotopes

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Introduction

Historic studies show that from the end of the eighth century to the beginning of the thirteenth century, feudal lordship and parish networks were set up, initiating transformations in the economic and social structures of medieval Europe (Feller 2017). Recent years have seen a renewal of archeological data from South-East France (Languedoc region), revealing new information on how the mechanisms of this new organization impacted the region. Village formations (Schneider 2010; Maufras et al. 2014), the reorganization of the funeral space (Treffort 2006), and land occupation (Maufras 2015) or the intensification of agro-pastoral activities (Durand and Ruas 2004; Durand 2014) are some of the many ways the people of Languedoc experienced changes in social, economic, and cultural organizations. This reorganization probably also impacted on the daily lives of individuals. To determine how, identifying individual diets through isotopic analyses of bone collagen is particularly relevant.

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Individual food choices are the expression of biological (i.e. what a person can digest), cultural (i.e., what a person is authorized and/or chooses to eat), and economic (i.e. what a person can afford to eat) constraints. Therefore, through food choices, it is possible to approach all aspects (sex, age, wealth, religious doctrines) that can influence the daily lives of individuals and discuss the social and economic structure in which they find themselves. Similarly, isotopic analysis of bone collagen is also particularly interesting because it enables a discussion of nutrition at an individual level (Herrscher and Goude 2015) and, consequently, of the very fine variations in nutrition within a population and over time.

This method has already demonstrated its usefulness in identifying specific societal changes taking place in the early Middle Ages across Europe (e.g., Müldner 2009; Hakenbeck et al. 2010; Lightfoot et al. 2012; López-Costas and Müldner 2016; Kaupová et al. 2016; Olsen et al. 2018 Salazar-García et al. 2014a; Salazar-García et al. 2016; Guede et al. 2018). Our study focuses on the Missignac-Saint Gilles le Vieux site, whose occupation dated from the middle of the fifth to the early thirteenth century AD illustrating the modifications of settlement, agro-pastoral, and funerary practices taking place in South-East France during this period as described by historians. The presence of osteoarcheological material from both humans and non-human animals recovered at the site (Maufras et al. in press) provides the potential to assess (1) changes to dietary habits according to societal modifications occurring across time and (2) the relationships between biological characteristics and individual dietary choices.

Missignac-Saint Gilles le Vieux

Missignac-Saint Gilles le Vieux is a rural site in South-East France (Aimargues, Gard), ca. 15 km from the Mediterranean Sea. It is located on a coastal plain of the Languedoc region at the edge of two rivers, the Vidourle and the Cubelle (Fig. 1). Discovered in 1995 (Barberan et al. 1996; Maufras and Mercier 2002, 2006), extensive excavations were conducted in 2013 (Maufras et al. in press). Early medieval occupation occurred between the end of the fifth century and the beginning of the thirteenth century AD. Eight hundred fifty-two burials, as well as contemporaneous settlement structures and several hundred grain pits, were exca- vated. The site is divided into six phases numbered from 1 to 6 (Table 1), corresponding to different changes in the site's occupation (Maufras et al. in press).

Phase 1 corresponds to the beginning of the settlement, around the middle of the fifth century, characterized by small independent agricultural units organized around a major regional road, probably near a newly transformed or abandoned Roman villa. No burials dated to this phase have been

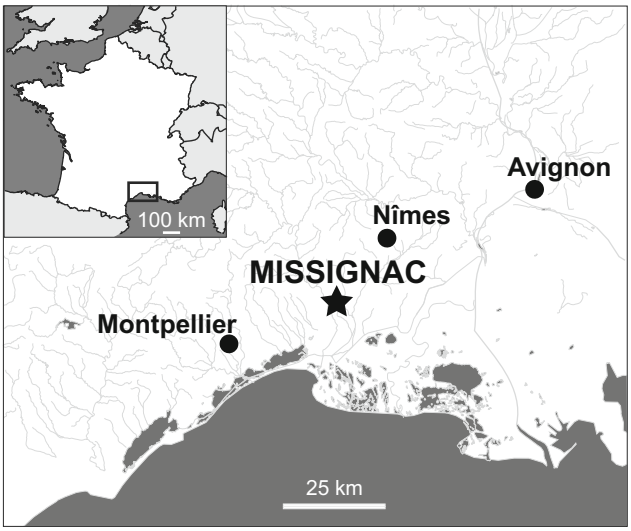

Fig. 1 Location of the site

identified. During phase 2, the settlement continued in a similar pattern. Around 20 graves were discovered dating to this phase. Phase 3 sees the settlement become denser with the cohabitation of several family units, each associated with a funerary area. During phase 4, the increase in density intensifies, and the settlement begins to tighten. At the end of the tenth century (end of phase 4A), a church is constructed, and the settlement slowly begins to reorganize itself around it. As for the funerary aspect, the small family areas of phase 3 continue to be used despite the set-up of an ecclesial cemetery south of the church. During phase 5, the settlement's density reaches a peak. At the same time, the ecclesial cemetery slowly becomes the main burial ground, certainly acquiring a parish status, but small secondary areas are still in use. Finally, phase 6 corresponds to the quick decline of the settlement despite the reconstruction of the church at the middle of the twelfth century. The site is abandoned at the beginning of the thirteenth century in favour of the near by *castra* Aimargues in a process of *incastellamento* (Maufras et al. 2014). Consequently, the funeral use is reduced. The burials are located directly above the western façade of the church and to the north of it, as the ecclesial cemetery continues in use.

Funeral practices are quite homogenous during the period of usage of the site. Pit burials constitute the best represented funerary architecture on the site but also within each phase. The use of stone and wood is anecdotal with only 4% of the tombs identified using stone outside the roofing and 1% having a wooden construction (Hernandez 2018; Maufras et al. in press). The other types of architecture consist of mixed forms, which combine the use of stone with wood and complete stone chests. The latter, which did not exist at the beginning of the funerary occupation, only became common during phases 5 and 6, and was concentrated in the enclosed cemetery to the south

Table 1 Chronological phases of the High Middle Ages occupation at Missignac-Saint Gilles le Vieux

Phase	Date (AD)	Settlement	Funerary areas
Phase 1	470–675	Small independent units	Not within the excavated area
Phase 2	675–850	Small independent units	Twenty burials along the road
Phase 3	850–925	Independent units Densification begins	An area for each settlement unit
Phase 4			
A	925–975	Grouping and densification—proto-village	Previous areas still in use New ones are created
B	975–1050	Construction of the church Spatial organization centered around church	Ecclesial cemetery installed south of the church Previous areas still largely in use
Phase 5			
A	1050–1075	Grouping and densification continue until a peak—village	Enclosed cemetery is the main funerary area Small areas still in use
B	1075–1125	Occupation of site continues at its peak	Cemetery extended into alleys at the east and west of the church
Phase 6			
A	1125–1175	Site begins to be abandoned Reconstruction of the church	Cemetery concentrated at the west of the church
B	1175–1200	Site continues to be abandoned	Cemetery begins to be abandoned

and along the western façade of the church. The dead appear stripped of their material possessions before being deposited in the tomb except for their clothes and, in some rare cases, a shroud. No ornaments or other accompanying accouterments have been discovered, compatible with the rules recommended by the Catholic Church (Hernandez 2018).

The 852 burials contained 900 individuals. The demographic structure of the population presents two anomalies. Firstly, there are few children present who died before reaching 1 year of age. The infants and young children identified have been discovered in areas reserved for them (Donat and Duchesne 2018). Secondly, the population shows a significant proportion of males. Indeed, they are 1.6 times more numerous than females. Identified males and females (328 adults) are spread all over the funeral sectors of the site. Therefore, the *sex ratio* does not seem to be associated to the presence of funeral areas reserved to females outside of the excavation site. The village could have welcomed, throughout its occupation or massively at a given time, a group of males devoted to the practice of one or more specific activities (Donat 2018). It is interesting to note that some of those males are distinguished by their high stature. The health status of the population reflects a generally unfavorable epidemiological context. There is a high frequency of individuals exposed to various chronic or acute diseases of infectious or nutritional origin such as tuberculosis or leprosy. The adult population is characterized by a high frequency of traumatic injuries, particularly fractures, which affect both males and females. Osteological data show that individuals have been highly exposed to repetitive biomechanical injuries and constraints, suggesting intense labor (Donat and Duchesne 2018).

The faunal study of the site reports that cattle (*Bos p. taurus*), pigs (*Sus scrofa domesticus*), and sheep (*Ovis aries*) and goat (*Capra a. hircus*), which form the *domestic triad*, represent the major sources of meat in the diet (Bardot-Cambot et al. 2018). Chicken (*Gallus gallus domesticus*) and probably equids (*Equus asinus* and *Equus ferus caballus*) were also consumed, but more anecdotally. Wild specimens are sparse, and marine shells are virtually non-existent despite the proximity to the sea. Cattle were slaughtered in adulthood: the older ones once their working lives were over (milking, reproduction), and the younger ones when they proved themselves unsuitable for certain tasks (locomotion difficulties, sterility of a female, violence of an animal). Sheep and goats were preferentially slaughtered after the age of 3. Most of the pigs were slaughtered before adulthood. All those species were raised locally (Bardot-Cambot et al. 2018), and the marsh near the site appears to have been exploited for grazing (Pradat 2018). Some fish remains have been retrieved. Most of the remains are from species living in freshwater environments (eel [*Anguilla anguilla*], northern pike [*Esox lucius*], European perch [*Perca fluviatilis*], cyprinids [*Cyprinidae*]; Cravinho 2018). Few marine species are also present (mullets [*Mugilidae*], flatfish [Pleuronectiformes], European bass [*Dicentrarchus labrax*]). The relatively small size of the fish discovered raises the issue of overfishing at the Missignac site during the beginning of the Middle Ages (Cravinho 2018).

Finally, agricultural production, as docu- mented by the preserved material, seems to be concentrated on wheat and barley with legumes (mainly lentils and vetches). Rye, oats, and millet are also present, but more anecdotally. Legumes (cloves, alfalfa, lentils) seem to have been used as fodder, just like barley (Pradat 2018).

Carbon and nitrogen isotope analyses for dietary reconstruction

Vertebrate bone tissue assimilates the carbon and nitrogen found in the diet. An isotopic fractionation in favor of the heavy isotope occurs during the incorporation of those elements in the collagen of bones. For nitrogen, the enrichment between $\delta^{15}N$ values of diet and collagen and between two consecutive trophic levels of the same trophic chain is comprised between 3 and 5‰ (DeNiro and Epstein 1981; Minagawa and Wada 1984) but can vary from 1 to 7‰ (O'Connell et al. 2012). For carbon, the enrichment between $\delta^{13}C$ values between diet and collagen is approximately of 5‰ but can vary accordingly to the quantity of proteins in the diet; indeed, $\delta^{13}C$ values of carbohydrate, fat, and protein are different (Ambrose and Norr 1993; Froehle et al. 2010; Fernandes et al. 2012). The variation in $\delta^{13}C$ values of collagen between two consecutive trophic levels of the same trophic chain is about 1‰ (Bocherens and Drucker 2003; Krajcarz et al. 2018). Therefore, the isotopic ratios of carbon and nitrogen ($\delta^{13}C$ and $\delta^{15}N$) measured in bone collagen reflect the isotopic values of dietary resources, mainly protein.

For both elements, plants at the base of the trophic chain condition the different isotopic ratios found throughout the food chain. Leguminous plants (*Fabaceae*) have isotopic nitrogen isotope values around 1‰ (Schoeninger and DeNiro 1984). The other plants have, on average, $\delta^{15}N$ values of 3‰ (Bocherens and Mariotti 2002). Environmental conditions and soil chemistry can influence these values. Aridity tends to increase $\delta^{15}N$ values, as well as some agricultural practices (manuring) (Bogaard et al. 2007; Fraser et al. 2011) or soil salinity (Virginia and Delwiche 1982; Britton et al. 2008). Non-nitrogen-fixing marine plants tend to have $\delta^{15}N$ values of around 7‰ (Schoeninger and DeNiro 1984). Physiology also impacts $\delta^{15}N$ values. Ruminants have, on average, higher $\delta^{15}N$ values than non-ruminants (Sponheimer et al. 2003) despite a relatively similar trophic level. Furthermore, individuals subject to hormonal (Fuller et al. 2004), pathological (Katzenberg and Lovell 1999; Olsen et al. 2014), or nutritional (Fuller et al. 2005; Mekota et al. 2006) stress may have $\delta^{15}N$ values that no longer reflect the trophic relationships of the ecosystems in which they live.

Trees, most plants from temperate and cold climates, and most aquatic plants follow the C_3 photosynthetic pathway that results in $\delta^{13}C$ values ranging from −36 to −22‰. Herbaceous plants like millet, sorghum, or sugarcane, in both temperate and warm environments, mostly follow the C_4 photosynthetic process resulting in $\delta^{13}C$ values ranging from −19 to −6‰ (Smith and Epstein 1971; DeNiro and Epstein 1978; Deines 1980; Boutton 1991). Plants' $\delta^{13}C$ values are also affected by carbon sources. Terrestrial plants use atmospheric CO_2 (−7‰ in pre-industrial times). Marine ones mainly use dissolved carbonate (0‰). Carbon for freshwater plants comes from both atmospheric CO_2 and dissolved bicarbonate or carbonate, as well as from organic carbon, very depleted in ^{13}C, from waste and decomposition products from plants and animals living in the water (DeNiro 1985; Farquhar et al. 1989; Dufour et al. 1999; Katzenberg and Weber 1999). In brackish and estuarine environments, the mix of fresh and marine waters results in lower $\delta^{13}C$ values than in marine ones but higher $\delta^{13}C$ than in terrestrial ones (Salazar-García et al. 2014b). Similarly, a *canopy effect* can affect isotope ratios and can result in significantly lower $\delta^{13}C$ values for plants from closed terrestrial environments compared to their counterparts from open ones (Farquhar et al. 1989; Heaton 1999). Finally, aridity, soil salinity, and physiological stress can result in higher $\delta^{13}C$ values (Tieszen 1991).

Material

In total, 152 human individuals were sampled, all adult (a proximal phalanx per individual from a hand HPP or from a foot FPP, Table 2). They were selected to form a corpus of as many males as females (males: $n = 77$, females: $n = 75$) and of individuals from all the chronological phases where funerary occupation is documented. The chronological phase and sex of the individuals sampled are given with their elemental and isotopic values in Table 2.

In addition, 75 faunal remains found in the storage pits area and the garbage dump of the settlement area have also been sampled. They consist of specimens from the domestic triad (cattle, sheep/goat, pig), from less common species (chicken, donkey, horse, dog [*Canis lupus familiaris*] and goose [*Anser* cf *anser*]), marine and freshwater fishes (mullets, eel, European perch, northern pike), and terrestrial wild animals (toad [*Bufo* cf *bufo*], deer [*Cervus* cf *elaphus*], rabbit [*Oryctolagus* cf *cuniculus*], and duck [*Anas* cf *platyrhynchos*]). Bone samples are only from adult specimens. The chronological phase, species, elemental, and isotopic values of the specimen sampled are given in Table 3.

Methods

Sex was determined using the probabilistic sexual diagnosis (PSD) method developed by Murail et al. (2005) and recently implemented in free software (Brůžek et al. 2017). This

Table 2 Results of carbon and nitrogen isotope analyses and collagen quality criteria of human samples

Lab code	Chronological phase	Sex	Age at death (years)	Phalanx type	Yield (%)	Carbon content (%)	Nitrogen content (%)	C/N	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
MISH001	5a	F	20–49	HPP	17.6	41.5	15.2	3.2	− 18.6	9.8
MISH002	3	F	≥40**	HPP	7.2	39.1	14.3	3.2	− 18.6	10.1
MISH003	5a	F	20–49	HPP	7.2	38.9	14.2	3.2	− 18.8	11.8
MISH004	3	F	20–49	HPP	14.8	40.9	15.1	3.2	− 19.0	11.2
MISH005	4a	F	≥50**	HPP	6.4	42.7	15.5	3.2	− 18.8	11.2
MISH006	3	M	40**	HPP	7.8	40.0	14.6	3.2	− 18.3	11.5
MISH007	4a	M	20–49	HPP	7.1	40.7	14.8	3.2	− 19.0	11.7
MISH008	5a–5b	M	20–49	HPP	10.9	42.2	15.3	3.2	− 18.9	9.0
MISH009	3	M	≥50**	HPP	8.3	42.3	15.0	3.3	− 18.9	9.5
MISH010	5a	F	≥40**	HPP	11.5	41.8	15.3	3.2	− 18.7	11.6
MISH011	3	F	≥30	HPP	10.6	41.3	15.1	3.2	− 18.6	10.6
MISH012	5a	F	20–39	HPP	8.9	38.7	14.2	3.2	− 19.0	9.8
MISH013	5b–6a	M	20–49	HPP	13.6	41.8	15.3	3.2	− 18.4	10.1
MISH014	5a–5b	F	20–29*	HPP	10.0	42.1	15.4	3.2	− 19.4	6.7
MISH015	3	M	20–29*	HPP	16.1	42.1	15.5	3.2	− 19.0	11.0
MISH016	3	F	≥40**	HPP	7.1	37.9	13.8	3.2	− 18.6	9.6
MISH017	5a	M	≥30	HPP	10.4	42.0	15.4	3.2	− 18.7	9.9
MISH018	*4a*	*M*	*20–29**	*HPP*	*3.9*	*5.5*	*1.9*	*3.3*	*− 19.4*	*8.9*
MISH019	6a	M	≥60**	HPP	15.5	41.7	15.2	3.2	− 18.9	10.7
MISH020	3	M	≥30	HPP	4.3	32.5	11.9	3.2	− 18.7	10.2
MISH021	3	M	20–29*	HPP	14.0	41.3	15.3	3.2	− 18.7	10.6
MISH022	3	F	≥30	HPP	12.5	42.1	15.3	3.2	− 19.1	8.5
MISH023	5a	F	≥30	HPP	8.9	40.5	14.9	3.2	− 18.8	10.2
MISH024	5b	M	≥40**	HPP	3.8	37.3	13.6	3.2	− 18.8	8.6
MISH025	4b	M	20–39	HPP	15.9	42.4	15.6	3.2	− 18.6	9.9
MISH026	3	F	20–29*	HPP	9.1	41.6	15.0	3.2	− 19.0	9.6
MISH027	5a	M	≥40**	HPP	10.5	41.4	15.1	3.2	− 19.0	10.6
MISH028	4b	M	≥40**	HPP	11.8	42.1	15.4	3.2	− 18.5	10.6
MISH029	5b	F	≥50**	HPP	12.9	41.4	15.2	3.2	− 18.5	9.7
MISH030	5b	F	20–49	HPP	8.5	39.0	14.2	3.2	− 17.8	11.3
MISH031	4b	M	≥40**	PP	5.5	39.5	14.2	3.3	− 18.9	9.6
MISH032	3	F	≥30	HPP	17.1	41.2	15.2	3.2	− 18.7	10.6
MISH033	3	F	≥30	HPP	14.5	41.9	15.4	3.2	− 18.7	10.0
MISH034	3	F	20–49	HPP	17.4	43.3	15.7	3.2	− 18.2	9.7
MISH035	3	F	20–29*	HPP	15.6	41.5	15.3	3.2	− 18.7	8.5
MISH036	3	F	20–49	HPP	4.0	40.5	14.7	3.2	− 18.6	9.9
MISH037	6a	F	20–49	HPP	11.0	41.6	15.3	3.2	− 18.5	10.1
MISH038	4a	F	≥40**	HPP	14.0	42.2	15.5	3.2	− 18.4	11.0
MISH039	3	F	≥30	HPP	16.4	42.3	15.5	3.2	− 18.8	10.0
MISH040	5b–6a	F	20–29*	HPP	15.2	43.0	15.7	3.2	− 18.8	8.8
MISH041	*5a*	*M*	*20–49*	*HPP*	*12.0*	*47.5*	*13.7*	*4.0*	*− 21.0*	*10.8*
MISH042	4a–4b	M	20–29*	HPP	10.6	41.7	15.3	3.2	− 18.8	9.9
MISH043	5b	F	20–29*	HPP	9.4	41.5	15.3	3.2	− 18.8	12.5
MISH044	5b	F	≥40**	HPP	7.2	38.1	14.0	3.2	− 19.0	11.3
MISH045	5a	F	≥30	HPP	15.9	42.7	15.7	3.2	− 18.9	11.7
MISH046	4a–4b	M	20–39	HPP	9.4	42.0	15.4	3.2	− 19.0	8.8
MISH047	3	M	20–39	HPP	6.0	38.4	14.2	3.2	− 18.5	10.3
MISH048	3	M	≥30	HPP	5.0	36.9	13.6	3.2	− 18.7	10.9
MISH049	5a	M	≥30	HPP	9.2	41.7	15.3	3.2	− 19.2	10.6
MISH050	3–4a	M	≥30	HPP	13.8	42.3	15.5	3.2	− 18.6	10.9
MISH051	3	M	≥30	HPP	5.7	40.3	14.8	3.2	− 18.8	10.6
MISH052	3	M	≥30	HPP	14.3	42.0	15.5	3.2	− 18.7	10.2
MISH053	3	F	20–49	HPP	16.3	42.5	15.5	3.2	− 18.9	9.4
MISH054	4b	F	≥30	HPP	9.8	40.9	15.0	3.2	− 18.9	9.2
MISH055	5a	F	20–29*	HPP	9.5	41.1	15.1	3.2	− 18.9	13.1
MISH056	5a	F	≥30	HPP	11.8	41.6	15.3	3.2	− 19.1	12.1
MISH057	4a	M	≥50**	HPP	17.6	43.2	15.9	3.2	− 18.9	9.6
MISH058	5a	F	≥30	HPP	11.0	41.1	15.1	3.2	− 18.9	11.5
MISH059	4a	M	≥30	HPP	8.1	39.9	14.7	3.2	− 19.0	7.7
MISH060	5a	F	30–59	HPP	15.1	41.4	15.1	3.2	− 18.9	11.2
MISH061	6a	M	≥30	HPP	16.9	41.8	15.3	3.2	− 18.9	11.9
MISH062	4a	F	≥40**	HPP	15.5	41.1	15.0	3.2	− 18.9	10.8
MISH063	4a–4b	M	20–29*	HPP	14.7	41.5	15.1	3.2	− 18.5	11.3

Table 2 (continued)

Lab code	Chronological phase	Sex	Age at death (years)	Phalanx type	Yield (%)	Carbon content (%)	Nitrogen content (%)	C/N	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
MISH064	5b	F	≥30	HPP	14.0	41.5	15.1	3.2	−18.6	10.1
MISH065	5b	M	20–49	HPP	4.5	37.8	13.7	3.2	−18.8	10.3
MISH066	3	F	20–49	HPP	10.5	40.1	14.5	3.2	−18.3	8.1
MISH067	3	M	≥30	HPP	13.6	41.4	15.1	3.2	−19.3	10.1
MISH068	4b	F	≥50**	HPP	8.1	34.2	12.6	3.2	−18.7	11.1
MISH069	*4a–4b*	*F*	*≥50***	*HPP*	*2.5*	*18.0*	*5.9*	*3.5*	*−20.9*	*9.5*
MISH070	4a	M	≥40**	HPP	13.7	42.0	15.3	3.2	−18.4	10.4
MISH071	4b	M	≥40**	HPP	15.9	42.7	15.4	3.2	−18.8	10.9
MISH072	*5b–6a*	*F*	*≥40***	*HPP*	*7.0*	*23.7*	*8.8*	*3.2*	*−18.6*	*9.7*
MISH073	3–4b	M	20–49	HPP	3.4	39.9	14.5	3.2	−18.6	10.7
MISH074	5b	M	20–39	HPP	15.3	42.5	15.5	3.2	−18.3	10.3
MISH075	3	F	20–49	HPP	15.4	41.6	14.8	3.3	−18.8	11.0
MISH076	5a	F	20–49	HPP	14.1	42.8	15.6	3.2	−18.4	10.4
MISH077	3	M	20–29*	HPP	8.9	39.3	14.2	3.2	−18.8	9.7
MISH078	3	M	≥30	HPP	7.8	40.9	14.9	3.2	−18.5	9.7
MISH079	3–4b	M	≥30	HPP	5.0	42.6	15.6	3.2	−18.5	9.0
MISH080	5b	M	≥30	HPP	19.0	41.3	15.1	3.2	−18.9	10.3
MISH081	3–4a	F	≥30	HPP	11.6	42.3	15.4	3.2	−18.6	10.3
MISH082	5a	F	20–49	HPP	11.0	41.8	15.1	3.2	−19.2	11.4
MISH083	3	M	≥40**	HPP	16.0	42.0	15.2	3.2	−19.2	9.5
MISH084	3	M	≥30	HPP	4.0	31.4	11.4	3.2	−18.2	10.3
MISH085	*3*	*F*	*20–49*	*HPP*	*4.5*	*2.8*	*0.8*	*3.9*	*−19.8*	*7.9*
MISH086	5b	M	20–29*	HPP	15.3	43.0	15.7	3.2	−18.8	9.1
MISH087	3–4a	M	≥40**	HPP	15.3	41.5	15.2	3.2	−18.8	11.7
MISH088	3–4b	M	≥30	HPP	6.5	41.3	15.0	3.2	−18.6	11.3
MISH089	3	F	≥40**	HPP	12.1	36.5	13.3	3.2	−18.6	9.3
MISH090	3	F	20–29*	HPP	10.6	36.2	13.1	3.2	−18.3	9.1
MISH091	3	F	≥30	HPP	6.4	37.5	13.5	3.2	−19.1	9.0
MISH092	5b	F	≥30	HPP	9.7	40.4	14.7	3.2	−18.3	9.1
MISH093	3–4b	M	≥50**	HPP	9.1	41.2	15.0	3.2	−18.5	10.8
MISH094	3–4b	M	20–49	HPP	10.3	40.6	14.8	3.2	−18.7	9.6
MISH095	3–4b	F	20–49	HPP	11.2	41.2	15.0	3.2	−18.8	9.7
MISH096	3	M	30–59	HPP	12.5	41.3	15.1	3.2	−18.8	9.6
MISH097	3	M	≥30	HPP	13.1	41.2	15.1	3.2	−18.7	9.8
MISH098	3	M	≥30	HPP	15.1	41.8	15.3	3.2	−18.5	9.6
MISH099	3	F	20–29*	HPP	2.9	33.3	12.1	3.2	−18.4	9.2
MISH100	3	M	≥60**	HPP	10.6	39.5	14.5	3.2	−18.8	8.4
MISH101	3–4b	M	20–49	HPP	13.7	41.8	15.2	3.2	−18.8	9.2
MISH102	3	M	≥50**	HPP	15.9	40.5	14.9	3.2	−18.7	9.9
MISH103	6a	F	20–29*	FPP	7.5	40.6	14.8	3.2	−18.9	9.9
MISH104	3	F	20–39	HPP	13.7	40.9	15.1	3.2	−18.7	10.1
MISH105	3	M	20–49	HPP	15.3	42.9	15.7	3.2	−18.4	8.8
MISH106	3	F	≥30	HPP	11.4	40.3	14.7	3.2	−19.1	10.1
MISH107	3	M	≥40**	HPP	17.1	41.6	15.3	3.2	−18.8	9.6
MISH108	3	F	20–49	HPP	15.8	42.0	15.4	3.2	−18.5	10.6
MISH109	4b	F	20–29*	HPP	11.4	41.0	15.1	3.2	−18.7	8.5
MISH110	3	F	20–29*	HPP	17.4	41.7	15.3	3.2	−18.8	9.0
MISH111	3	M	20–29*	HPP	15.7	41.9	15.4	3.2	−18.9	9.3
MISH112	3	M	20–49	HPP	8.7	39.3	14.4	3.2	−18.7	10.4
MISH113	3	F	20–49	HPP	4.0	32.6	11.9	3.2	−18.9	8.6
MISH114	3	F	20–49	HPP	10.8	40.4	14.8	3.2	−18.9	10.2
MISH115	4b	M	≥40**	HPP	16.7	40.6	14.9	3.2	−19.1	10.3
MISH116	5a	F	20–49	HPP	6.9	40.1	14.7	3.2	−19.0	10.6
MISH117	4a–4b	M	≥40**	HPP	19.7	42.0	15.3	3.2	−18.8	11.4
MISH118	3	M	20–39	HPP	9.1	40.8	15.0	3.2	−18.3	9.0
MISH119	5b	M	≥40**	HPP	14.8	40.7	14.9	3.2	−19.6	8.3
MISH120	3–4b	F	≥30	HPP	14.7	42.0	15.3	3.2	−18.8	9.7
MISH121	*4a–4b*	*F*	*≥50***	*HPP*	*3.7*	*28.7*	*9.7*	*3.4*	*−19.5*	*10.8*
MISH122	3	F	20–29*	HPP	11.9	41.9	15.3	3.2	−18.8	9.4
MISH123	3	M	≥40**	HPP	13.4	42.3	15.5	3.2	−18.4	10.4
MISH124	5b	F	≥30	HPP	8.8	40.3	14.8	3.2	−20.1	10.7
MISH125	5b	F	20–49	HPP	9.4	40.9	14.9	3.2	−18.5	11.2
MISH126	3	F	≥60**	HPP	14.0	41.3	15.0	3.2	−18.8	10.4

Table 2 (continued)

Lab code	Chronological phase	Sex	Age at death (years)	Phalanx type	Yield (%)	Carbon content (%)	Nitrogen content (%)	C/N	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
MISH127	5b	M	20–39	HPP	8.3	41.3	15.1	3.2	− 18.7	10.4
MISH128	3	F	≥ 30	HPP	12.5	40.7	14.9	3.2	− 19.5	8.6
MISH129	3	M	≥ 30	HPP	6.8	39.6	14.4	3.2	− 18.9	9.9
MISH130	3	M	20–29*	HPP	6.2	37.2	13.6	3.2	− 18.5	10.4
MISH131	5b	F	≥ 30	HPP	10.9	39.0	14.2	3.2	− 18.6	10.7
MISH132	5b	M	20–49	HPP	12.7	41.4	15.1	3.2	− 19.0	11.4
MISH133	3	M	≥ 30	HPP	13.4	41.5	15.1	3.2	− 18.7	10.4
MISH134	5b	F	≥ 50**	HPP	10.4	41.7	15.2	3.2	− 18.4	10.5
MISH135	3	F	≥ 30	HPP	19.2	39.5	14.5	3.2	− 18.7	10.0
MISH136	5b	F	≥ 30	HPP	13.4	40.3	14.8	3.2	− 19.0	10.4
MISH137	3	M	20–49	HPP	2.3	34.9	12.8	3.2	− 18.5	8.9
MISH138	4a	M	≥ 40**	HPP	5.6	33.7	12.3	3.2	− 18.6	12.1
MISH139	4a	M	≥ 30	HPP	10.9	40.1	14.7	3.2	− 18.5	10.6
MISH140	5b	M	20–29*	HPP	6.8	40.6	14.9	3.2	− 18.7	10.8
MISH141	5b	M	20–49	HPP	16.2	41.3	15.2	3.2	− 19.5	8.5
MISH142	4a	F	≥ 30	HPP	11.5	41.5	15.2	3.2	− 19.0	9.8
MISH143	2	F	≥ 30	HPP	3.7	39.5	14.3	3.2	− 18.8	10.6
MISH144	4b	F	≥ 30	HPP	14.0	41.1	15.1	3.2	− 18.4	11.0
MISH145	5a–5b	M	≥ 50**	HPP	10.7	40.9	15.0	3.2	− 18.9	10.1
MISH146	4a	F	≥ 30	HPP	12.3	41.1	15.2	3.2	− 19.2	12.1
MISH147	5a	M	20–49	HPP	15.3	39.9	14.7	3.2	− 18.9	11.4
MISH148	5a	F	20–49	HPP	16.1	41.2	15.2	3.2	− 18.9	8.3
MISH149	4b–5a	M	≥ 40**	HPP	11.6	41.6	15.3	3.2	− 19.1	10.9
MISH150	4b	M	≥ 30	HPP	16.7	41.3	15.2	3.2	− 18.8	10.9
MISH151	5a	M	≥ 30	HPP	6.9	38.0	14.2	3.1	− 18.7	10.8
MISH152	5a	M	≥ 30	HPP	6.3	35.5	13.2	3.1	− 19.2	11.7

Samples in italic fall out with van Klinken (1999) conservation criteria and are not considered in the discussion

F female, *M* male, *HPP* hand proximal phalanx, *FPP* foot proximal phalanx, *PP* undetermined proximal phalanx

*The "20–39" age class

**The "≥ 40" age class

method is based on ten metric variables measured on the coxae and allows sex estimation even on incomplete bones (Brůžek et al. 2017).

Age of death was estimated according to methods of Schmitt (2005) and Owings Webb and Suchey (1985). Two age groups were used to estimate the relationship between age at death and diet: the class "20–39" regrouping the individuals aged of 20–29 years and 20–39 years and the class "more than 40" regrouping the individuals aged of more than 40 years old including more than 50 and more than 60 (≥ 40: $n = 38$, 20–39: $n = 30$, Table 2).

Human and non-human animal bone collagen was extracted at the LAMPEA laboratory (UMR 7269, Aix-en-Provence, France). The bone samples were first cleaned by a sandblasting technique. Then, the mammalian (including humans) and avian bone samples were pre-treated using the protocol described by Longin (1971) and modified by Bocherens et al. (1991) (see Mion et al. 2016 for details). Fish bone samples were pre-treated using the protocol described by Richards and Hedges (1999) adding an ultrafiltration step (> 30-kDa Amicon ultrafilters; Brown et al. 1988). This protocol is less aggressive and more suitable for fragile fish bones (Szpak 2011; Sealy et al. 2014).

The carbon and nitrogen isotope ratio measurements were performed in the isotope facilities at the University of Cape Town (South Africa), using a Finnigan Delta plus XP continuous-flow isotope ratio mass spectrometer (Thermo Fisher Scientific, USA) after being combusted in the elemental analyzer Flash EA 1112 interfaced with it (Thermo Fisher Scientific, USA). Repeated analysis of three internal standards ("Merk Gelatin," "Valine," and "Seal Bone") determined an analytical error inferior to 0.01‰ for $\delta^{13}C$ and $\delta^{15}N$.

For each sample, the extraction yield of collagen, the elemental composition of carbon and nitrogen, and the atomic ratio (C/N) were measured. These values were compared to the published ranges for well-preserved collagen in order to assess the samples' extracted collagen quality and the reliability of the isotopic data produced from each sample (more than 1% collagen yield, between 30 and 45% of carbon content, between 11 and 16% of nitrogen content, and C/N ratio between 2.9 and 3.6) (DeNiro 1985; Van Klinken 1999). The absence of correlation between those criteria and $\delta^{13}C$ and $\delta^{15}N$ values was also verified.

Table 3 Results of carbon and nitrogen isotope analyses and collagen quality criteria of faunal samples

Lab code	Species	Anatomical element	Data	Yield (%)	Carbon content (%)	Nitrogen content (%)	C/N	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
MIS F01	Goat	Tibia	4–6	8.0	40.4	14.8	3.2	− 19.0	5.7
MIS F02	Equid	Mandible	4–6	2.4	33.4	12.5	3.1	− 17.6	6.0
MIS F03	Sheep	Radius	4–6	8.1	39.5	14.7	3.1	− 21.0	5.5
MIS F04	Pig	Tibia	4–6	12.0	40.2	14.9	3.2	− 19.9	7.6
MIS F05	Cattle	Radius	2–6	10.6	41.9	15.3	3.2	− 20.5	5.1
MIS F06	Chicken	Ulna	4–6	16.5	42.3	15.4	3.2	− 19.6	10.1
MIS F07	Sheep	Femur	2–3	5.3	38.9	14.3	3.2	− 20.3	3.8
MIS F08	*Equid*	*Metatarsus*	*2–3*	*2.0*	*22.6*	*8.4*	*3.1*	*− 21.9*	*5.9*
MIS F09	Goat	Radius	2–3	16.4	42.0	15.4	3.2	− 19.4	4.2
MIS F10	Deer	Metatarsus	2–3	7.0	39.4	14.5	3.2	− 20.1	4.4
MIS F11	Pig	Tibia	2–3	10.9	42.4	15.5	3.2	− 20.0	6.9
MIS F12	Chicken	Tibiotarsus	2–3	12.7	41.1	15.0	3.2	− 19.1	10.1
MIS F13	Goat	Radius	2–6	13.0	40.8	14.9	3.2	− 19.4	6.7
MIS F14	Sheep	Metacarpus	2–6	9.9	40.0	14.7	3.2	− 20.2	5.9
MIS F15	Sheep	Tibia	4–6	3.7	40.7	14.9	3.2	− 19.5	7.5
MIS F16	Cattle	Metatarsus	4–6	12.2	40.8	15.0	3.2	− 19.0	8.6
MIS F17	*Sheep*	*Tibia*	*4–6*	*2.4*	*31.6*	*10.6*	*3.5*	*− 19.8*	*8.1*
MIS F18	*Equid*	*Metapod*	*4–6*	*3.0*	*26.9*	*10.2*	*3.1*	*− 19.8*	*6.1*
MIS F19	Cattle	Tibia	2–6	3.7	31.0	11.4	3.2	− 19.1	8.6
MIS F20	Pig	Femur	2–6	10.8	39.3	14.3	3.2	− 19.9	6.2
MIS F21	Rabbit	Tibia	2–6	7.1	37.5	13.7	3.2	− 20.9	3.7
MIS F22	Equid	Radius	2–6	9.5	39.8	14.6	3.2	− 19.0	6.2
MIS F23	Cattle	Radius	2–6	10.5	39.8	14.5	3.2	− 19.8	8.6
MIS F24	Pig	Radius	2–6	9.5	38.3	14.0	3.2	− 20.0	8.7
MIS F25	Sheep	Tibia	2–6	2.6	30.6	11.1	3.2	− 19.1	7.7
MIS F26	Northern pike	Vertebrae	4–6	3.6	36.9	13.4	3.2	− 21.1	8.7
MIS F27	European perch	Vertebrae	4–6	–					
MIS F28	Mullet	Vertebrae	4–6	–					
MIS F29	Eel	Vertebrae	4–6	4.3	41.0	15.4	3.1	− 21.3	10.8
MIS F30	Donkey	Tibia	2–6	6.1	41.4	14.9	3.2	− 20.7	6.4
MIS F31	Deer	Coxal	2–6	12.3	40.9	15.0	3.2	− 20.4	4.5
MIS F32	Cattle	Mandible	2–6	7.8	38.2	14.1	3.2	− 18.5	8.4
MIS F33	Sheep	Tibia	2–6	8.3	35.0	12.9	3.2	− 19.7	7.2
MIS F34	Dog	Tibia	2–6	4.7	40.3	14.6	3.2	− 18.4	9.4
MIS F35	Sheep	Tibia	2–6	6.3	38.2	14.1	3.2	− 20.1	8.9
MIS F36	Chicken	Coracoid	2–6	15.1	40.7	14.9	3.2	− 19.3	9.1
MIS F37	Cattle	Tibia	2–6	8.8	40.1	14.6	3.2	− 18.6	5.3
MIS F38	*Equid*	*Humerus*	*4–6*	*3.6*	*23.5*	*8.6*	*3.2*	*− 21.9*	*7.6*
MIS F39	Pig	Tibia	4–6	13.3	41.4	14.9	3.2	− 20.3	4.8
MIS F40	Cattle	Radius	4–6	7.3	38.8	14.2	3.2	− 19.1	7.4
MIS F41	*Cattle*	*Tibia*	*2–3*	*2.1*	*19.4*	*7.2*	*3.2*	*− 19.8*	*8.1*
MIS F42	Cattle	Femur	2–3	7.1	40.1	14.6	3.2	− 20.0	4.9
MIS F43	Pig	Ulna	2–3	10.8	41.2	15.0	3.2	− 19.9	6.5
MIS F44	Donkey	Radius	2–3	7.6	40.0	14.6	3.2	− 19.8	7.6
MIS F45	Sheep	Tibia	2–3	4.6	40.2	14.5	3.2	− 20.0	5.9
MIS F46	Cattle	Femur	4–6	11.5	40.6	14.9	3.2	− 20.6	4.1
MIS F47	Mullet	Vertebrae	4–6	3.6	41.7	15.1	3.2	− 11.4	15.9
MIS F48	Northern pike	Vertebrae	4–6	3.5	42.1	15.4	3.2	− 24.6	8.7

Table 3 (continued)

Lab code	Species	Anatomical element	Data	Yield (%)	Carbon content (%)	Nitrogen content (%)	C/N	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
MIS F49	Duck	Humerus	4–6	16.3	41.8	14.7	3.3	− 23.6	7.8
MIS F50	Sheep	Ulna	4–6	13.8	42.1	15.3	3.2	− 20.7	5.4
MIS F51	Eel	Vertebrae	4–6	7.1	41.6	15.3	3.2	− 24.4	7.8
MIS F52	Cattle	Metatarsus	4–6	9.7	39.4	14.5	3.2	− 18.9	9.9
MIS F53	*Cattle*	*Metacarpus*	*4–6*	*2.3*	*28.9*	*9.7*	*3.5*	*− 19.8*	*8.8*
MIS F54	Cattle	Mandible	4–6	5.9	37.9	13.8	3.2	− 19.5	8.1
MIS F55	Pig	Tibia	4–6	4.4	39.4	14.4	3.2	− 20.1	6.2
MIS F56	Sheep	Tibia	2–3	13.9	41.8	15.3	3.2	− 20.7	7.8
MIS F57	Pig	Humerus	2–3	9.1	39.4	14.4	3.2	− 20.6	6.7
MIS F58	Chicken	Radius	2–3	16.2	41.6	15.0	3.2	− 18.2	10.8
MIS F59	Pig	Fibula	2–3	11.1	40.6	14.8	3.2	− 19.1	6.2
MIS F60	Cattle	Humerus	2–3	13.5	41.9	15.2	3.2	− 19.0	10.1
MIS F61	Chicken	Humerus	2–3	12.4	38.4	14.0	3.2	− 19.0	7.8
MIS F62	Goat	Phalanx	4–6	18.3	41.1	15.2	3.2	− 20.8	10.3
MIS F63	Sheep	Tibia	4–6	5.6	36.3	13.1	3.2	− 20.9	5.5
MIS F64	*Pig*	*Ulna*	*4–6*	*8.9*	*29.4*	*10.8*	*3.2*	*− 20.8*	*7.0*
MIS F65	Chicken	Humerus	4–6	13.5	40.6	14.7	3.2	− 18.8	9.5
MIS F66	Pig	Tibia	4–6	14.5	42.4	15.4	3.2	− 19.8	6.5
MIS F67	Toad	Ilion	4–6	6.7	42.6	15.6	3.2	− 19.6	7.3
MIS F68	Pig	Femur	4–6	7.7	40.1	14.6	3.2	− 19.9	8.4
MIS F69	*Chicken*	*Femur*	*4–6*	*2.8*	*26.7*	*9.9*	*3.1*	*− 19.1*	*9.5*
MIS F70	*Horse*	*Phalanx*	*2–3*	*3.9*	*12.6*	*4.7*	*3.1*	*− 20.9*	*7.7*
MIS F71	*Cattle*	*Tibia*	*2–3*	*2.4*	*27.9*	*10.3*	*3.2*	*− 20.9*	*7.2*
MIS F72	Sheep	Humerus	2–3	7.4	40.5	14.8	3.2	− 20.2	4.9
MIS F73	Sheep	Metacarpus	2–3	15.6	40.7	14.9	3.2	− 20.1	8.1
MIS F74	Goose	Femur	2–3	16.1	41.3	15.1	3.2	− 18.8	7.6
MIS F75	Pig	Femur	2–3	5.4	41.0	14.8	3.2	− 19.5	6.6

Samples in italic fall out with van Klinken (1999) conservation criteria and are not considered in the discussion

Correlations were tested using the Spearman test (Monte Carlo simulation with a level of accepted significance: $p < 0.05$ and $R^2 > 0.5$). Differences between groups were tested with the exact Mann-Whitney and Kruskal-Wallis tests (Monte Carlo simulation, 1,000,000 replications, level of accepted significance: $p < 0.05$). The difference of variance between groups was tested with the Levene test. All the statistical tests were conducted on ©R (version 3.3.1) Rcmdr 2.3-0 with the Coin package. The statistical information for every test performed is given in the Supplementary Material.

Results and discussion

Collagen preservation

Collagen was extracted from 225 of the 227 bone samples. Unfortunately, the extraction for two fish bone samples (MISF27, MISF28) was not successful. Yields range from 1.9 to 19.7%, carbon contents range from 2.8 to 47.5%, nitrogen contents range from 0.8 to 15.9%, and C/N ratios range from 3.1 to 4.0 (median [first/third quartiles], yield = 11.1 [8.0/14.7], carbon contents = 41.2 [39.9/41.8], nitrogen contents = 15.1 [14.5/15.3], C/N ratios = 3.2 [3.2/3.2], $n = 225$). Sixteen samples have values not in accordance with the abovementioned preservation recommendations and were therefore excluded from the discussion (six human and ten faunal samples, Tables 2 and 3). For the remaining 209 samples, yields and elemental values (carbon and nitrogen content, C/N ratios) are not correlated with the isotopic values (Spearman tests $p > 0.05$). Isotopic information is therefore considered as non-degraded and unaltered.

Faunal data and exploitation of local environments

Isotopic values for all faunal specimens are listed in Tables 3 and 4 and illustrated in Fig. 2. The $\delta^{13}C$ values

of the faunal samples range from − 24.6 to − 11.4‰ and their $\delta^{15}N$ values from 3.7 to 15.9‰ ($\delta^{13}C$ = − 19.8 [− 20.3/− 19.1], $\delta^{15}N$ = 7.3 [5.8/8.6], n = 63, Tables 3 and 4). This variability is explained by the presence of specimens from three different ecosystems: marine, freshwater, and terrestrial (Fig. 2).

The marine ecosystem is represented by the mullet ($\delta^{13}C$ = − 11.4‰, $\delta^{15}N$ = 15.9‰). Its values are in accordance with the published values for specimens of ancient or medieval fish from the Mediterranean coasts (Table 5).

$\delta^{13}C$ values of the two eels and two northern pikes range from − 24.6 to − 21.1‰ and their $\delta^{15}N$ values from 7.8 to 10.8‰ (Fig. 2). They are consistent with published values for freshwater fish in Europe (Dufour et al. 1999; Fuller et al. 2012; Häberle et al. 2016; Colleter et al. 2017). The duck's isotopic values fall in the same range and suggest a common habitat ($\delta^{13}C$ = − 23.6‰, $\delta^{15}N$ = 7.8‰, Fig. 2). Considering the surrounding freshwater environment around the site, those specimens are likely to be local.

Terrestrial animal $\delta^{13}C$ values range from − 21.0 to − 17.6‰, and their $\delta^{15}N$ values range from 3.7 to 10.8‰ ($\delta^{13}C$ = − 19.8 [− 20.2/− 19.1], $\delta^{15}N$ = 6.9 [5.7/8.4], n = 58, Fig. 2). One equid specimen shows a remarkable value of − 17.6‰ (MIS F02) according to the variation of $\delta^{13}C$ values for the other terrestrial animals, ranging from − 21.0 to − 18.2‰. This equid specimen seems to have a significant proportion of C_4 plants in its diet in complement to C_3 plants, probably millet as it is the only domesticated C_4 plant in Europe for medieval times. The $\delta^{13}C$ values of the other animals are consistent with diet where C_3 plants are dominant (Schoeninger and DeNiro 1984). The range of their $\delta^{15}N$ values reflects the presence of several trophic levels.

The isotopic values of the four wild herbivores (rabbit, deer) range from − 20.9 to − 20.1‰ for $\delta^{13}C$ values and from 3.7 to 4.4‰ for the $\delta^{15}N$ values (Table 4). They have the lowest isotopic values of carbon and nitrogen in the corpus of terrestrial animals as the exception of two sheep (Fig. 2). Feeding in a closed environment like the Mediterranean

Table 4 Summary of the $\delta^{13}C$ and $\delta^{15}N$ values of the different faunal species

	Number	$\delta^{13}C$ (‰)			$\delta^{15}N$ (‰)		
		Min	Max	Median [IIQ][a]	Min	Max	Median [IIQ][a]
Duck	1	− 23.6			7.8		
Eel	2	− 24.4	− 21.3		7.8	10.8	
Northern pike	2	− 24.6	− 21.1		8.7	8.7	
Mullet	1	− 11.4			15.9		
Goose	1	− 18.8			7.6		
Toad	1	− 19.6			7.3		
Dog	1	− 18.4			9.4		
Rabbit	1	− 20.9			3.7		
Deer	2	− 20.4	− 20.1		4.4	4.5	
Equid	2	− 19.0	− 17.6		6.0	6.2	
Donkey	2	− 20.7	− 19.8		6.4	7.6	
Goat	4	− 20.8	− 19.0		4.2	10.3	
Chicken	6	− 19.6	− 18.2	− 19.1	7.8	10.8	10.8
Pig	12	− 20.6	− 19.1	− 19.9 [− 20.1/− 19.8]	4.8	8.7	6.6 [6.2/7.1]
Cattle	12	− 20.6	− 18.5	− 19.1 [− 19.8/− 18.9]	4.1	10.1	8.3[5.3/8.6]
Terrestrial	3	− 20.6	− 20.0		4.1	5.1	
Lagoon	9	− 19.8	− 18.5	− 19.0	5.3	10.1	8.6
Sheep	13	− 21.0	− 19.1	− 20.2 [− 20.7/− 20.0]	3.8	8.9	6.5 [5.5/7.7]
Terrestrial	8	− 21.0	− 20.2	− 20.7	3.8	7.8	5.5
Lagoon	6	− 20.1	− 19.1	− 19.9	5.9	8.9	7.6
Domestic triad [b]	41	− 21.0	− 18.5	− 19.9 [− 20.2/− 19.4]	3.8	10.3	6.7 [5.5/8.1]
Phases 2–3	13	− 20.7	− 19.0	− 20.0 [− 20.2/− 19.5]	3.8	10.1	6.5 [4.9/6.9]
Phases 4–6	16	− 21.0	− 18.9	− 19.9 [− 20.6/− 19.4]	4.1	10.3	7.0 [5.5/8.2]
Total	63	− 24.6	− 11.4	− 19.1 [− 20.3/− 19.1]	3.7	15.9	7.5 [5.8/8.6]

[a] IIQ: first/third quartiles; median is provided when n is ≥ 5 and IIQ is provided when n is ≥ 10

[b] Domestic triad: cattle, and pig

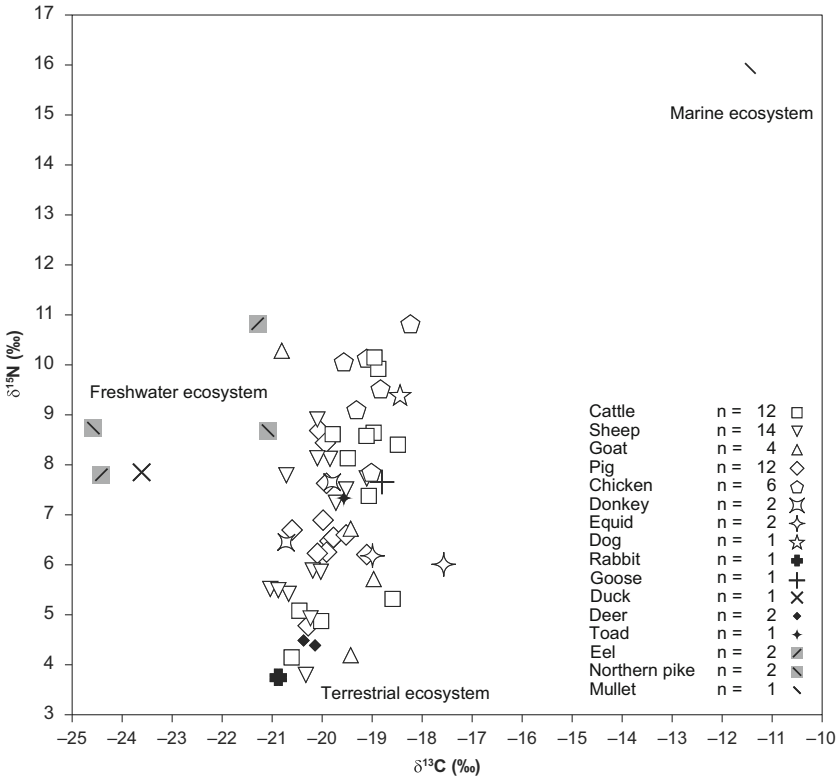

Fig. 2 Isotopic values for the faunal specimens

forests, with a low nutrient intake, is probably the source of these values (Makarewicz and Tuross 2006). The toad's values are consistent with an insectivore diet from the same habitat ($\delta^{13}C = -19.6‰$, $\delta^{15}N = 7.3‰$).

The chickens and the dog have $\delta^{13}C$ values ranging from −19.6 to −18.2‰ and $\delta^{15}N$ values ranging from 7.8 to 10.8‰. Those values are enriched compared to those of herbivorous specimen. This enrichment is coherent with a trophic enrichment, and as the isotopic values of chickens are comparable to those of human, a diet based on human wastes is likely (Fig. 3).

The pigs have lower $\delta^{13}C$ and $\delta^{15}N$ values than the chickens and dog ($\delta^{13}C = -19.9$ [−20.1/−19.8], $\delta^{15}N = 6.6$ [6.2/7.1], $n = 12$, Table 4, Fig. 2). They are comparable to those of domestic herbivores (cattle, sheep, goat, equids, goose), which range from −21.0 to −17.6‰ for $\delta^{13}C$ values and from 3.8 to 10.3‰ for $\delta^{15}N$ values ($\delta^{13}C = -19.7$ [−20.3/−19.0], $\delta^{15}N = 6.9$ [5.5/8.1], $n = 34$). Pigs seem, as a consequence, to have more plant input in the diet than chickens and dog. Historical sources attest that, in French medieval times, pigs had a mostly vegetal diet and were often brought into the forest where they fed on acorns, mushrooms, and occasionally, small animals (Audoin-Rouzeau 1998).

The isotopic values of the goat and equid specimens are noticeable for their great variability, which suggests different diets for each specimen, some of which are not consistent with

Table 5 Values of the ancient and medieval Mediterranean marine fish from the bibliography

		$\delta^{13}C$ (‰)			$\delta^{15}N$ (‰)		
		Min	Max	Median[a]	Min	Max	Median[a]
Craig et al. (2009)	$n = 4$	−14.9	−12.6		9.1	12.1	
Craig et al. (2013)	$n = 5$	−15.4	−13.9	−14.5	8.5	5.7	6.6
Lightfoot et al. (2012)	$n = 1$	−11.0			8.2		
Keenleyside et al. (2009)	$n = 2$	−11.8	−10.2		7.8	10.4	
Pennycook (2008)	$n = 2$	−12.1	−10.4		10.2	15.8	
Carlier et al. (2014)	$n = 4$	−12.5	−13.8		9.9	12.1	
Alexander et al. (2015)	$n = 6$	−11.4	−9.4	−11.0	8.1	12.6	10.2

[a] Statistical parameters are provided when n is ≥ 5

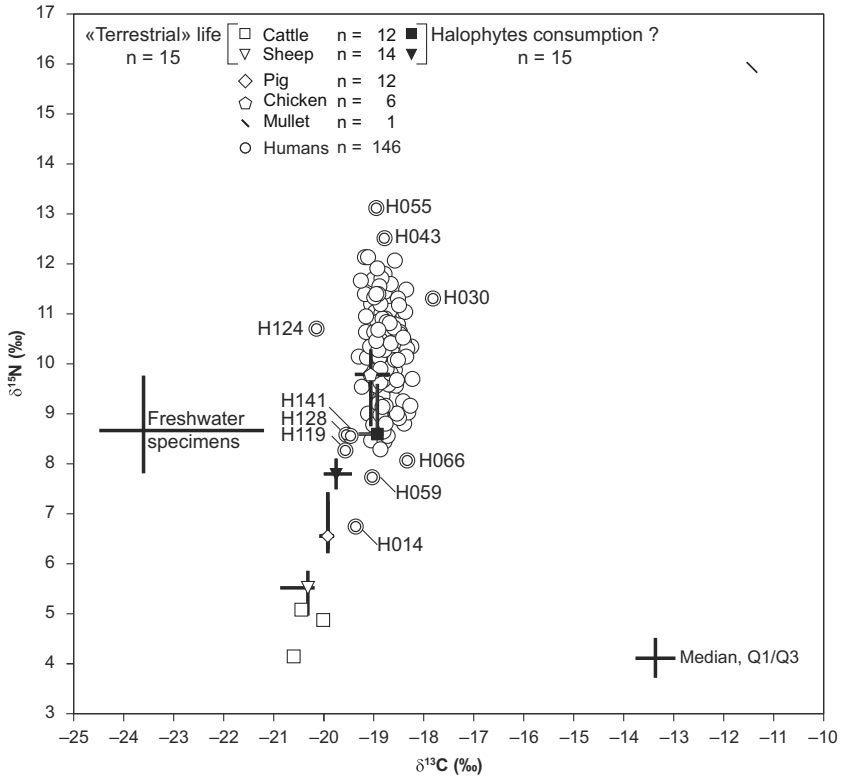

Fig. 3 Human individual isotopic values compared to median isotopic values of main animal resources (human outliers are highlighted)

the biotopes characterized by the other herbivorous sampled (Fig. 2). Those specimens could have been coming from a distant area, as hypothesized by archaeozoologists. Equids are indeed supposed to come from a different area used as transport for human traveling (Bardot-Cambot 2018). Sheep and cattle can be separated into two groups based on their isotopic values. One group appears to have high carbon and nitrogen values, which may indicate a consumption of C_3 halophyte plants (Fig. 2) (Britton et al. 2008; Müldner et al. 2014). Those plants are documented in the Languedoc Mediterranean coast and are especially numerous in the Camargue area (Braun-Blanquet et al. 1952; Géhu et al. 1992; Médail 1994). The other group has lower $\delta^{13}C$ and $\delta^{15}N$ values which are representative of a C_3 open-area plant consumption.

In summary, the great variability of animal values attests to the presence at the site of animals that lived in numerous biotopes. Wild animals were hunted probably from the forest near to the site. Fish came from the Mediterranean Sea and local freshwater rivers or lakes. Most of the domestic animals lived in a terrestrial habitat, although some cattle and sheep suggest the exploitation of coastal plains for breeding. The territory of Missignac would have been of around 750 ha (Maufras et al. in press) and would not have contained all the biotopes characterized by the isotopic values (i.e., coastal and marine), demonstrating that animal supply was not solely local at the site and confirms a carpology study of the marsh exploitation (Pradat 2018). The individual specific values of some goats and equids are unique in the species groups and in the domestic groups, and therefore,show an individual-specific diet. This could also be related to a medium- to long-distance animal supply for those species. Isotopic values of the domestic animals highlight also specific species-breeding practices for chicken and pigs. Pigs had an outdoor life as recorded in other medieval isotopic studies (Hamilton and Thomas 2012; Hammond and O'Connor 2013). Chicken had a diet mostly based on human waste that supposed a more constrained habitat.

Transformation of human isotopic signal over time

Isotopic values for all human specimens are listed in Tables 2 and 6 and illustrated in Figs. 3 and 4. Humans' $\delta^{13}C$ values range from −20.2 to −17.8‰, and their $\delta^{15}N$ values range from 6.7 to 13.1‰ ($\delta^{13}C$ = −18.8 [−18.9/−18.6], $\delta^{15}N$ = 10.2 [9.6/10.8], n = 146, Tables 2 and 6). Ten individuals show $\delta^{13}C$ or $\delta^{15}N$ values outside the variability of the whole population: H014, H030, H043, H055, H059, H066, H119, H124, H128, and H141 (> ± 2 SD from the mean, Fig. 3). Excluding the outliers, the $\delta^{13}C$ values for humans range from −19.3 to −18.2‰, and their $\delta^{15}N$ values

Table 6 Summary of the isotopic values for humans according to chronological phases and biological criteria: sex and age at death

	Number	$\delta^{13}C$ (‰)				$\delta^{15}N$ (‰)			
		Min	Max	Median [IIQ][a]	Mean ± SD[b]	Min	Max	Median [IIQ][a]	Mean ± SD[b]
Chronological phases									
Phase 2	1	−18.8				10.6			
Phase 3	58	−19.5	−18.2	−18.7 [−18.9/−18.5]	−18.7 ± 0.3	8.1	11.5	9.9 [9.3/10.4]	9.8 ± 0.8
Phase 3/4	11	−18.8	−18.5	−18.6 [−18.8/−18.6]		9.0	11.7	10.3 [9.6/10.9]	
Phases 4 to 6									
Phase 4	25	−19.2	−18.4	−18.8 [−18.9/−18.6]	−18.8 ± 0.2	7.7	12.1	10.6 [9.8/11.1]	10.4 ± 1.1
Phase 4/5	1	−19.2				10.9			
Phase 5	44	−20.1	−17.8	−18.9 [−19.0/−18.7]	−18.8 ± 0.4	6.7	13.1	10.6 [9.9/11.3]	10.4 ± 1.2
Phase 5/6	2	−18.8	−18.4			8.8	10.1		
Phase 6a	4	−18.9	−18.5			9.9	11.9		
Total	76	−20.1	−17.8	−18.8 [−19.0/−18.6]	−18.3 ± 0.3	6.7	13.1	10.6 [9.9/11.2]	10.4 ± 1.2
Biological criteria: sex									
Male									
Phase 3	29	−19.3	−18.2	−18.7 [−18.8/−18.5]	−18.7 ± 0.2	8.4	11.0	9.9 [9.6/10.4]	9.9 ± 0.6
Phase 3/4	8	−18.8	−18.5	−18.7		9.0	11.3	10.2	
Phase 4	16	−19.2	−18.3	−18.8 [−18.9/−18.7]		8.3	11.9	10.4 [9.5/10.9]	
Phase 4/5	1	−18.8				8.8			
Phase 5	18	−19.6	−18.3	−18.9 [−19.0/−18.6]		6.7	11.4	10.3 [9.3/10.7]	
Phase 5/6	1	−18.9				9.9			
Phase 6a	2	−19.0	−18.8			11.7	11.7		
Total	75	−19.6	−18.2	−18.8 [−18.9/−18.6]	−18.8 ± 0.3	7.7	12.1	10.3 [9.6/10.8]	10.2 ± 0.9
Female									
Phase 2	1	−18.8				10.6			
Phase 3	29	−19.5	−18.2	−18.7 [−18.9/−18.6]	−18.7 ± 0.3	8.1	11.2	9.7 [9.1/10.1]	9.7 ± 0.8
Phase 3/4	3	−18.8	−18.6			9.7	12.1		
Phase 4	9	−19.2	−18.3	−18.8 [−18.9/−18.4]		9.2	12.1	11.0 [10.8/11.2]	
Phase 5	26	−20.1	−17.8	−18.9 [−19.0/−18.6]	−18.8 ± 0.4	7.7	13.1	10.7 [10.1/11.5]	10.8 ± 1.1
Phase 5/6	1	−18.9				10.1			
Phase 6a	2	−18.5	−18.5			10.1	10.6		
Total	71	−20.1	−17.8	−18.8 [−18.9/−18.6]	−18.8 ± 0.3	6.7	13.1	10.1 [9.5/11.0]	10.2 ± 1.1
Biological criteria: age									
20–39									
Phase 3	14	−19.0	−18.3	−18.7 [−18.8/−18.5]		8.5	11.0	9.5 [9.1/10.3]	
Phase 3/4	2	−18.6	−18.5			10.8	12.1		
Phase 4	4	−18.8	−18.3			8.5	10.4		
Phase 5/6	1	−18.9				10.1			
Phase 5	9	−19.4	−18.5	−18.8		6.7	13.1	9.9	
Total	29	−19.4	−18.3	−18.8 [−18.9/−18.6]	−18.7 ± 0.2	6.7	13.1	9.8 [9.1/10.4]	9.8 ± 1.2
≥40									
Phase 3	10	−19.2	−18.4	−18.8 [−18.8/−18.6]		8.4	10.4	9.6 [9.5/10.1]	
Phase 4	11	−19.1	−18.3	−18.8 [−18.9/−18.6]		8.6	11.5	10.9 [10.0/11.1]	
Phase 4/5	1	−18.8				8.8			
Phase 5	10	−19.6	−18.4	−18.9 [−19.0/−18.6]		8.3	11.6	10.6 [10.4/11.2]	
Phase 5/6	1	−18.9				9.9			
Phase 6a	1	−18.8				11.7			
Total	35	−19.6	−18.3	−18.8 [−18.9/−18.6]	−18.8 ± 0.3	8.3	12.1	10.4 [9.6/11.0]	10.3 ± 0.9
Total	146	−20.2	−17.8	−18.8 [−18.9/−18.6]	−18.8 ± 0.3	6.7	13.1	10.2 [9.6/10.8]	10.2 ± 1.0

[a] IIQ: first/third quartiles; median is provided when n is ≥5 and IIQ is provided when n is ≥10

[b] Statistical parameters are provided when n is ≥20

range from 8.3 to 12.1‰ ($\delta^{13}C$ = −18.8 [−18.9/−18.6], $\delta^{15}N$ = 10.3 [9.6/10.8], n = 136).

Male $\delta^{13}C$ values range from −19.6 to −18.2‰, and their $\delta^{15}N$ values range from 7.7 to 12.1‰ ($\delta^{13}C$ = −18.8 [−18.9/−18.6], $\delta^{15}N$ = 10.3 [9.6/10.8], n = 75, Tables 2 and 6). Female $\delta^{13}C$ values range from −20.1 to −17.8‰, and their $\delta^{15}N$ values range from 6.7 to 13.1‰ ($\delta^{13}C$ = −18.8 [−18.9/−18.6], $\delta^{15}N$ = 10.1 [9.5/11.0], n = 71, Tables 2 and 6). There are no statistically significant differences between the $\delta^{13}C$ and the $\delta^{15}N$ values of males and females for all the population or inside each chronological phase group (Mann-Whitney tests, Supplementary Material). Consequently, males and females had a similar protein diet at Missignac unlike other rural populations in Europe (Reitsema and Vercellotti 2012;

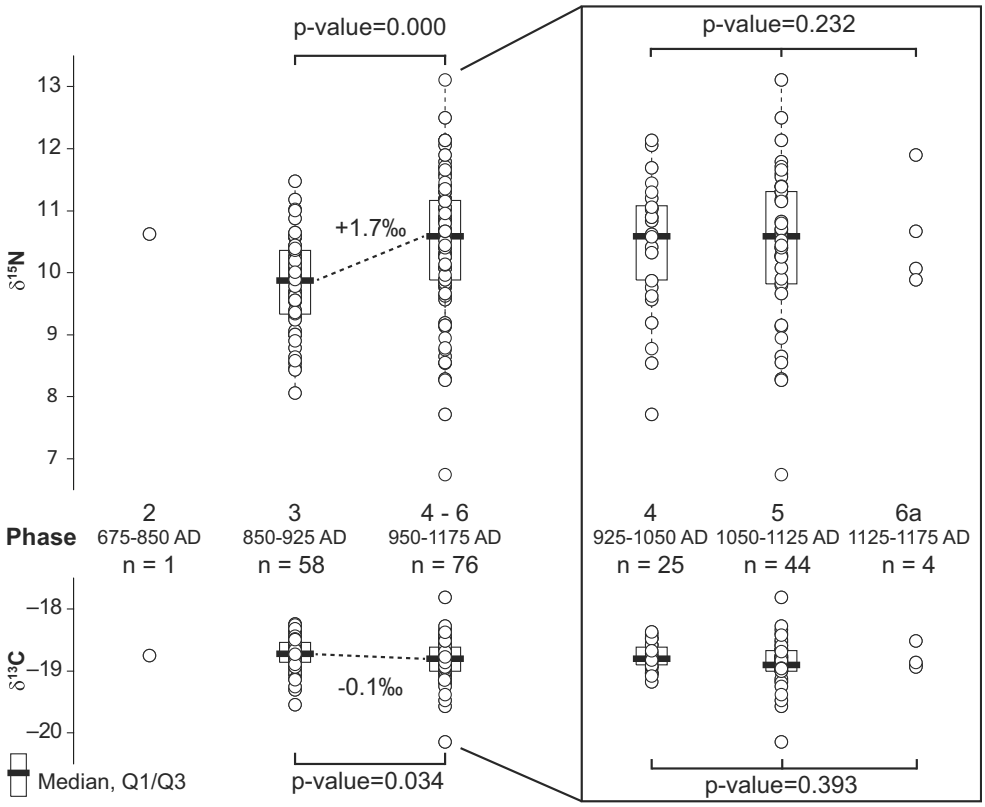

Fig. 4 Human isotope ratios variation according to archeological phases. The frame on the right details the values of individuals dated from phases 4, 5, and 6a. "Phase 4–6" regroups the individuals of the frame and the individuals dated between phases 4 and 5 and between phases 5 and 6a (see Table 6)

Kaupová et al. 2016). Seven of ten of the outliers previously listed are females maybe because of a short-term mobility before death. The median enrichment between the isotopic values of the domestic triad and humans is of 1.1‰ and 3.2‰ for $\delta^{13}C$ and $\delta^{15}N$, respectively, which is in agreement with the trophic enrichment between two consecutive trophic levels (Krajcarz et al. 2018). Those four species could have been the main protein source for humans. This confirms the low consumption of terrestrial wildlife species, freshwater specimen, and secondary domestic species such as equids, chickens, or goats hypothesized from the zooarcheological studies (Fig. 3; Bardot-Cambot et al. 2018). It is interesting to note that despite the presence of the sea, Missignac humans do not seem to have eaten substantial quantities of marine resources. Similarly, estuarine or brackish water resources do not seem to be a major source of protein.

Chronologically, isotopic values of the individuals dated from phase 4, phase 5, and phase 6 are statistically similar (Table 6, Fig. 4, Kruskal-Wallis tests, Supplementary Material). The isotopic values of the individuals from phase 3 are statistically different from the ones from the more recent phases pooled all together (Table 6, Fig. 4, Mann-Whitney tests, Supplementary Material).

The beginning of the Middle Ages is known as the Medieval Warm Period (Le Roy 2004). In Mediterranean contexts like South-East France, this phenomenon is characterized by an intensification of aridity, an increase in temperature, and climate instability (Vernet et al. 1996; Jalut et al. 2000; Araus et al. 1997). Keeping this in mind, the chronological trend of human isotopic values could be linked to a change in the isotopic values of the main dietary resources, related directly to climatic variations. Indirectly, climate change could have also an impact on agricultural practices such as an increase use of manure. To test this hypothesis, isotopic values of the domestic triad from phases 2–3 and phases 4–6 were compared (Table 4). There is no statistical difference between $\delta^{13}C$ and $\delta^{15}N$ values of the phase 3 contemporaneous faunal specimens and the more recent ones (Mann-Whitney tests, Supplementary Material). Therefore, the difference of human isotopic values does not appear to be associated with a change over time of the main protein sources' isotopic values due to climatic conditions.

Overall, the trend of human isotopic values is also consistent with the introduction of freshwater resources into the food supply. The beginning of the village formation during phase 4 is therefore contemporaneous with a change in the consumption of food resources by the inhabitants of the site. Once the village begins to form, the freshwater resources remain to be a constant food source despite demographic or economic changes. Historical sources mention that at that time, a change in doctrine occurred: fish and aquatic resources, in general, were now authorized during the days of abstinence of the Catholic calendar (120/150 days per year, Montanari 2017). Therefore, the change in diet at Missignac at the beginning of the tenth century could be related to the

religious affiliation of its inhabitants. The influence of the "aquatic resources" doctrine on diet has been highlighted in previous isotopic studies on early medieval populations (Barrett and Richards 2004; Müldner and Richards 2007; Salamon et al. 2008). Moreover, our results show for the first time the application of this doctrine with the consumption of freshwater resources despite the proximity of the Mediterranean coast (less than 20 km).

Christianity is well established in the region before the tenth century. In Missignac, there is an object decorated with a chrismon (or Chi Rho) from the fifth century. There is, therefore, no doubt that by then, there already is at least one Christian individual if not a family at the site (Maufras et al. in press). The graves of the site are all laid out according to the Christian practice of the early Middle Age, even the early ones preceding the implantation of the church. The population is assumed to be predominantly Christian by the end of the seventh century. On the other hand, Missignac has its own customs, like that of burying the dead at the limits of the settlement, a custom that persisted even after the construction of the church. What the construction of the church brings is probably the permanent presence of a cleric, prior, or pastor, who regularly celebrates mass and certainly encourages his flock to follow the rules of the Christian Church such as fasting and burying the dead in the church cemetery. One may note that his influence is less effective on funeral practices even if rules concerning the unique funeral area are promulgated at the same times as those on fasting (Treffort 1996). Indeed, at Missignac, dietary changes occurred faster than funeral changes. Most of the inhabitants followed the "funerary Catholic doctrine" only from phase 5 while the "dietary Catholic doctrine" would have been followed since phase 4.

The second trend is that the variance of $\delta^{15}N$ values for individuals from phase 3 is statistically lower than that for individuals from phases 4 to 6 pooled all together (Levene tests, Supplementary Material, Fig. 4). Phase 3 peoples have a more homogenous protein diet than phase 4–6 individuals. There would be then a change in the individual access to animal protein once the village begins to be formed. Meat consumption is often linked with status during medieval times. People with wealth and/or power would be expected to eat more meat than less-privileged ones (Montanari 2008). This point is the base of numerous studies on the impact of socio-economic stratification on diet in the medieval isotopic literature (e.g., Lightfoot et al. 2012; Reitsema and Vercellotti 2012; Iacumin et al. 2014; Alexander et al. 2015; Miclon et al. 2017; Kaupová et al. 2018). Hoever it seems that at the beginning of the medieval period, access to animal products (including meat) was less strictly linked to wealth (Montanari 1995; Gautier 2010). It would be only after 1000 AD, in the context of the birth of feudal power, that meat begins to be reserved to elites (Montanari 1995; Gautier 2010). The increase of diversity in the diet of Missignac inhabitants from phase 4 could reflect this evolution of the social organization. Being more egalitarian at the beginning of the occupation, it would become more hierarchized with the establishment of the village, at least in terms of meat access.

At the same time, village development could result in an increased diversity of dietary choice. The highest variance of $\delta^{15}N$ values is observed for the individuals of phase 5 (Table 6, Fig. 4), and most of the individuals with noticeable values are dated from the same phase (Table 2). This phase corresponds to the village maximum density and a noticeable diversification of the ceramic production (Maufras et al. in press). The variability of the isotopic data after phase 4 will then reflect the diversity of individual choice inside the village. Interestingly, this diet diversity seems to reach its peak while the inhabitants of Missignac can be perceived by the funerary archeology as a single community. Phase 5 is indeed the period during which most of the sepultures are located inside the ecclesial cemetery (Hernandez 2018). Isotopic values and funerary practices do not allow to see the same picture of Missignac population. Although they are influenced by the religious identity of the individuals, the implementation and the timing of this influence are different.

Individuals who died before 40 have $\delta^{13}C$ values ranging from − 19.4 to − 18.3‰ and $\delta^{15}N$ values ranging from 6.7 to 13.1‰ ($\delta^{13}C = -18.8$ [− 18.9/− 18.6], $\delta^{15}N = 9.8$ [9.1/10.4], $n = 29$, Table 6). Those who died after 40 years have $\delta^{13}C$ values between − 19.6 and − 18.3‰ and $\delta^{15}N$ values between 8.3 and 12.1‰ ($\delta^{13}C = -18.8$ [− 18.9/− 18.6], $\delta^{15}N = 10.4$ [9.6/11.0], $n = 35$, Table 6). Statistically, for all the population, the two groups differ in their $\delta^{15}N$ values. The oldest have higher values (Mann-Whitney tests, Supplementary Material). But, this difference disappears when the two groups are compared inside each chronological phase group (Mann-Whitney tests, Supplementary Material). Therefore, the difference observed for all the population is likely due to a sampling bias. The sample of "> 40" individuals is mainly composed by individuals dated from phases 4 to 6 (24/35), and the difference detected is probably more linked to the chronological differences than to a difference of diet.

Conclusions

The agricultural use of at least five ecosystems is discernible from faunal $\delta^{13}C$ and $\delta^{15}N$ values at Missignac ($n = 73$): the Mediterranean Sea, a freshwater ecosystem, the forest, and two distinct open environments (among them, one dominated by halophytes). Some of the specimens analyzed (goat, equids) show individual-specific diet. This exploitation raises the question of a medium- to long-distance animal supply at Missignac and of its relation to other productive sites in the region.

The $\delta^{13}C$ and $\delta^{15}N$ values of Missignac human individuals ($n = 146$) are consistent with a diet mainly based on the domestic triad. No statistical differences between the isotopic values of males and females exist. A change in diet is observed concomitantly to the beginning of the medieval village formation at the first quarter of the tenth century. From this point onwards, freshwater resources seem to begin to be a considerable part of the inhabitants' diet and diverse individual access to food resources starts taking shape. Our data would suggest this is a consequence of both the religious identity of the individuals analyzed and the increased diversity of the population living at the site. The visible change in the diet happens at its own rhythm compared to that of the funerary practices. Thanks to isotopic diet reconstruction, it has been possible to properly assess the impact of religious identity and socio-economic status on the day-to-day life of Missignac individuals. The inhabitants that are one community by their unique cemetery can also be seen as multiple groups by their dietary habits highlighting the complexity of Christian medieval populations.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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