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The palaeoenvironmental potential of bioarchaeological isotope data

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Bioarchaeology not only provides insights into human, animal, and environmental ecology, but also generates huge amounts of stable and radiogenic isotope data that are not well recognised by other disciplines. Here, we present potential avenues for the integration and interpretation of archaeological isotope data into environmental studies. We emphasise the large spatio-temporal scales on which isotope patterns can be observed, for example using isoscapes, the limitations and potential pitfalls that come with isotope data from archaeological research, and future cross-disciplinary collaborations between bioarchaeology and other palaeo-disciplines.

Isotope analyses were introduced in archaeological research in the late 1970s, when J. C. Vogel and N. J. van der Merwe applied carbon isotope analyses to investigate maize cultivation in North America[1]. In 1985, J. E. Ericson[2] provided the basis for mobility studies using strontium isotopes. A few decades later, isotope analyses of carbon (δ^{13}C), nitrogen (δ^{15}N), oxygen (δ^{18}O), radiogenic strontium (^{87}Sr/^{86}Sr)[3–5] and increasingly sulphur (δ^{34}S)[6], hydrogen (δD)[7], stable strontium (δ^{88}Sr)[8], zinc (δ^{66}Zn)[9], lead (^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb, ^{208}Pb/^{204}Pb)[10], neodymium (^{143}Nd/^{144}Nd)[11] and also compound specific approaches[12] have become common tools in archaeological research.

In bioarchaeology, i.e. the study of biological remains including humans, faunal and flora (but not restricted to osteoarchaeology), isotope sampling is limited to a fraction of sites (depending on preservation and access) and the research questions are formulated by archaeological interest. The resulting archives consist of individual high-quality records (Supplementary Note 1) in which ^{87}Sr/^{86}Sr, ^{208}Pb/^{206}Pb, and more recently ^{143}Nd/^{144}Nd isotopes are mostly dedicated to mobility studies[10,11,13], δ^{18}O and δD to mobility and climatic reconstruction[14,15] and δ^{13}C, δ^{15}N, δ^{2}H, δ^{66}Zn[16] and δ^{34}S isotopes are applied to investigate dietary, social, environmental, climatic and agricultural changes[17–19]. The sample size strongly varies depending on the goals of the study: a single individual can represent an entire case study, whereas community-level targeted investigations can comprise sample sizes of many tens of individuals[20]. Various isotope systems are moreover increasingly combined into multi-proxy and multi-tissue approaches to improve the measured signals[11,19,21], to contrast differing signals related to skeletal remodelling and isotope turnover processes[22], and to minimise the negative effects of destructive sampling[22–24]. To our knowledge no study has yet integrated δ^{13}C, δ^{15}N, δ^{18}O, δ^{34}S, ^{87}Sr/^{86}Sr, and ^{208}Pb/^{206}Pb, although protocols exist to enable this[25].

Several initiatives have started to create regional, temporal and thematic datasets to gather and centralise these fragmented datasets[26–30]. Moreover, some archaeological studies have taken advantage of such huge datasets to track large-scale cultural[31,32], ecological[33–36], climatic[37,38] or environmental[39,40] patterns. However, the scientific potential of this archive remains comparatively untapped, especially in the perspective of multidisciplinary research. This implies that palaeo-environmental, -ecological and -climatic research is restricted to areas where proxies such as ice cores, speleothems, tree-rings, molluscs or lake/marine sediments are available, which cannot necessarily be easily connected to human activity, while bioarchaeological samples have a nearly global coverage and intrinsically enable to investigate human-environment interactions. This paper hence suggests how bioarchaeological isotope data can be integrated into palaeostudies as they provide complementary environmental and climatic information that is not available from other archives.

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Recycling bioarchaeological isotope data in environmental research

Bioarchaeological studies have contributed to palaeoecological research by revealing migratory and dietary behaviour of domesticated (affected by agropastoral and husbandry practices) and wild species—including now extinct ones[36,41,42]—and by highlighting their interaction with humans[43–45]. In most cases, these isotope data are biased towards human activity (see Supplementary Note 1)—with the exception of studies conducted in collaboration with palaeontology[46–48]. But more importantly, isotope ratios from bioarchaeological tissues can serve as palaeoclimatic and palaeoenvironmental proxies, which is not recognised in other palaeo-disciplines. This section presents the palaeoclimatic and palaeoenvironmental potential of bioarchaeological isotope data using several examples and emphasising both the spatial and the temporal dimensions.

Environmental aspects

The δ^{2}H and δ^{18}O values of animal tissues are ultimately related to the δ^{2}H and δ^{18}O values of consumed environmental water, and thus reflect, e.g. latitude and longitude, altitude, distance to the moisture source and seasonality (see a review in O[49] and H[7]). Other isotope systems can be targeted in faunal tissues reflecting other aspects of local palaeoclimatic conditions (see Stevens et al in press[50] for a review). For example, plant δ^{13}C, δ^{15}N, δ^{34}S and δ^{66}Zn values are affected by local variability in humidity and aridity, salinity, daylight, or forest cover versus open landscapes. These 'signatures' are transferred through the food chain so that the isotopic composition of animal and human tissues reflect the organisms dietary choices and contain information about the palaeoenvironmental and palaeoecological context of their habitat[9,49–51]—provided that the archaeozoological material is not biased towards grazers or browsers only, or that mixed-feeding herbivores are available from the site. Such isotope data can thus be used to retrace palaeoenvironmental diversity at a given archaeological site during a specific time frame[21,38], or to reconstruct surrounding ecosystems, for example in coastal areas[52,53], wetlands[54], or steppe[21] (Fig. 1). This approach also had particular success for reconstructing environmental change, for example associated with MIS 3, when the Neanderthals became extinct[55], or the Last Glacial Maximum (LGM) and refugia regions[34,56].

Several examples thus underline the ecological and palaeoenvironmental potential of bioarchaeological isotope data. In C$_3$-dominated ecosystems under peri-arctic, boreal and temperate conditions, contrast in δ^{13}C and δ^{15}N values reflect the habitat and foraging preferences of herbivores. A striking example of niche partitioning based on specialised diet is observed among large ungulates of the mammoth steppe during the Last Glacial Period, a pattern that persisted across broad temporal and geographical scales. Reindeer exhibit the highest δ^{13}C values due to their specific and substantial consumption of lichen, showing few if any overlap with horses, which have among the lowest δ^{13}C values[36]. Mammoths show the highest δ^{15}N values, likely due to grazing on more mature plants and possibly coprophagy, while woolly rhinoceroses and large bovids present

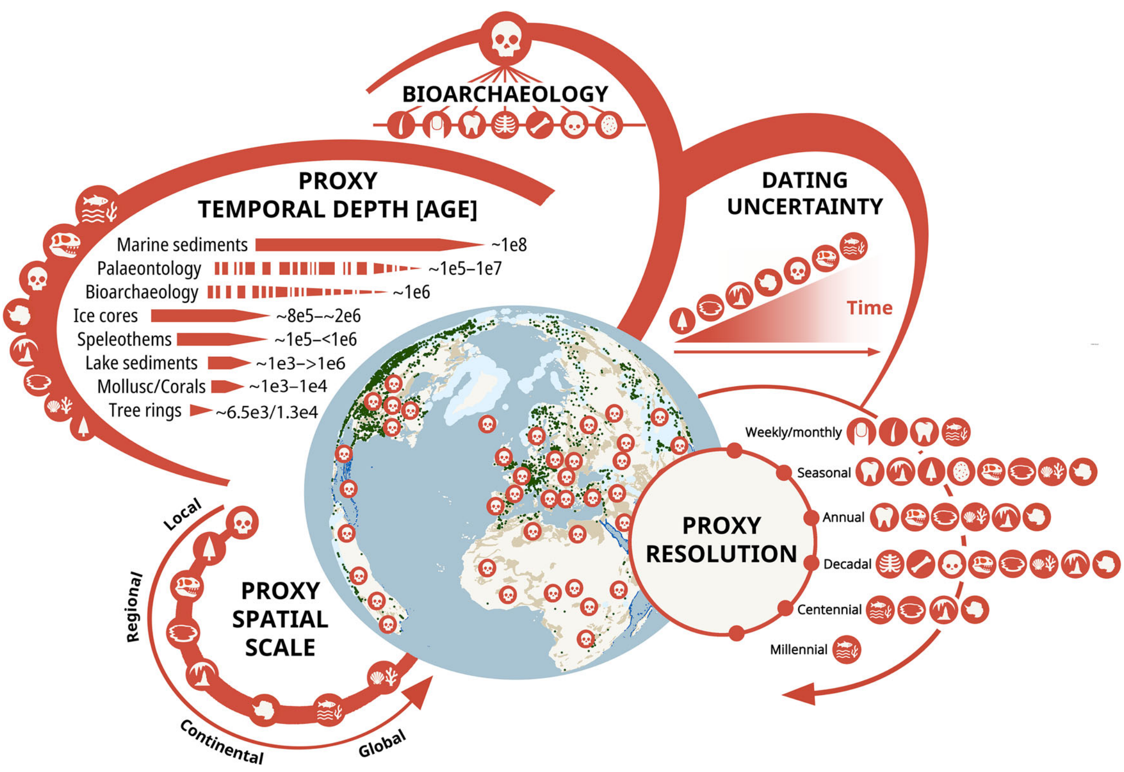

Fig. 1 | Characteristics of bioarchaeological and environmental proxy archives. The bioarchaeological samples are (from left to right): hair, nail, tooth, bones with short or long turnover rates, bones from young animals/individuals, and charred grains. The temporal depth varies between proxies, yet the palaeontology and bioarchaeology hardly provide any continuous time series and the bioarchaeological sample frequency is considerably reduced towards the oldest samples. The dating uncertainty or precision can reach one calendar year for tree-rings, speleothems, varved lake's sediments, speleothems, young ice cores, corals and molluscs, but it can be decadal to millennial for most proxies depending on the temporal depth and the datation method. The proxy resolution varies from sub-annual to decadal for most proxies, it can be (multi-)centennial for marine sediments and other layers that form slowly. The global spatial distribution vary between proxies: ice cores depend on global glacier distribution (light blue signature; source: https://wgms.ch/downloads/DOI-WGMS-FoG-2025-02b.zip); speleothems depend on karst regions (light brown signature; source: https://download.bgr.de/bgr/grundwasser/whymap/shp/WHYMAP_WOKAM_v1.zip); corals are restricted to tropical areas (dark blue signature; source: https://databasin.org/datasets/b983863c0a1a41e8839383b40ade437d/); molluscs are restricted to water bodies or archaeological sites, marine and lakes sediments originate from the respective water bodies, tree-rings depend on past forest covers and to some extent on archaeological sites (green signature: global tree ring record distribution; source: https://gis.ncdc.noaa.gov/kml/paleo_tree.kmz, last data access: 06th June 2025), palaeontological and bioarchaeological samples have a global extent but depend on past human activities, excavated sites and preservation conditions. The spatial scale reflected by each proxy goes from the local to the global scale, but even local proxies may inform about supra-regional processes when considered altogether. These characteristics are summarised in Supplementary Table 1. Figure © Michael Kempf 2025.

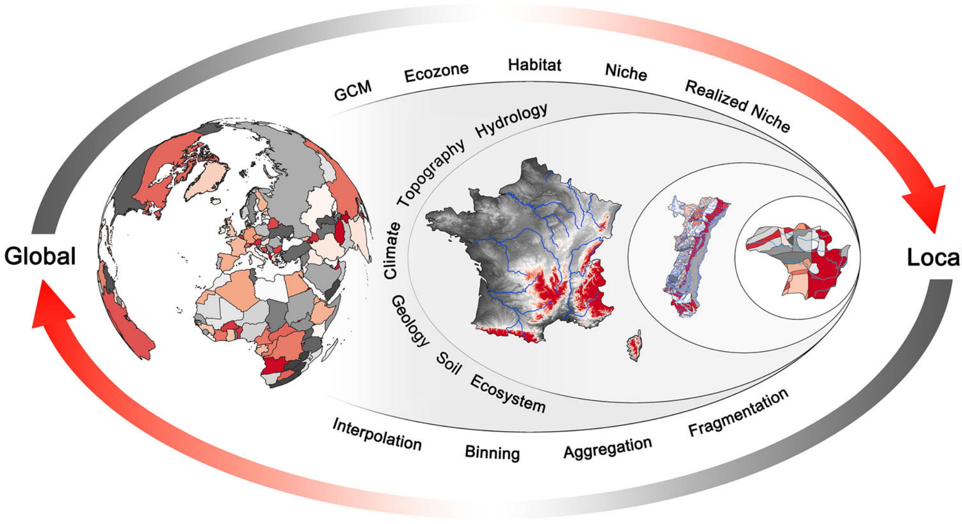

Fig. 2 | Scale dependency of ecological functionality. The upper panel shows decreasing climatic and ecological scales from GCMs (Global Climate Models) to supraregional ecozones, regional habitats, and local and micro niches (realised niches). The lower panel shows increasing spatial operations, including small-scale fragmentation, simplification such as regional aggregation and binning, and estimation processes such as interpolation. Figure © Michael Kempf 2025.

intermediate δ^{15}N values[50,57]. Change in the δ^{15}N baseline is associated with complex, though sometimes decipherable, environmental conditions. In particular, the increase in δ^{15}N across Europe during the Lateglacial to early Holocene transition may be linked indirectly to rising temperatures[35,58–61]. Geographical variation in δ^{15}N values of large ungulates during the Lateglacial period is best explained by local environmental conditions, through the lingering effects of permafrost on N-cycling in soils[35,59,62]. A decline in isotopic niche partitioning reflects the changing post-LGM conditions, as seen in the ^{15}N-depleted mammoths in Central Europe[63] and the increasing overlap in δ^{13}C and δ^{15}N values among large ungulates[62,64].

From a palaeoclimatic perspective, archaeological charcoals and molluscan shells represent further well-suited materials for investigating seasonal patterns and climate change on the site scale[65]. At the global scale, bioarchaeological proxies further allow for tracking larger climatic processes such as El Niño[66] or variability in the monsoon[67]. When considered separately, archaeological sites thus offer site-specific or micro-regional insights into the effects of large-scale phenomena, while the accumulation of bioarchaeological data from one or several regions provides itself a record of large-scale phenomena (see Figs. 1, 2 and Section 3.2). Moreover, isotope data from diverse species further reflect different trends depending on their individual niches[34], while palaeoenvironmental changes are not always reflected across all niches, such as the impact of LGM on ibex, but not on red deer dietary ecology in Northern Spain[56], or the impact of the Heinrich 4 (~39/40 Ka BP) event on reindeer feeding ecology at Les Cottés (France) relative to other species[36]. Bioarchaeological isotope data are therefore complementary datasets to fill gaps among proxies from the environmental sciences.

This also applies in terms of geographical distribution of the records, as (zoo-)archaeological remains often survive when other environmental proxies do not. Stable isotope analysis of faunal remains provides a proxy for local environmental conditions, when many other proxies such as ice cores, sea cores, and speleothems are often distant from these locations and/or do not necessarily reflect local climatic conditions[68]. Zooarchaeological remains that originate from human activity can even provide contrasting evidence to other site-specific proxies that may not be contemporary to human site-use. For example, δ^{18}O data from bovid teeth at the site of La Ferrassie, France, demonstrated that Neanderthals used the site during milder phases of a (broadly) cool period[69]. The data contrasted with wider regional environmental records for the period, as well as certain sediment records at the site itself, which also attested to these cooler conditions. This highlights the diverse scales of the different proxies, and the unique insights afforded through the isotope analysis of anthropogenically-derived faunal remains in reconstructing climate at the scale of human behaviour[69]. When combining and comparing different proxy datasets, the use of modern data is also important for testing the application of these proxies and feed current models in terms of spatial representativity[70]. This further offers the potential to use bioarchaeological isotope data to model phenomena for which proxies exist only in recent times[71]. Combining either contemporaneous records from different regions or diachronic records from a defined geographical area thus represent invaluable records for past processes that are otherwise recovered only in specific contexts or restricted geographical areas[72,73].

When working with archaeological datasets, wider consideration needs to be given to the impact of anthropogenic activity on the stable isotope record. Concerning hunter-gatherer populations, the faunal record is a product of hunting strategies employed, and reflect times when a site was occupied by human populations, potentially reflecting seasonal occupation preferences or occupation only during particular climatic conditions, as seen at the Middle Palaeolithic site of Axlor in Northern Spain[74]. When working with material pertaining to (agro-)pastoralist populations the application of manure to fodder crops can impact on observed values[75,76] as well as keeping animals in pens or enclosures[77], transhumance[77–79] the provision of specific[80] or unusual fodder or graze such as salt-marsh, seaweed and marine resources[81,82], or the use of diverse or distinctive pasture locations such as forests[83] can all impact on the stable isotope record. In contrast to palaeontological material[84–86] the potential of such bioarchaeological samples to reflect palaeoenvironmental conditions would be biased by the human impact on feeding habits. Small mammals such as rodents from the archaeological context are good alternatives to target the local environment[87,88]. However, as explained above, the targeting of anthropogenically-derived remains of prey-species (specifically large obligate-drinking ungulates) can conversely be viewed as an inherent bias that is favourable, resulting in a climatic proxy that is directly linked to human site-use.

Moreover, a certain degree of mobility of humans, animals (e.g. for food, transport), food resources and animal fodder can always be expected, in particular for the historical periods[18,89]. Likewise, trading of resources between rural and urban locations and between central places and hinterlands[90] can result in the displacement of remains. In such cases, the isotope composition of bioarchaeological material would not be representative for local conditions and hence could not be used for reconstructing the local palaeoenvironment. It must be further kept in mind that regardless of the economy (hunter-gatherer, pastoralists, farmer), the material found at an archaeological site results from human selection and is biased towards what survived until today due to cultural choices or preservation issues. It might therefore not represent all biomes from the past local ecosystem—which is, however, a problem known from modern samples as well[91]. Working with archaeologists who understand such a record can help to ensure that consideration is given to some of these nuances and how they might be influencing any trends observed.

Temporal and seasonal aspects

Isotope analysis of incrementally developed structures such as speleothems[68,73], tree-rings[72,92], shells[93], and stratified sequences like lake sediments[94], provide multifaceted archives of past climatic and environmental conditions. Such records are valuable taken separately or combined, producing complementary proxy datasets[95,96]. Data from these archives cover different chronological and geographical scales on varying temporal resolutions with proxy-inherent limitations (Fig. 1). The analysis of speleothems and tree rings, for example, captures two different seasonal signals: mean annual or cooler season (fall to spring) precipitation in speleothems[68,73] and the growing season signal in tree rings[92]. Climatic variability deriving from one or the other is a characterisation of a specific period of the year and an enhanced drought signal in one proxy does not necessarily occur in the other—triggering an overestimation of climatic extremes across a multi-annual period.

In comparison, the measured isotopic composition of bioarchaeological samples informs on contexts as old as several millions of years, with a resolution varying from a few weeks to several decades depending on the tissue and the sampling method (Table 1 and Supplementary Note 1). For example, δ^{2}H isotope analysis of bone collagen can provide insight into time-averaged (i.e. supra-annual) precipitation[97]. Similarly, δ^{18}O values from 'bulk' enamel samples (when undertaken to ensure a full year of growth is sampled) can allow the reconstruction of mean annual temperatures[98,99]. On the other hand, high-resolution intra-tooth microsampling on animal teeth offers continuous data for the period during which a particular tooth formed, covering both the fall/winter and the spring/summer seasons[100], thus permitting the reconstruction of seasonal palaeoclimatic conditions[14,38] over a full year. This approach has been applied at a number of Neanderthal and early modern human sites in Europe. For example, at Ilsenhöhle in Ranis, Germany, intra-tooth sampling and O isotope analysis of horses (combined with δ^{13}C and δ^{15}N analysis of faunal collagen) revealed decreasing temperatures throughout the sequence but also that extreme seasonality and coolest winter temperatures coincided with earliest modern human use of the site (the initial Upper Palaeolithic)[21].

However, such approaches rely on dating and clear stratigraphic association, and the precision of the sample's absolute dating depends on the period considered, and on the method used, e.g. radiocarbon dating[101], luminescence[102], dendrochronology[92], stratigraphy, typology[103]. In contrast to the possibility of dating tree-rings, ice cores or speleothems to one specific calendar year, the associated chronological uncertainty among bioarchaeological samples (despite radiocarbon dating, for example) can vary dramatically and stratigraphic (or other) relationships at sites remain pivotal. The duration of the occupation might further be difficult to estimate[104]. The absolute dating resolution of bioarchaeological samples may be as large as several hundreds of years in the case of the oldest samples, when there is a prolonged lack of change in archaeological material culture, or when the calibration curve for radiocarbon dates hits a plateau[105–108], while it can reach a few years or decades when methods are combined and/or when the archaeological context provides a high-resolution chronology such as during the Early Middle Ages[109,110]. Nevertheless, bioarchaeological research can provide time sequences in the same way as ice cores or lake varves.

Following the tree-ring approach by Loader and colleagues[111] and by Black et al. on molluscs[112] it may be possible to compare large sequential isotope datasets from animal teeth to, e.g. tree-ring and/or speleothem isotope data, and thus to integrate these bioarchaeological records into existing time series via cross-dating. A machine learning approach at the global scale and over long chronologies[113], would facilitate linking of bioarchaeological sequential isotope data to palaeoclimatic and palaeoenvironmental parameters and completion or testing of existing models. This will imply further treatment of the data (i.e. interpolation, imputation, averaging), creating a loss of information (see also Fig. 2). Introducing various modelling procedures represents a first step to deal with these issues.

Following metadata guidelines provided by environmental sciences[96] may further facilitate the integration of bioarchaeological isotope data into existing datasets such as the global Iso2k database, expanding the latter to the BCE time scale (see also ref. 26 and the Pandora initiative since 2023). Despite being discontinuous and uneven sequences, they would fill temporal and seasonal gaps and provide new insights and dimensions on phenomena recorded elsewhere. Yet a preliminary cross-disciplinary discussion is required to make sure that workflows align not only within[72] but also between disciplines. Targeted sampling strategies within an area where comparable proxy data from speleothems, tree rings or others are available—and where a satisfying criterion regarding sample size can be met—would allow testing of this approach.

Isoscapes and the spatial dimension of isotope variability

The production of isotope data covering a wide geographical area provides the potential for generating isoscapes, which are detailed maps of isotope distributions across landscapes. These are fundamental isotope baselines for archaeological and ecological research, food sciences, and forensics in order to investigate mobility patterns and provenance. This is crucial when the isotope composition varies considerably over space in a predictable way according to known factors[10,114–116]. In parallel, some isotope systems are particularly sensitive to environmental and climatic changes and/or to human activities: their isoscapes thus allow for tracking spatial variations in environmental settings at a specific time—or over time[61,117]. In this context, bioarchaeological research has strongly contributed to the production of isoscapes, as O, S, Sr, and Pb isoscapes are purposely created to interpret the bioarchaeological isotope data in terms of mobility patterns[5,10,117,118]. This unique and extended dataset can be used in the past as it is in ecological research, since it provides a reference framework for several regions of the world, enabling the investigation of animal ecology and migration patterns[119,120]. It may also contribute to baselines used to establish the authenticity of product origins[121,122]. As a by-product of isotope data accumulation in bioarchaeology, isoscapes for C and N isotopes can now also be produced, enabling to track spatial and temporal variations in environmental parameters[35]. Yet the anthropocentric questions triggering the production of these bioarchaeological isoscapes and the diversity of approaches applied in this making process need to be considered to facilitate the reusability of isoscapes generated in bioarchaeological research.

Archives for targeted isoscapes

The development of isoscapes relies on primary or secondary data that can be anchored to a specific region, terrain or environment. The breadth of potential archives for these data across the lithosphere, biosphere, hydrosphere and atmosphere is almost limitless, yet bioarchaeological research targets specific samples to meet specific needs, as the modern ecosphere may differ considerably from the past. It is not only modern chemical contamination (which is a key part of the provenancing process[123]), but also natural chemical cycling and environmental processes that cause these chronological shifts in certain isotope proxies (e.g. δ^{15}N[61]; ^{87}Sr/^{86}Sr[124], δ^{34}S[40], and Stevens et al.[50] in for a general review). The most work on this issue relates to ^{87}Sr/^{86}Sr analysis (see summary in Holt et al.[115]), but most considerations are applicable across isotope systems.

The impact of these processes varies across isotope systems, and archives for bioarchaeological research are selected accordingly. For example, to overcome the problem of Pb pollution in the modern environment—whose impact is noticeable since the advent of metallurgy[10] and in particular from the Roman time[125]—base geological samples are generally favoured in Pb isoscapes instead of environmental samples (e.g. plants, soils and water), with prehistoric faunal samples providing an additional useful source[10]. Environmental samples are of greater value for ^{87}Sr/^{86}Sr, but the bioarchaeological approach prefers samples from 'pristine' landscapes, away from roads, urban areas or arable agriculture to avoid modern contamination[126]. Even traditional agricultural practices, such as the use of seaweed as a fertiliser, may shift biosphere signatures—i.e. closer to marine values in Sr[127] and S[128].

Table 1 | Overview of the main bioarchaeological samples and analysed tissues and their potential with respect to diverse isotope systems ([1]: When considering no particular diet such as low- or high-protein diet)

Sample type	Tissue type	Tissue properties	Maximal age of sample	Individuals lifespan represented	Susceptibility to diagenesis	Measurements	fractionation between diet and tissue	part of the diet[1] (mainly) reflected
Dental enamel bulk sample	Biomineral	Incremental formation, acellular, avascular, no remodelling or regeneration, high density, low porosity, high crystallinity, high-order prismatic structure, low organic matter content, great post-mortem stability	Millions of years	Discrete growth period (from in utero time up to ca. 20 years of age for the third molar), representing an average of the several years of enamel formation + may be affected by 'old-Sr' available in the body (reservoir effect)	Relatively immune	δ^{13}C	Approx. +14‰	Whole diet, i.e. all dietary macronutrients/energy components (incl. components without proteins)
						δ^{18}O	Variable depending on boby mass, physiological processes, and drinker type	Drinking and food water
						^{87}Sr/^{86}Sr	Negligible	Plant food and water; food high in Ca and/or Sr
Dental enamel sub-sample				Discrete gowth period of a tooth layer: depending on the method: a few to a couple of months (if assuming that there is no or few impact of old Sr) or even weekly resolution		δ^{13}C	Approx. +14‰	Whole diet, i.e. all dietary macronutrients/energy components (incl. components without proteins)
						δ^{18}O	Variable depending on boby mass, physiological processes, and drinker type	Drinking and food water
						^{87}Sr/^{86}Sr	Negligible	Plant food and water; food high in Ca and/or Sr
Bone bioapatite	Biomineral	High porosity, low crystallinity, highly substitued, high organic matter content, slow formation and remodelling turnover (rate depending on the bone type, might be much shorter than for collagen: maybe seasonal)	(millions of years in arid environments)	Either a long-term average of the last several years or decades of life (depending on age at death) or no lifespan at all (in case of contamination)	Strongly affected (although regarding δ^{18}O, bioapatite phosphate is much more resistant than carbonate)	δ^{13}C	Approx. +14‰	Non-calcined: maybe none, maybe only reflects burial soil or local biosphere; calcined: not preserved
						δ^{18}O	Variable depending on boby mass, physiological processes, and drinker type	Non-calcined: maybe none, maybe only reflects burial soil or local biosphere; calcined: not preserved
						^{87}Sr/^{86}Sr	Negligible	Non-calcined: reflects mixed, undifferentiable signal of burial soil and plant food and water; calcined: plant food and water; food high in Ca and/or Sr
Dentine collagen	Proteinaceous, robust biomolecule	Grows incrementally, negligible remodelling, but secondary and tertiary dentine form later and dentinal tubules keep providing nutrients	Over 100,000 years	Discrete growth period (from in utero time up to ca. 20 years of age for the third molar) representing an average of the few years of dentine formation + issue of secondary and tertiary dentine	Affected	δ^{13}C	Up to +5‰ diet-to-collagen, ca. 1‰ collagen-to-collagen	Protein components of the diet
						δ^{15}N	Between +3 and +5‰ for each trophic level	
						δ^{18}O	Variable depending on boby mass, physiological	Structural oxygen in food, food water and drinking water

Table 1 (continued) | Overview of the main bioarchaeological samples and analysed tissues and their potential with respect to diverse isotope systems ([1]: When considering no particular diet such as low- or high-protein diet)

Sample type	Tissue type	Tissue properties	Maximal age of sample	Individuals lifespan represented	Susceptibility to diagenesis	Measurements	fractionation between diet and tissue	part of the diet[1] (mainly) reflected
							processes, and drinker type	
						$\delta^{34}S$	Between −1.8 and +0.7‰	Protein components of the diet (especially the methionine, i.e. only a small section of of the larger amino-acids pool)
Bone collagen	Proteinaceous, robust biomolecule	High organic matter content, slow formation and remodelling turnover (rate depending on the bone type: few years up to several decades)	Over 100,000 years	Long-term average of the last several years or decades of life (depending on age at death)	Relatively immune	$\delta^{13}C$	Up to +5‰ diet-to-collagen, ca. 1‰ collagen-to-collagen	Protein components of the diet
						$\delta^{15}N$	Between +3 and +5‰ for each trophic level	
						$\delta^{18}O$	Variable depending on boby mass, physiological processes, and drinker type	Structural oxygen in food, food water and drinking water
						$\delta^{34}S$	Between −1.8 and +0.7‰	Protein components of the diet (especially the methionine, i.e. only a small section of of the larger amino-acids pool)

Whenever the site location and its surroundings are still accessible, plant sampling from landscapes with little anthropogenic impact has become the mainstay for ^{87}Sr/^{86}Sr isoscapes built on primary data[115,129]. Environmental alternatives for ^{87}Sr/^{86}Sr include surface water sources[130], soils and soil leachates[131] and land molluscs[65]. However, concerns have been raised in relation to contamination and the degree to which these archives are consistently representative of the bioavailable Sr of the local area[132]. As the base of the food chain, and since their local provenance can be assured, plants have many benefits for isoscape production[115]. However, they do not provide a homogenised signature for an area and are susceptible to extreme values, which are generally most likely in shallow rooted plants. Therefore, dense sampling is advantageous and assessing results from shallow, medium and deep-rooted plants is a good approach to characterise variability[133]. Homogenising plant samples from the same locality provides an alternative, cost-effective approach[134], but reduces resolution to some degree.

Some diversity in taxa is of value due to plant-specific environmental processes that can impact local values (e.g. the forest-effect on ^{87}Sr/^{86}Sr[87]). Plants are also used for δ^{34}S mapping[114], but can often be subject to the impact of modern pollution[135], though this problem is much reduced in many areas due to clean air legislation[54]. Faunal sources such as sheep wool[136] or archaeological bone[54] provide alternatives. Archaeological fauna is a good alternative in areas where pollution remains an issue as long as there is strong evidence for local origin. Therefore, small-bodied wild mammals (such as small rodents) with a limited home range are a good choice[137], though these are generally sparse in faunal assemblages. Because the currently only global δ^{34}S isoscape is based on bioarchaeological remains[118], which may show the limits mentioned above, it is advisable to complete it with other samples such as plants[114] to test for the local reliability—although the non-local and diagenetically altered samples were sorted out before producing the isoscape.

Using larger mammals, whether modern or ancient, provides homogenised values and helps to characterise a landscape rather than pinpointing extreme values[138]. They moreover sometimes represent the only available resource, especially at sites within modern urban areas or which are not accessible anymore due to building activities or some other restrictions. However, using this material requires a dialogue with experts on this archaeo(zoo)logical context, as animals may have had substantial grazing ranges, or may have been involved in transhumance practices and carcass parts found on sites may have been transported from elsewhere by humans, meaning they would not represent local bioavailability. In this context, using environmental analyses to model the site's catchment area is an efficient way to determine the extent of environmental similarities or differences represented by the faunal sample compared to other proxies[24,139].

Using bone or dentine in archaeological animals for ^{87}Sr/^{86}Sr is further ill-advised as these results represent a blend of biogenic (life) and diagenetic (burial) and are therefore non diagnostic[140]. In bioarchaeology, infants also have some potential for providing homogenised local values[141], provided that early mobility can be excluded. δ^{18}O isoscapes are invariably generated on baseline water sources, typically precipitation and/or groundwater[116,142] as these sources dominate the O in organisms and the complexities of variable fractionation mean other archives are problematic. However, these are also subject to environment-specific impacts, for example through variable fractionation effects associated with evaporation depending on the depth of surface waters[142], and the results may vary depending on the conversion equation used to compare tissue, drinking, and environmental water[143].

Bioarchaeological isoscapes in ecological and palaeo-research

The geographical scale of isoscapes generated in bioarchaeological research depends strongly on the scope of the study, spanning from the site-specific or micro-regional[54,139] to the regional and supra-regional[10,129,144] or the global scale[145]. In addition, regional Sr isoscapes are getting increasingly produced with the only goal of serving as isotope background for future research, reflecting the main geological and environmental units of the area[129], yet remaining a first step for bioarchaeological—and ecological or forensic—investigations. Depending on the research question, denser sampling might be required to complete this first approximation of the overall isotope diversity within the targeted area.

The geographical scale has in turn an impact on the resolution of the isoscape. At a reduced geographical scale, the isotope diversity of the local environment can be as detailed as to represent every ecological unit within a site's catchment area using an important diversity of samples and sampling locations[53,146]—although bioarchaeological isoscapes often target places suitable for anthropogenic land-use[17,139]. On the other hand, large-scale isoscapes rather interpolate more scattered measurements based on the geological background, topography, hydrology, distance to the coast, or any relevant variable[10,144,145]. Importantly, local isotope values do not necessarily match the values predicted by global isoscapes (e.g. Ireland[129,145]), because increasing the geographical area often leads to a loss of resolution among the parameters used for the interpolation, while the relevant environmental parameters vary between ecosystems and local specificities thus cannot be considered at the large scale (Fig. 2). In this context, bioarchaeology contributes significantly to characterising the isotope variability in context- and region-specific environmental conditions. In this context, it is essential to create models that integrate multiple environmental and climatic variables to account for all factors influencing isotope variability at the investigated scale[17,139,147]. For more transparency in the interpolation process, isoscapes (of mean or median values) are meanwhile frequently published together with a map showing the error ranges[129].

By integrating bioarchaeological isoscape data in palaeo-research, the discrepancy in terms of geographical and temporal resolution of the various proxies may require the use of categorised data or average values, which necessarily leads to a loss of information. In this context, it is worth engaging a cross-disciplinary discussion regarding targeted processes and gaps that need to be filled in terms of isoscapes, to determine which proxies and sample types are required and suitable. Yet with the large diversity of proxies derived from all disciplines as well as their great temporal and geographical dimension, it may be possible to disentangle locally from globally driven triggers of isotope variability within various ecological processes. It would be also important to discuss issues related to disturbed environments and their impact on local isotope composition.

For example, in temperate zones such as the UK areas of high precipitation in the west, the bioavailable ^{87}Sr/^{86}Sr is shifted from the geological value towards the value of rainfall[146]. Similarly, contexts of marine inundation, seaspray (causing increasing values) and waterlogging (generally reducing values), altering bioavailable δ^{34}S, δ^{13}C, δ^{18}O and ^{87}Sr/^{86}Sr[52–54], require specific attention. And since the deposition of aeolian dust can have a major impact in altering bioavailable ^{87}Sr/^{86}Sr away from underlying lithology[132], bioarchaeological samples may track previous stages of the landscape. Such an attempt has been done in the Peak District, England, where the considerable change in ^{87}Sr/^{86}Sr over time may be due to the expansion of blanket peat and/or of leaching[148]. A bioarchaeological study in Sweden further demonstrated the potential variation of ^{87}Sr/^{86}Sr over time in areas affected by melting glaciers[149].

Formal isoscapes tend not to be developed for δ^{13}C and δ^{15}N due to the manifold factors dictating variability. However, there is evidence that cultural practices such as dietary habits (e.g. marine versus terrestrial food, C_3 versus C_4 crops, high versus low-protein diet) or agricultural strategies (e.g. manuring) as well as geographical, environmental and climatic settings such as latitude, lithology or moisture have an impact on these isotope ratios, with archaeological fauna providing a useful archive to explore large-scale patterns[35,37,61,150]. The exponential amount of isotope data produced in bioarchaeology thus allows the investigation of changes in ecological, geological, and geomorphological processes in the long-term and recent studies have taken advantage of both the diachronic perspective and the large geographical distribution of bioarchaeological isotope data to determine new indicators for large-scale evolution of environmental conditions[35,40,151]. By combining bioarchaeological isotope data with further approaches and proxies[152,153], there might be, for instance, potential to investigate changes in forest cover using the canopy effect[154].

This opportunity to translate the huge amount of isotope data into isoscapes is further useful for the investigation of habitats and animal ecologies[155]. It can also be used to track mobility patterns, because specific geographically constrained environmental conditions, agricultural practices, or dietary habits produce typical isotopic signatures—especially when considering multiple isotopic systems[150,156]. It may be a challenge, however, to correlate changes in isotope baselines with changes in environmental conditions, especially when one needs to consider and quantify a potential anthropogenic impact on the isotope variability – including manuring fields or consuming boiled, stewed or fermented food and drinks, which can considerably alter the original local stable isotope ratio[75,157]. A first step in this direction would be to constrain the research area in terms of period and region, in which we can rule out some factors of variability (targeting especially periods at which the human impact was absent or negligible), to focus on the herbivores (to avoid animals with more flexible dietary habits), and to integrate different proxies, although it remains key to consider the potential effect of both mobility and seasonality on isotope variability[158] as well as the time lag and varying isotope accumulation rate related to tissue formation[159].

Conclusions and perspectives

Bioarchaeological research has achieved considerable advances in the understanding of past human and animal behaviours and how this has shaped or impacted on the environment. It hence actively contributed to palaeoenvironmental and ecological research, yet this contribution is mainly restricted to the acknowledgment of resulting narratives and created knowledge. On the contrary, the tremendous amount of isotope data derived from a large diversity of bioarchaeological samples and contexts remains underexploited. With this paper, we present potential and limits of integrating bioarchaeological isotope data into other palaeo-disciplines and identify future directions and strategies enabled by a cross-disciplinary collaboration, starting from the research designs and models.

The huge diversity of sampled tissues and materials provides complementary information about various aspects of past ecologies and environments and can contribute to track processes such as precipitation patterns, climate change, or the evolution of palaeoenvironmental conditions in regions where other proxies are not available. In this context, there is an urgent need to start integrating these data into existing models to test how they can be used, for instance, in predictive/inductive models. More importantly, the large geographical distribution of bioarchaeological data and their deep chronology allow for tracking large-scale and long-term processes. In turn, the diversity and density of the existing dataset make it possible to question the impact of large-scale processes as well as of short-term or long-term changes at the local or regional scale. As the data is easily related to human activity, one can address questions related to human-environment interactions over the long term.

In this context, it is paramount to recognise the complexity derived from bioarchaeological research, and to consider the different meanings of the various samples, to accurately deal with uncertain or imprecise chronologies, and to acknowledge the bias in the sample related to archaeological research procedures. This paper offers a wide spectrum of answers to these issues. It would, however, be of great value for greater engagement between bioarchaeologists and other palaeo-scientists to foster collaboration and design joint research programs that benefit from analytical advances and interdisciplinary methodological transfer. There is a great potential in targeting common research areas of interest, identifying gaps in terms of chronology, location or types of data/proxies (i.e. the types of sampled tissue/material), creating joint monitoring programs, and testing for instance physiological, climatic, ecological, and environmental models. Based on this, one could adapt future sampling procedures and hence produce data and proxies as meaningful and reusable as possible for the various disciplines.

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The authors declare no competing interests.

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