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Human Lifeways in Late Roman and Medieval Europe. A Multi-Scale and Multi-Proxy Stable Isotope Approach

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In memoria di Mario Russo

Questa tesi è dedicata ai miei genitori

This dissertation is dedicated to my parents

Diese Dissertation ist meinen Eltern gewidmet

SUMMARY

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MENSCHLICHE LEBENSWEGE UND ERNÄHRUNGSWEISEN IM SPÄTANTIKEN UND MITTELALTERLICHEN EUROPA. EIN MULTI-SKALEN- UND MULTI-PROXY-ANSATZ UNTER VERWENDUNG STABILER ISOTOPE - ZUSAMMENFASSUNG

Die Untersuchung vergangener menschlicher Lebensweisen, zu denen Subsistenzpraktiken, Ernährungsstrategien für Kleinkinder, kleine regionale Bewegungen und/oder größere Migrationen gehören, führt zu einem Palimpsest von Informationen über vielfältige und miteinander verknüpfte historische Variablen, die sich mit alten Gesellschaften befassen. Selbst in der Neuzeit kann das alltägliche Verhalten der Menschen mit einem gemeinsamen Wertesystem in Verbindung gebracht werden, das von wirtschaftlicher Organisation, politischer Agenda, sozialem Status, technologischem Niveau, kulturellen Ansichten, Ethik und Religion beeinflusst wird. So ist zum Beispiel die Ernährung eine biologische Notwendigkeit, die dem Organismus Wachstum, Überleben und Fortpflanzung ermöglicht. Der unterschiedliche Verzehr verschiedener Nahrungsmittel wird aber in den meisten Fällen durch komplexe menschliche Entscheidungen bestimmt. Auch die Ernährung von Säuglingen ist ein besonderer Aspekt der Ernährung. Säuglinge können sich nicht selbst ernähren, sondern sind auf die Entscheidungen ihrer Eltern angewiesen, unter anderem darauf, wie und wann sie gestillt werden. Muttermilch ist eine sichere und leicht verdauliche Kalorien- und Makronährstoffquelle für Neugeborene. Doch wenn sie fehlt oder auf eine kurze Zeit reduziert wird, können Neugeborene ernsthafte gesundheitliche Probleme bekommen. Bei der Entwöhnung wird die Muttermilch mit Beikost kombiniert. Die Still- und Entwöhnungszeiten sind heutzutage ein wichtiges Forschungsthema in der Archäologie, da sie von Fundort zu Fundort und sogar von Familie zu Familie stark variieren können. Dies ist auf eine Mischung aus kulturellen Normen, wirtschaftlicher Erschwinglichkeit und medizinischem Wissen zurückzuführen. Die räumliche Mobilität von Menschen und Tieren auf verschiedenen geografischen Ebenen kann sich auch auf die menschlichen Subsistenzpraktiken und andere Aspekte der Lebensweise auswirken, die in einer bestimmten Gemeinschaft geteilt werden. Kleinere regionale Bewegungen auf individueller Ebene können mit sozioökonomischen Phänomenen in Verbindung gebracht werden, während breitere

Massenmigrationen stattdessen lokale kulturelle Traditionen beeinflussen, neue Technologien, Religionen und politische Systeme einführen und sich an neue landwirtschaftliche Wirtschaftsformen anpassen können. Diese und weitere Fragestellungen können u. a. mit Hilfe der Analyse stabiler Isotope beantwortet werden.

Die vorliegende kumulative Dissertation umfasst insgesamt sechs wissenschaftliche Veröffentlichungen sowie in der Einleitung weitere bislang unpublizierte Daten. Ziel der Arbeit ist es, raum-zeitliche Verschiebungen in der menschlichen Lebensweise im spätrömischen und mittelalterlichen Europa zu untersuchen. Dabei fokusiert diese Dissertation auf einen grundlegenden Aspekt der Lebensweise - die Ernährungsweise der Menschen. Außerdem wird auch die Mobilität im Raum angesprochen. Angesichts der Existenz zahlreicher historischer Variablen kann eine höhere Auflösung bei der Rekonstruktion vergangener menschlicher Lebensweisen durch einen transdisziplinären Multi-Proxy-Ansatz erreicht werden. Wann immer unterschiedliche Proxies verfügbar sind, können diese verglichen und gegenübergestellt werden. Dies gilt insbesondere für das römische und mittelalterliche Europa, da ein hohes Maß an archäologischer Erhaltung oft mit einer großen Menge an schriftlichen Dokumenten und Verträgen einhergeht. Darüber hinaus nehmen archäobotanische, zooarchäologische und bioarchäologische Studien für diese Zeiträume zu, was die Möglichkeit bietet, hochauflösende diachrone und synchrone Veränderungen der Ernährung, des Ressourcenmanagements und der räumlichen Mobilität zu untersuchen. Während des Zeitraums, der für diese Dissertation von Interesse ist, d. h. von der spätrömischen Zeit bis zum späten Mittelalter (ca. viertes bis fünfzehntes Jahrhundert), wirkten sich mehrere historische Ereignisse in unterschiedlichem Tempo und Ausmaß auf europäische Regionen aus. Politische Übergänge lassen sich an den Wiedervereinigungsversuchen nach dem Untergang des westlichen Teils des Römischen Reiches beobachten, wie z. B. das Karolingerreich (751-919 n. Chr.) und das Heilige Römische Reich (962-1806 n. Chr.). Darüber hinaus wurden neue „proto-nationale“ Königreiche gegründet. Die Einwanderung verschiedener germanischer und – später – slawischer Stämme prägte Europa zumindest in der gesamten Spätantike und im frühen Mittelalter (im Wesentlichen 300-1000 n. Chr.). Dies führte zu einer Kombination aus soziokulturellen und rechtlichen Systemen, die auf dem früheren römischen Substrat basierten und an die gemeinsamen Traditionen dieser neuen Völker angepasst wurden. Auch die Religionen, ihre Konfessionen und zahlreiche dogmatische Aspekte (z. B. Fastenregeln) spielten in der spätrömischen und mittelalterlichen Gesellschaft eine zentrale Rolle. Seit der Krönung Karls des Großen in der Weihnachtsnacht des Jahres 800 war die wirksamste weltliche Macht, die von einem religiösen Oberhaupt ausgeübt wurde, die des Papstes, der eine ausgleichende und manchmal auch eine führende Rolle unter den christlichen Staaten spielte. Andere besondere Dynamiken betrafen klimatische Ereignisse von begrenzter zeitlicher Reichweite (z. B. der

Vulkanwinter von 536) oder von größerem Ausmaß (z. B. die mittelalterliche Warmzeit). Schließlich sind auch Pandemien wie die „Justinianische Pest“ (541-544) oder der „Schwarze Tod“ (1346-1353) gut dokumentierte historische Ereignisse, die die europäischen Gesellschaften nachhaltig beeinflussten.

Alle oben genannten historischen Entwicklungen kennzeichnen dieses Zeitalter als eine äußerst heterogene Periode in der europäischen Geschichte, und aus diesem Grund wird erwartet, dass synchrone und diachrone Verschiebungen in den früheren menschlichen Ernährungsgewohnheiten, in der Kinderernährung, in den Strategien der Tier- und Pflanzenhaltung und in der räumlichen Mobilität diese Ereignisse widerspiegeln. Heutzutage kann eine breite Palette archäologischer Methoden eingesetzt werden, um diese Veränderungen nachzuweisen. In dieser Dissertation wird die Analyse stabiler Isotope als wichtigstes Forschungsmittel eingesetzt und mit anderen Beweismitteln kombiniert, um die größtmögliche Auflösung zu erzielen. Stabile Isotopenverhältnisse, die an osteologischen menschlichen oder tierischen Überresten und an verkohlten organischen Pflanzenproben gemessen wurden, sind in der Archäologie zur Beantwortung zahlreicher archäologischer Fragen verwendet worden. Dazu gehören u. a. die Rekonstruktion menschlicher Ernährungsgewohnheiten, die Untersuchung von Praktiken der Tierhaltung und des Pflanzenanbaus, das Erkennen wahrscheinlicher Wohnorte bestimmter Individuen und/oder die Untersuchung von Still- und Entwöhnungszeiten in früheren Bevölkerungen. Die menschlichen Lebenswege wurden hier durch „Big Data“-Sammlungen, Meta-Analysen, Bayes‘sche Modellierung und umfangreiche eigene Isotopenanalysen untersucht. Es wurden auch nicht-isotopische Proxies verwendet, da mehrere Formen archäologischer Beweise in ein Modell einbezogen werden können, um die Genauigkeit und Präzision der Rekonstruktion zu erhöhen. Mithilfe dieses transdisziplinären, Multi-Proxy- und Multiskalen-Ansatzes konnten Veränderungen in den menschlichen Subsistenzpraktiken, den Ernährungsstrategien für Kleinkinder und der räumlichen Mobilität sowohl auf regionaler Ebene (z. B. spezifische archäologische Fundorte) als auch in größeren räumlich-zeitlichen Koordinaten nachgewiesen werden.

Ein wichtiger Punkt in dieser Arbeit ist daher der Multiskalenansatz. Je nach Forschungsfrage kann eine Analyse auf verschiedenen Skalen durchgeführt werden. Big-Data-Meta-Analysen können in der Tat Verschiebungen und/oder die Verbreitung bestimmter archäologischer Daten belegen, die ansonsten auf Standortebene unsichtbar sind oder unterschätzt werden. Unterschiedliche Maßstäbe können zu unterschiedlichen Auflösungen und Interpretationseinschränkungen führen. Je größer der Maßstab, desto größer ist die Möglichkeit zu beobachten, wie sich menschliche Lebensweisen über eine begrenzte Anzahl historischer Variablen hinweg verändert haben (oder auch nicht). Eine „Big

Data“-Meta-Analyse verringert die Auswirkungen abweichender Verhaltensweisen auf die endgültige Interpretation und ermöglicht somit die Erkennung der wichtigsten Trends. Kürzlich wurden neuartige statistische Modelle vorgeschlagen, um diese zu untersuchen. Die Entwicklung von Programmen für maschinelles Lernen und die Implementierung künstlicher Intelligenz wird es wahrscheinlich auch ermöglichen, historische Korrelationen zu verfeinern. Dies gilt jedoch immer dann, wenn die gewählte Skala der Menge und Art der verfügbaren Daten angemessen ist. In dieser Dissertation wurden einige der räumlich-zeitlichen Bayes'schen „Big Data“-Optionen von https://isomemoapp.com/ (IsoMemo) zum ersten Mal vorgestellt. Darüber hinaus wurde die Verwendung der neuesten Version von FRUITS (jetzt ReSources), einem Bayes‘schen Ernährungsmischungsmodell, als mögliche hochauflösende Anwendung von Bayes‘schen Softwares auf verschiedenen Skalen vorgestellt. Darüber hinaus wurde das Modell OsteoBioR in einer ausgewählten Fallstudie eingesetzt, um Säuglingsernährungspraktiken auf lokaler Ebene zu vergleichen.

Den Veröffentlichungen, aus denen sich diese kumulative Dissertation zusammensetzt, geht eine ausführliche Einleitung über die Lebenswege des Menschen im Sinne von Ernährung und Mobilität, stabile Isotope, Bayes‘sche Modellierungswerkzeuge, die Erstellung von Datenbanken und eine kurze Zusammenfassung der Artikel voraus. Abschließende Gedanken, Einschränkungen des Projekts und künftige Forschungsrichtungen sind ebenfalls enthalten. Diese Dissertation besteht aus sechs wissenschaftlichen Beiträgen. Drei davon beziehen sich auf die Erstellung von Datenbanken, und zwar: 1) Amalthea, eine Datenbank mit etwa 15000 Einträgen für die inkrementelle Dentin-Stabilisotopenanalyse; 2) der Datensatz zum Zahnbildungsalter für bioarchäologische und medizinische Studien zur frühen Kindheit, eine nicht-isotopische Datenbank, die als Referenz für die Untersuchung der frühkindlichen Ernährung verwendet werden kann; 3) das Compendium Isotoporum Medii Aevi (CIMA), eine Datenbank, mit mehr als 50000 Isotopenmessungen an menschlichen, tierischen und pflanzlichen Proben aus dem mittelalterlichen Europa. Generell können Datensammlungen Forschungslücken aufzeigen und große Datenarchive bereitstellen, die zum Vergleich neuer Messungen genutzt werden können. Wie bereits erwähnt, können diese Sammlungen jedoch auch groß angelegte raum-zeitliche Daten-Meta-Analysen über Ernährung, landwirtschaftliche Wirtschaft, räumliche Mobilität und Säuglingsernährung liefern. Vorläufige Ergebnisse haben mögliche Verbindungen zwischen Verschiebungen in der menschlichen Lebensweise und historischen Entwicklungen während der Spätantike und des Mittelalters aufgezeigt. Dies wird auch durch die Entwicklung einer gut charakterisierten Metadatenstruktur unterstützt, die mehrere archäologische, historische und biologische Variablen umfasst. So wurden beispielsweise die sich verändernden Ernährungsgewohnheiten der Menschen im kaiserlichen, spätantiken und frühmittelalterlichen Rom mit dem demografischen Rückgang, dem Zusammenbruch der politischen und wirtschaftlichen Struktur Roms und neuen, anpassungsfähigen Agrarwirtschaften in Verbindung gebracht. Auch auf europäischer Ebene wurde eine große regionale Variabilität der Ernährungsgewohnheiten beobachtet, was darauf hindeutet, dass unterschiedliche Klimazonen, Umgebungen, politische Programme, sozioökonomische Systeme und kulturelle Traditionen unterschiedliche Auswirkungen auf menschliche Gemeinschaften hatten. Eine zusätzliche „Big Data"-Metaanalyse mit Bayes'scher Modellierung von Pollenvariablen auf kontinentaler Ebene wurde ebenfalls in diese Dissertation aufgenommen. Diese zeigte, wie die Sterblichkeitsraten des Schwarzen Todes in der historiografischen Rekonstruktion überschätzt wurden.

Zwei ausgewählte Fallstudien bilden ebenfalls einen Teil dieser Dissertation. Diese ermöglichten die Beobachtung sich verändernder menschlicher Lebensgewohnheiten auf lokaler Ebene. Hier konnten stabile Isotope und Bayes'sche Modellierungsoptionen eingesetzt werden, um frühere Säuglingsfütterungspraktiken in der römischen Siedlung von Bainesse (Großbritannien) und menschliche Ernährungsgewohnheiten, landwirtschaftliche Wirtschaft und räumliche Mobilität in Süditalien zu untersuchen. Diese Fallstudien ergaben kleinere Variationen innerhalb und zwischen den Standorten, die auf das Vorhandensein mehrerer lokaler Variablen schließen lassen, die die Lebensweise der Menschen beeinflussen. Im römischen Bainesse beispielsweise deutete eine auffällige Korrelation zwischen antiken medizinischen Empfehlungen und Säuglingsernährungspraktiken, die anhand von Isotopen nachgewiesen wurden, darauf hin, dass erstere sogar an der Nordgrenze des römischen Reiches bekannt gewesen sein könnten. Dies hängt wahrscheinlich mit der militärischen und kommerziellen Mobilität in diesem Gebiet zusammen. Das Alter, in dem die Entwöhnung abgeschlossen wurde, variierte jedoch von Person zu Person, was darauf hindeutet, dass die Entscheidungen von anderen Faktoren beeinflusst werden konnten. Dies hing mit Familientraditionen und/oder dem sozioökonomischen Status zusammen. In Tertiveri (Apulien, Italien) wurde anhand von Isotopen ein mäßiger Verzehr von C4-Pflanzen (wahrscheinlich Hirse) nachgewiesen, was im Vergleich zu anderen archäologischen Indikatoren in der Region eine interessante Anomalie darstellt. Dies stand im Zusammenhang mit einer lokalen Wirtschaft, die in das süditalienische Transhumanzsystem einbezogen war. Darüber hinaus wurden historische Entwicklungen, die wahrscheinlich mit militärischen Expeditionen zusammenhängen, mit mobilen Personen in Verbindung gebracht, die in Tertiveri gefunden wurden und von außerhalb Apuliens gekommen zu sein scheinen.

Insgesamt konnte in dieser Dissertation nachgewiesen werden, dass die Lebensweisen und vor allem die Ernährung der Menschen im spätrömischen und mittelalterlichen Europa auf verschiedenen

Ebenen und unter Verwendung mehrerer Proxies äußerst heterogen waren. Dies war auf Standortebene zu erwarten, da viele lokale Variablen und einzelne menschliche Entscheidungen Subsistenzpraktiken, landwirtschaftliche Ökonomien, Säuglingsernährungsstrategien und Mobilitätsmuster beeinflussen können. Vorläufige „Big Data"-Bayes-Meta-Analysen, die an großen Mengen isotopischer Daten durchgeführt und mit bekannten Belegen aus der Zooarchäologie, Archäobotanik, Anthropologie und schriftlichen Quellen kombiniert wurden, haben jedoch gezeigt, dass dieser Punkt auch auf breiterer Ebene gilt. Dies ist nicht notwendigerweise eine a priori Konsequenz von Unterschieden im lokalen Maßstab, da große menschliche Trends kleinere lokale Unterschiede überschatten würden. Vielmehr bestätigt dies, dass die menschlichen Gesellschaften in ihrer Gesamtheit von den wichtigsten historischen Entwicklungen und Umweltunterschieden beeinflusst werden. Dies deutet also darauf hin, dass die menschliche Lebensweise nicht nur auf biologische Einflüsse reagiert. Beim gegenwärtigen Stand der Forschung ist es schwer abzuschätzen, welche historischen und/oder Umweltvariablen die Lebensweise der spätrömischen und mittelalterlichen Menschen am stärksten beeinflusst haben. Eine Richtung, die es zu verfolgen gilt, ist die Einbeziehung von Software für maschinelles Lernen in die Analyse von "Big Data". Für die künftige Forschung über das römische und mittelalterliche Europa und seine Randgebiete wird daher vorgeschlagen, einen ähnlichen transdisziplinären Multiskalen- und Multiproxy-Ansatz zur Untersuchung der menschlichen Lebensweise zu verwenden.

HUMAN LIFEWAYS IN LATE ROMAN AND MEDIEVAL EUROPE. A MULTI-SCALE AND MULTI-PROXY STABLE ISOTOPE APPROACH - ABSTRACT

The investigation of past human lifeways, which include subsistence practices, infant feeding strategies, small regional movements, and/or broader migrations, leads to obtaining a palimpsest of information on multiple and interconnected historical variables that engage with ancient societies. Even in modern times, how people behave in quotidian aspects can be associated with a shared system of values that is influenced by economic organisation, political agenda, social status, technological level, cultural views, ethics and religion. For example, nutrition is a biological necessity that grants the organism to grow, survive, and reproduce, but the varying consumption of different foods is, in most cases, driven by complex human choices. Also infant feeding practices are a particular aspect of nutrition. Infants cannot provide nourishment for themselves but they have to rely on their parents' choices, including how and when being breastfed. Breastmilk is a safe and easily digestible source of calories and macronutrients for neonates but when this is lacking or reduced to a short time, neonates may face serious health issues. Weaning is the process that involves breastmilk paired with complementary food. Breastfeeding and weaning timings are nowadays an important research topic in archaeology, considering that these may vary significantly across sites or even families, following a mixture of cultural norms, economic affordability and medical knowledge. Human and animal spatial mobility at different geographic scales may also impact human subsistence practices plus other lifeway aspects that are shared in a given community. Smaller regional movements at individual level may be associated with socio-economic phenomena, whereas broader mass migrations may instead affect local cultural traditions, bring in new technologies, religions and political systems, and adapt to novel farming economies.

This cumulative dissertation includes multiple scientific publications with the aim of exploring spatiotemporal shifts in human lifeways across late Roman and medieval Europe. Given the existence

of multiple historical variables, a higher resolution in reconstructing past human lifeways can be obtained through a transdisciplinary multi-proxy approach. Whenever disparate proxies are available, these can be compared and contrasted. This is particularly applicable to Roman and medieval Europe, given that a high level of archaeological preservation is often paired with a large number of written documents and treaties. In addition, archaeobotanical, zooarchaeological, and bioarchaeological studies for these periods are increasing and this provides hence the possibility of exploring high-resolution diachronic and synchronic changes in diet, resource management, and spatial mobility. During the period interested by this dissertation, i.e. Late Roman to late Medieval (c. third-fifteenth centuries), several historical events affected European regions at different rates and scales. Political transitions can be observed in reunification attempts made after the fall of the western part of the Roman Empire, such as the Carolingian (751-919 CE) and Holy Roman (962-1806 CE) empires. Moreover, new 'proto-national' kingdoms were established. The migration of several Germanic and Slavic tribes interested Europe at least for the whole Late Antique and Early Middle Ages (broadly 300-1000 CE). This created a combination of socio-cultural and legislative systems based on the previous Roman substrate and adapted to shared traditions from these incoming populations. Religions, their denominations and multiple dogmatic aspects (e.g. fasting rules) also had a central role in Late Roman and Medieval society. From Charlemagne's coronation on Christmas night in 800 CE, the most effective temporal power expressed by a religious head was that of the Pope, who played a role of balance and sometimes of leadership among Christian states. Other particular dynamics involved climatic events on a limited temporal range (e.g. the volcanic winter of 536) or on a broader scale (e.g. the Medieval Warm Period). Finally, pandemics such as the 'Justinian Plague' (541-544 CE) or the 'Black Death' (1346-1353 CE) also are well documented historical events that impacted European societies.

All of the above historical developments marked this age as an extremely heterogeneous period in European history and, for this reason, synchronic and diachronic shifts in past human diets, infant feeding practices, animal and crop management strategies, and spatial mobility are expected to reflect these events. A large array of archaeological methods can nowadays be employed to detect these shifts. In this dissertation, stable isotope analysis is used as the main research proxy and combined with other sources of evidence to obtain the highest resolution available. Stable isotope ratios measured on osteological human or animal remains, and on charred plant organic samples, have been used in archaeology to answer multiple archaeological questions. These include, but are not limited to, the reconstruction of human diets, the investigation of animal and crop management practices, the recognition of probable dwelling places for given individuals, and/or the inspection of breastfeeding and weaning timings in past populations. As such, human lifeways were here approached through

‘Big Data’ collections, meta-analyses, Bayesian modelling, and newly generated measurements. Also non-isotopic proxies were employed, as several forms of archaeological evidence can be included in a model to increase the accuracy and precision of the reconstruction. Using this transdisciplinary, multi-proxy, and multi-scale approach, changes in human subsistence practices, infant feeding strategies, and spatial mobility were detected both at regional level (e.g. archaeological sites) and following broader spatiotemporal coordinates.

An important point within this work is hence the multi-scale approach. Depending on the research question, an analysis can be carried out at different scales. ‘Big Data’ meta-analyses can in fact attest shifts and/or the spread of given archaeological data that are otherwise invisible or underestimated at site level. Different scales can provide for different resolutions and interpretative limitations. In particular, the wider the scale, the higher is the possibility of observing how human lifeways shifted (or did not) across a more restricted number of historical variables. A ‘Big Data’ meta-analysis reduces in fact the impact of diverging behaviours on the final interpretation, hence allowing the detection of main trends. Novel statistical models have been recently proposed to investigate these. Developing machine learning programs and artificial intelligence implementations will also likely allow refining historical correlations. However, this is valid whenever a chosen scale is adequate to the amount and typology of data that is available. In this dissertation, some of the ‘Big Data’ spatio-temporal Bayesian options available from https://isomemoapp.com/ (IsoMemo) were presented here for the first time. Moreover, the use of the latest version of FRUITS (now ReSources), a Bayesian dietary mixing model, was also introduced as a potential high-resolution application of Bayesian softwares on different scales. In addition, the model OsteoBioR was employed on a selected case study to compare infant feeding practices on a local scale.

Publications composing this cumulative dissertation are preceded by an extensive introduction on human lifeways, stable isotopes, Bayesian modelling tools, database production and brief summary of the articles. Conclusive thoughts, constraints of the project, and future research directions are also included. This dissertation consists of six articles. Three of these relate to database production and these are: 1) Amalthea, a database for incremental dentine stable isotope analysis; 2) the Tooth formation age dataset for early childhood bioarchaeological and medical studies, a non-isotopic database that can be used as a reference for addressing early childhood diets; 3) the *Compendium Isotoporum Medii Aevi* (CIMA), a database collecting all isotopic measurements on human, faunal and plant samples from medieval Europe (more than 50000). As a general rule, data collections can highlight research gaps and provide for large data archives that can be used to compare new measurements. However, as mentioned, these compilations can provide for large scale spatiotemporal data meta-analyses concerning diet, farming economies, spatial mobility and infant feeding practices. Preliminary results have shown potential links between shifts in human lifeways trends and historical developments during the late Roman and medieval ages. This is also enhanced by the designing of a well-characterised metadata structure that includes several archaeological, historical, and biological variables. For example, shifting human dietary practices compared across imperial, late antique, and early medieval Rome were associated with demographic decrease, collapse of the political and economic Roman structure, and new adaptative farming economies. A large regional dietary variability was also observed on an European scale, suggesting that different climates, environments, political agenda, socio-economic systems, and cultural traditions had different impacts on human communities. An additional 'Big Data' meta-analysis using Bayesian modelling of pollen variables on a continental scale was also included in this dissertation. This showed how mortality rates of the Black Death were overestimated in the historiographic reconstruction.

Two selected case studies also compose this dissertation. These allowed observing shifting human lifeways on a local scale. Here, stable isotopes and Bayesian modelling options could be employed to explore past infant feeding practices in the Roman site of Bainesse (UK), and human diets, farming economies, and spatial mobility in southern Italy. These case-studies revealed smaller intra- and inter-site variations that suggested the existence of multiple local variables influencing human lifeways. For example, in Roman Bainesse (UK), some striking correlation between ancient medical recommendations and infant feeding practices as revealed through isotopes, suggested that the former could have been known, even at the northern frontier of the Roman empire. This is likely linked to military and commercial mobility in the area. However, the completion age of weaning varied across individuals and this still indicates that given choices could be influenced by other factors. This was associated with family traditions and/or socio-economic status. In Tertiveri (Italy), a moderate consumption of C_4 plants (likely millet) detected through isotopes is an interesting anomaly in respect to what is observed from other archaeological indicators in the region. This was connected to a local economy based on transhumance routes. Moreover, historical developments, likely linked with military expeditions, were associated with mobile individuals found in Tertiveri, who appear to have travelled from outside the region.

Overall, this dissertation proved that, at different scales and using multiple proxies, human lifeways in late Roman and medieval Europe were extremely heterogeneous. This was expected at site level, as many local variables and single human choices can influence subsistence practices, farming economies, infant feeding strategies, and mobility patterns. However, preliminary 'Big Data' Bayesian meta-analyses carried out on large volumes of isotopic data and combined with known evidence obtained from zooarchaeology, archaeobotany, anthropology, and written sources have revealed this point as valid even on a wider scale. This is not necessarily an *a priori* consequence of differences in the local scale, given that large human trends would overshadow smaller local differences. More likely, this instead confirms that human societies are impacted as a whole by main historical developments and environmental differences. This indicates hence that human lifeways do not only respond to biological inputs. At the state of the arts, it is hard to estimate which historical and/or environmental variables impacted late Roman and Medieval human lifeways the most. A direction to follow will be that of including into the analysis machine learning softwares applied to 'Big Data'. Future research concerning Roman and Medieval Europe and its margins is therefore suggested to employ a similar multi-scale and multi-proxy transdisciplinary approach to investigate human lifeways.

1. INTRODUCTION

The investigation of past human lifeways, which include subsistence practices, infant feeding strategies, small regional movements, and/or broader migrations, leads to obtaining a palimpsest of information on multiple and interconnected historical variables that engage with ancient societies. Even in modern times, how people behave in quotidian aspects can be associated with a shared system of values that is influenced by economic organisation, political agenda, social status, technological level, cultural views, ethics and religion. As a brief example, in the early 1970's the lowest infant breastfeeding rate since the post-war period was observed in northern England (Taitz 1983). This phenomenon was associated with a major marketing promotion of milk powder, substituting breastmilk (Taitz *et al.* 1981). The breastfeeding rate was then newly increased in the late 1970's, after a promotional campaign on the benefits of this natural process (Taitz *et al.* 1981; Taitz 1983). Thus, the existence of oscillating breastfeeding rates in such a limited temporal window shows how the association of technological progress, economic factors, and political agenda, influence human lifestyles across and/or within societies.

Whereas nutrition is a biological necessity that grants the organism to grow, survive, and reproduce, the varying consumption of different foods is driven by complex human choices. Historical variables can therefore affect human diets (Fig. 1). However, in a society, these rarely act as independent proxies, yet are often interconnected. For example, in hierarchical communities, marine resources can be associated with high status people, assuming an overall higher economic value of these foods compared to other protein sources (Graser 1940; Montanari 1988; Dyer 1989; Adamson 2004; Alcock 2006; Woolgar 2006; Garnsey 2008). Nonetheless, marine food accessibility may vary across sites and periods, as this is dependent on proxies such as different fishing technologies, proximity to a coastal environment and shifting market demands (Dahl & Oglend 2015). A similar consideration also applies to terrestrial animal and crop management practices. Zooarchaeological evidence from early Imperial (27 BCE - 235 CE) and late antique (c. 3rd - 7th centuries CE) Italy has shown substantial changes in farming economies, shifting from intensive field manuring and husbandry (especially pigs) to silvopasture (Salvadori 2019; MacKinnon 2019). This was hypothesised to be correlated with both a demographic reduction and the collapse of the economic and political proto-welfare system that Late Roman Italy gradually observed. Clearly, also seasonal availability and environmental accessibility of food sources, e.g. plants and marine sources, should be considered (Dyer 2006). These examples, among others, indicate how food production, management and consumption varied across societies as reacting to different and co-dependent historical conditions.

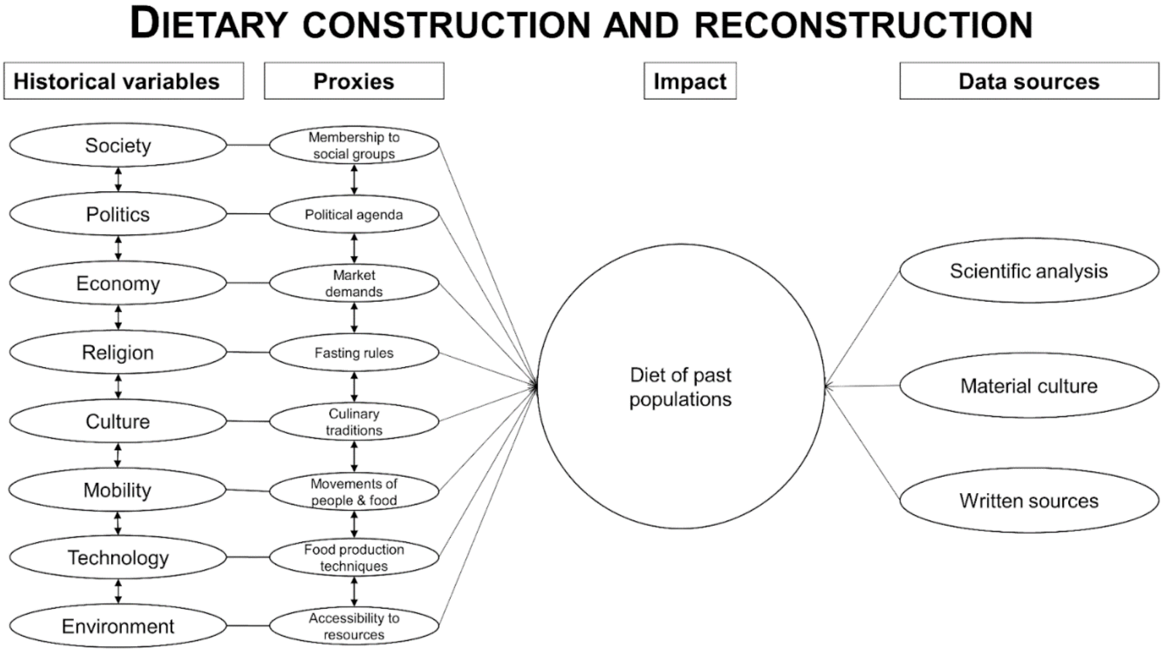


Fig.1. Here is presented a link between interconnected historical variables and human diets. These can be reconstructed via archaeological and written evidence.

A particular aspect of nutrition involves infant feeding practices. Infants cannot provide nourishment for themselves but they have to rely on their parents' choices. This includes how and when being breastfed. Breastmilk is a safe and easily digestible source of calories and macronutrients for neonates (World Health Organization 2014). When this is lacking or reduced to a short time, neonates may face serious health issues such as diabetes, celiac disease, inflammatory and cardiovascular issues or even cancer (Davis 2001). Whenever neonates could not rely on their mother’s breastmilk (e.g. because they died in giving birth) a possibility involved the employment of wet-nurses. This behaviour was particularly common in elite Roman society (Centlivres-Challet 2017; Parca 2017; Pedrucci 2018), as confirmed by contractual evidence and medical treatises (e.g. *Soranus* of Ephesus, *Gynaikeia* (Gynaecology), II, 12-15, 21). In alternative, animal milk could be used as a substitute, but this was likely unsafe for neonates given the presence of pathogens in unpasteurised milk (Angulo *et al.* 2009). The entire dietary process that starts when exclusive breastfeeding is paired with the first semi-solid foods and is completed once no more breastmilk or substitutes are given, is called weaning

(World Health Organization & United Nations Children's Fund (UNICEF) 1988). Its timing is nowadays an important research topic in archaeology, considering that this may vary significantly across sites or even families, following a mixture of cultural norms, economic affordability and medical knowledge (Wells 2006).

Human and animal spatial mobility at different geographic scales may also impact human subsistence practices plus other lifeway aspects that are shared in a given community. Smaller regional movements at individual level may be associated with socio-economic phenomena such as transhumance and intra-regional trade (Jones 2005). Broader mass migrations may instead affect local cultural traditions, bring in new technologies, religions and political systems, and adapt to novel farming economies (Hatton & Williamson 1998). Moreover, both small movements and larger migrations may be associated with specific social groups and imply multiple historical events. For example, a still ongoing debate in northern Italian early medieval archaeology involves shifting farming economies during the establishment of the Longobard Kingdom in 568/569 CE. The Longobards were a Germanic population that, from the first to the sixth centuries CE, had been wandering across Central Europe (Jarnut 1982). In 568 CE, this population moved from the Pannonian plains (Hungary) towards northern Italy. An overall increase in C_4 plants (likely millet or sorghum) consumption in the Po valley (Northern Italy) during the Longobard domination has been detected through different sources of evidence (e.g. historical sources: Montanari 1988; archaeobotany: Castiglioni & Rottoli 2013; stable isotopes: Iacumin *et al.* 2014). However, this historical correlation has not been properly cleared and explanations may involve dietary discrimination based on ethnic/social differences, new farming adaptations to overcome a century-long crisis, and/or dietary traditions brought in from the Pannonian plains.

Given the existence of multiple historical variables, a higher resolution in reconstructing past human lifeways can be obtained through a transdisciplinary approach. Whenever disparate proxies are available, these can be compared and contrasted. This is particularly applicable to Roman and medieval Europe, given that a high level of archaeological preservation is often paired with a large number of written documents and treaties. In addition, archaeobotanical (van der Veen *et al.* 2013), zooarchaeological (MacKinnon 2018), and bioarchaeological studies (Gowland 2017) for these periods are increasing. This provides hence the possibility of exploring high-resolution diachronic and synchronic changes in diet, resource management, and spatial mobility. During the period interested by this dissertation, i.e. Late Roman to late Medieval (c. third-fifteenth centuries), several historical shifts affected European regions at different rates and scales (Brown 1971, 1978; Holmes 2002; Backman 2003; Ward-Perkins 2006; Wickham 2006, 2010, 2016; Hoffmann 2014). Political transitions can be observed in reunification attempts made after the fall of the western part of the Roman Empire, such as the Carolingian (751-919 CE) and Holy Roman (962-1806 CE) empires. Moreover, new ‘proto-national’ kingdoms were established (e.g. England). The migration of several Germanic and Slavic tribes interested Europe at least for the whole Late Antiquity and Early Middle Ages (broadly 300-1000 CE). This created a combination of socio-cultural and legislative systems based on the previous Roman substrate and adapted to shared traditions from these incoming populations. Religions, their denominations and multiple dogmatic aspects (e.g. fasting rules) also had a central role in Late Roman and Medieval society. From Charlemagne’s coronation at Christmas of the year 800, the most effective temporal power expressed by a religious head was that of the Pope, who played a role of balance and sometimes of leadership among Christian states. Other particular dynamics involved climatic events on a limited temporal range (e.g. the volcanic winter of 536, Gunn 2000) or on a broader scale (e.g. the Medieval Warm Period, Broecker 2001). Finally, pandemics such as the ‘Justinian Plague’ (541-544 CE, Sarris 2022) or the ‘Black Death’ (1346-1353 CE, Izdebski *et al.* 2022) also are well documented historical events that impacted European societies.

All the events described above could possibly affect past human diets (e.g. Lightfoot *et al.* 2012), infant feeding practices (e.g. Kwok *et al.* 2018), animal and crop management strategies (e.g. Paxinos 2017), and spatial mobility (e.g. Alt *et al.* 2014) at different rates and scales. A large array of archaeological methods can nowadays be employed to detect these shifts. In this dissertation, stable isotope analysis was used as the main research proxy and combined with other sources of evidence to obtain the highest resolution available. Stable isotopes are proxies that have been largely employed in the last forty years to reconstruct human diets (e.g. Alexander *et al.* 2015), crop and animal management practices (e.g. Sirignano *et al.* 2014), weaning timings (Eerkens *et al.* 2017), and migrations (Knudson *et al.* 2012). These include, but are not limited to, $\delta^{13}C$ (Vogel & Van Der Merwe 1977), $\delta^{15}N$ (Schoeninger & DeNiro 1984), $\delta^{18}O$ (Longinelli 1984), $\delta^{34}S$ (Leach *et al.* 1996), and $^{86}Sr/^{87}Sr$ ratios (Ericson 1985) that are nowadays commonly employed to answer specific research questions (e.g. stress and weaning, Beaumont *et al.* 2013; manuring, Bogaard *et al.* 2007; diet and mobility, Lee-Thorp 2008; Nehlich 2015; Pederzani & Britton 2019; ancient agricultural practices: Szpak 2014). Stable isotope analysis is mostly carried out on osteological human and animal remains plus vegetal samples wherever available. Hard tissues such as bones, teeth, antlers and rostra are usually the most preserved organic human and animal remains recovered from archaeological sites. An important difference among sampled osteological materials may refer to the sample turnover rates. Bone cells have different remodelling rates depending on typology, biological sex, genetics and pathological lesions (Fahy *et al.* 2017). Moreover, tooth dentine and enamel do not remodel in mammals (Gage *et al.* 1989). This leads to different intra-individual isotopic signatures that reflect either an average temporal value of a number of years before the death of the individual (in bones), or a specific tissue formation period (in teeth). Furthermore, an incremental analysis of tooth dentine allows obtaining temporal isotopic ratios across the formation period of the tooth (Fuller *et al.* 2003; Eerkens *et al.* 2011; Beaumont *et al.* 2013; Czermak *et al.* 2018, 2020).

In the last decade, the increased production of archaeological databases and data meta-analyses brought in novel research perspectives on the human past (Kriegel *et al.* 2009; Steckel *et al.* 2019; Etu-Sihvola *et al.* 2019; Fernandes *et al.* 2021, 2022; Hoggarth *et al.* 2021). Database production in archaeology can follow different approaches. These can be summarised in two main 'philosophies': 1) a hierarchical approach; 2) a distributive approach. In the first instance, 'data' (i.e. the archaeological variable) is collected and inserted in a rigid database structure that has the aim of including the whole existing data available. Within a hierarchical database, 'metadata' (i.e. a set of contextual information that describes the collected variable such as site description, chronological range, etc.) needs to be extremely broad in order to include as much data as possible. For example, even 19th century archaeological or epigraphical collections, such as the *Corpus Inscriptionum Latinarum (CIL)* partially compiled by Theodor Mommsen and including all known Latin epigraphical evidence available at the time, followed this kind of approach (https://cil.bbaw.de). In more recent times, a distributive approach is being proposed. Scientific publications describing this philosophy are forthcoming (Ricardo Fernandes, pers. comm.), but as an example it is possible to mention the IsoMemo initiative (https://isomemo.com/). This initiative gathers together isotopic databases from archaeology, ecology, and environmental and life sciences. When using a distributive approach, a database structure can therefore be created according to specific criteria that reflect well-defined research questions. A high level of metadata characterisation can be achieved and this has the potential of increasing the resolution of the meta-analysis, with the condition that sufficient data is available. The final aim of collecting the whole existing data can be achieved through a series of independent databases that differ according to structure, research aim and level of characterisation.

Other than aiming for an important archiving purpose, the additional scope of a database creation is that of developing new data meta-analyses. This is particularly valid when following a distributive approach. A 'Big Data' spatiotemporal meta-analysis can in fact attest shifts and/or the spread of given archaeological data (e.g. a specific burial rite, a ceramic type, etc.) that are otherwise invisible or underestimated at site level (VanValkenburgh & Dufton 2020). Moreover, this approach allows observing broader patterns that are not affected by specific local variables. Correlations between shifts and historical developments may also be investigated and additional multiple research goals can be pursued and achieved at different scales. Moreover, depending on the level of characterisation of the metadata structure, further social, cultural, economic, political, and religious variables can be explored. Novel statistical models have been recently proposed to investigate independent archaeological variables at different scales (Fernandes *et al.* 2014; Cubas *et al.* 2020; Wilkin *et al.* 2020; Wang *et al.* 2021; Sołtysiak & Fernandes 2021). In particular, when using a Bayesian approach, several forms of archaeological evidence can be included in a model to increase the accuracy and precision of the reconstruction.

1.1 Explaining the approach

In this cumulative dissertation, a combined multi-scale and multi-proxy transdisciplinary approach was used to explore spatiotemporal changes of past human lifeways in Late Roman and Medieval Europe. However, the limits of such a broad topic for a three-years doctoral project must be acknowledged. Hence, a main focus that included database production was pursued to set the foundation of future studies on Late Roman and Medieval Europe. Moreover, these are used to address a multi-scale approach, given that they render 'Big Data' meta-analyses possible. In addition, selected case studies were analysed to compare and contrast this approach at different scales and resolutions. The main proxy that was employed was stable isotope analysis, in particular through data collected from previous scientific publications (Cocozza & Fernandes 2021a; Cocozza *et al.* 2022a), but also new analyses (Cocozza *et al.* 2021, 2022b). Isotopic novel results were combined with known evidence from zooarchaeology, archaeobotany, anthropology, archaeology and written sources. However, in Cocozza & Fernandes (2021b) the collection of a non-isotopic database such as the "tooth formation ages database" is also presented. This provided for a meta-analysis of tooth formation periods that are used as a temporal reference in dentine incremental stable isotope analysis. This latter is used for investigating infant feeding strategies in past populations. Eventually, in Izdebski *et al.* (2022), the main proxy employed to address mortality rates across Europe during the Black Death pandemic (1346-1352) was pollen remains. Here, the 'Big Data' approach and the research aim was consistent with the topic of this dissertation and thus included as a further publication. The final aim of this doctoral project is that of proving a high regional variability in human lifeways across late Roman and medieval Europe on different scales. This would confirm that human lifeways are strongly affected by historical developments and different environments. Moreover, the potential of a multi-proxy and multi-scale approach to detect these shifts is explored as a starting point for future research.

2. STABLE ISOTOPE ANALYSIS, A PROXY FOR PAST HUMAN LIFEWAYS

Isotopes, i.e. “[elements] which each have the same number of electrons and protons but differ in the number of neutrons” (DeNiro 1987, 187), have multiple applications in archaeology. For example, one of the most common isotope applications in archaeology is radiocarbon (^{14}C). A carbon-14 isotope balance between an organism and the atmosphere (plus potential dietary offsets, Ascough *et al.* 2005) is kept until the former dies, as no longer an exchange of carbon molecules is possible. Given that ^{14}C isotopes are radioactive and, as such, these decay through time, they can be used as a dating proxy (Taylor & Bar-Yosef 2016). However, in stable isotopes (e.g. ^{13}C or ^{12}C), this decaying phenomenon is not occurring, and therefore the measured isotopic signal in organic material is still the one retained in the tissue at the time of death. Nonetheless, this may still differ from the original value as including a potential diagenesis effect due to humic acids and additional contaminants (DeNiro 1985; Ambrose 1990; van Klinken 1999; Guiry & Szpak 2021).

Stable isotope ratios are usually subjected to fractionation when measured in mass spectrometry (McKinney *et al.* 1950). For this reason, they must be corrected comparatively to accepted international standards (Brand *et al.* 2014). As a convention, most stable isotope corrected values are reported in the delta (δ) notation (with some exceptions, such as radiogenic strontium), which is obtained by the equation presented in fig. 2 (Coplen 2011; Roberts *et al.* 2018). Corrected isotopic ratios in delta (δ) notation are also reported in permil (‰) to increase the readability of the value.

$$\delta^{i}E_{sample} = \frac{\left(\frac{^{i}E}{^{j}E}\right) sample - \left(\frac{^{i}E}{^{j}E}\right) reference}{\left(\frac{^{i}E}{^{j}E}\right) reference}$$

Fig. 2. Equation that expresses the Delta (δ) notation (as reported in Roberts et al. 2018). E= Element; iE = heavier isotopic element; jE = lighter isotopic element.

In archaeology, stable isotopes on organic tissues were employed for the first time in Vogel & Van Der Merwe (1977). This study evidenced how $^{13}C/^{12}C$ ratios measured in archaeological bone collagen could be used to infer prehistoric diets. In particular, these carbon ratios addressed the introduction of maize in the state of New York by comparing values measured in hunter-gatherers and first farmers. Given that maize is a plant that follows a C_4-molecules photosynthetic pathway and as such ^{13}C-enriched, its stable carbon isotope ratios are higher when compared to plants following a C_3-molecules photosynthetic pathway. This has a reflection in human diets that include a contribution from these food sources. In this case-study, hunter-gatherers lived and ate in a C_3 environment, whereas early farmers show higher stable carbon ratios as a consequence of a predominant consumption of maize.

Since then, other isotopic proxies were adopted from ecology and geochemistry for archaeological purposes. In particular, stable nitrogen ($\delta^{15}N$) isotopes were paired with carbon ratios to increase the resolution of the dietary reconstruction (Schoeninger *et al.* 1983; Schoeninger & DeNiro 1984). The mineral part of bones (hydroxyapatite, also called bioapatite) and teeth (enamel) was also subjected to stable carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) isotope analysis for additional dietary insights (Krueger & Sullivan 1984) and to address spatial mobility (Longinelli 1984). Radiogenic strontium ($^{87}Sr/^{86}Sr$) ratios were often paired with stable oxygen or even analysed individually to also investigate past mobility (Ericson 1985). However, this was also proposed to be used as a dietary proxy (Sealy *et al.* 1991), but rarely employed as such. Similarly, stable sulphur ($\delta^{34}S$) isotopes were employed to address both past diets and spatial mobility (Leach *et al.* 1996; Vika 2009). A summary of these main isotopic proxies and their archaeological scopes is presented in fig. 3. More recently, also other elements such as hydrogen (δD, Reynard & Hedges 2008), zinc ($\delta^{66}Zn$, Jaouen *et al.* 2018), calcium ($\delta^{44/42}Ca$, Reynard *et al.* 2013), and lead ($^{207}Pb/^{206}Pb$; $^{208}Pb/^{206}Pb$, Montgomery 2010) have been proposed as dietary or mobility isotopes for archaeological scopes. A recent improvement in isotopic archaeology, that has dramatically increased the resolution of the dietary reconstruction, involves compound specific stable $\delta^{13}C$ and $\delta^{15}N$ isotope analysis (CSSIA) of single amino-acids composing collagen (Corr *et al.* 2005; Styring *et al.* 2010).

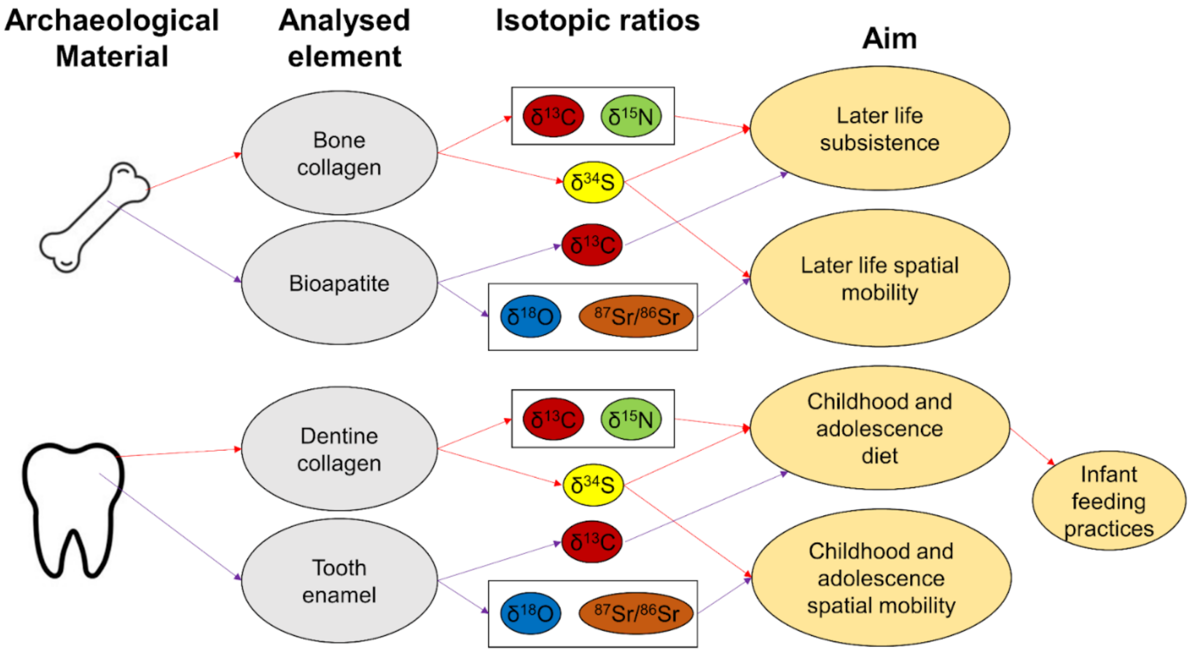


Fig. 3. Summary diagram of main isotopic proxies employed in archaeology and their scopes.

2.1. Bulk Collagen $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ analysis: Subsistence practices and resource management

Collagen is a protein that can be extracted from archaeological bones or teeth (via dentine) (fig. 3). The difference between these materials is turnover, given that teeth only mineralise during their formation period, whereas bone cells remodel *in vivo* at different rates (Gage *et al.* 1989; Fahy *et al.* 2017). This allows addressing human lifeways at different temporal scales. As a protein, collagen is composed of single amino-acids that contain molecules of carbon, nitrogen, sulphur, oxygen, and hydrogen. Therefore, stable isotopes of these elements can be measured on archaeological collagen to pursue multiple research goals, such as investigating past diets (e.g. Alexander *et al.* 2015), infant feeding practices (e.g. Eerkens *et al.* 2017), faunal and crop management practices (e.g. Sirignano *et al.* 2014; Dreslerová *et al.* 2021) and, to a lesser extent, spatial mobility (e.g. Vika 2009; Knudson *et al.* 2012). Stable carbon and nitrogen isotopes are the most widely measured ratios, followed by recent improvements in stable sulphur analysis (Nehlich 2015). However, some studies have also proposed to analyse stable oxygen and hydrogen isotope ratios in collagen, but this had limited applications due to analytical and diagenesis issues (Reynard & Hedges 2008; Kirsanow *et al.* 2008).

Bulk collagen stable isotope analysis is a proxy mainly used for reconstructing subsistence practices in past communities. Given that collagen is a protein, isotopic measurements reflect mainly the dietary protein contribution (Lee-Thorp 2008). Feeding experiments have evidenced that stable carbon ratios are routed for circa 74±4% from protein and the remaining percentage from a mix of carbohydrates and lipids (Fernandes *et al.* 2012). Stable nitrogen and sulphur isotope ratios instead reflect entirely the protein segment of diet (Fernandes *et al.* 2015). However, isotopic diet-to-collagen offsets are also produced during this metabolic process. These were calculated in collagen as 4.8±0.5‰ for δ^{13}C and 5.5±0.5‰ for δ^{15}N (Fernandes *et al.* 2015), whereas, in the case of δ^{34}S, a negligible offset is observed (0±0.5‰) (Nehlich 2015).

A link between human diet and isotopes is hence not straightforward, especially in absence of an isotopic baseline, i.e. isotopic values measured on expected animal and plant food sources. Stable carbon and nitrogen isotope ratios measured on bulk collagen would only approximately indicate whether isotopic values reflect a diet mainly composed of terrestrial *versus* marine resources. This is due to marine resources presenting higher δ^{13}C and δ^{15}N values comparatively to terrestrial baselines. This follows ^{13}C-enriched ratios in marine ecosystems and longer trophic chains among marine species (Schoeninger & DeNiro 1984). In the case of a purely terrestrial diet, a substantial dietary contribution of C_4 cereals such as millet or sorghum, can also be observed given that these present higher δ^{13}C values than C_3 plants, which include most cereals, plants and vegetables (Vogel & Van Der Merwe 1977). However, higher δ^{13}C values in terrestrial human diets can also reflect a high consumption of terrestrial animals that were fed with C_4 plants (Alexander *et al.* 2015). This is due to the fact that collagen mainly reflects the protein segment of a diet. A combination with δ^{34}S measurements can also improve dietary reconstruction. Stable sulphur isotope ratios are extremely homogeneous in marine resources (mean δ^{34}S: 20.3‰) due to constant cycling of water, whereas lower values are observed in terrestrial sources (Nehlich 2015). Terrestrial sources also present a large variability, as these are impacted by sulphur isotopes in local bedrock composition, aquatic sources, precipitation, and by coastal proximity (seaspray effect, see Göhring *et al.* 2018; 2019, on other isotopes). For this reason, and given no dietary offsets in sulphur isotopes, δ^{34}S can be employed also for spatial mobility purposes if an isotopic baseline is provided. A large variability in δ^{13}C, δ^{15}N, and δ^{34}S values can be observed in freshwater sources, complicating the dietary interpretation in certain environments.

Hence, an increased dietary resolution is provided by the measurement of an isotopic baseline. This should be produced through faunal and plant remains that belong to the same period and area of the investigated human community. Domesticated animals such as pigs, ovicaprines, cattle, and poultry as well as freshwater and marine fish remains found in sites should be sampled. Moreover, wild herbivores (e.g. deers) or rodent remains can also provide for comparative environmental isotopic signals. In addition, charred remains of wheat, barley, legumes, and millet, can increase even more the dietary resolution as providing reference values for the expected main consumed food sources. This is fundamental since wide isotopic ranges can be observed in archaeological food sources. These may vary across sites and periods as impacted by different environmental and anthropic variables such as climate (Hedges *et al.* 2004), altitude (Szpak *et al.* 2013), manuring (Bogaard *et al.* 2007), penning (Szpak 2014), and feeding (Alexander *et al.* 2015). Other than being used to reconstruct human diets, stable isotope analysis carried out on animal and plant remains are therefore also specifically employed to explore past resource management practices and farming economies (e.g. Sirignano *et al.* 2014; Buonincontri *et al.* 2017; Dreslerová *et al.* 2021).

2.2. Incremental dentine $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ analysis: Infant feeding practices

Infant feeding practices in past populations have been investigated through a variety of methods. Archaeological remains of baby bottles or breastfeeding depictions in statues, reliefs, and frescoes provide information on infant feeding techniques (Carroll 2018). However, material evidence is often found in funerary contexts and as such might be biased by symbolism and religious meaning. For Classical and medieval populations, more precise data can be obtained through the analysis of medical treaties and wet-nurse contracts (Fulminante 2015; Centlivres-Challet 2017; Parca 2017; Pedrucci 2018). Nonetheless, it must be borne in mind that these may indicate practices that were restricted to a specific portion of past societies.

Stable isotope analysis has provided invaluable information on timing and food sources involved in infant feeding practices (Prowse 2019). When an infant is being breastfed, a carer (i.e. the mother or a wet-nurse) provides nutrients to this latter through breastmilk. From an isotopic perspective, this process carries dietary stable isotopes, retained in the carer's milk, to the infant. However, given the existence of metabolic isotopic offsets, this latter will assume comparatively higher $\delta^{13}C$ and $\delta^{15}N$ values in their tissues than their carer (Fogel *et al.* 1989; Schurr 1998). Once the weaning process starts, the infant then consumes other food sources such as fruit, soft cereals and perhaps animal milk, paired with gradually lower amounts of breastmilk. These food sources are assumed to possess lower $\delta^{13}C$ and $\delta^{15}N$ values than breastmilk. Thus, it is possible to observe a temporal decreasing isotopic curve, which indicates at its pit when no more breastmilk is included in the infant's diet. In $\delta^{15}N$ values, the existence of a large metabolic offset (5.5±0.5‰) and the fact that nitrogen isotopes are routed entirely from protein (Fernandes *et al.* 2015) usually renders this decreasing curve extremely clear. In fact, breastmilk is a main source of protein from a ^{15}N-enriched source, whereas complementary foods are assumed to be low in protein and presenting relatively low stable nitrogen values. In $\delta^{13}C$ values, this trend should correspond to the $\delta^{15}N$ pattern but with a minor magnitude. Carbon isotopes, besides being impacted by a smaller metabolic offset (4.8±0.5‰) comparatively to $\delta^{15}N$, are also partially affected by carbohydrates and lipids during metabolic routing (Fernandes *et al.* 2012). However, carbon isotopes can also suggest the presence of physiological stress (Beaumont *et al.* 2018). This can also be shown macroscopically, radiologically or microscopically by the presence of unspecific stress marker like enamel hypoplasia (Berten 1895; Hillson 2014).

Bone bulk collagen stable isotope analysis has been often carried out on archaeological neonate and infant remains to detect a decreasing isotopic curve and assess a time range for the weaning onset at population level (Fig. 4a) (Reynard & Tuross 2015; Tsutaya & Yoneda 2015). Adult female measurements were also used as a reference value. Whereas this is a direct measurement of individuals that are expected to present a breastfeeding and weaning isotopic signal, the temporal resolution in these group comparisons is extremely low. This is due to relatively large temporal signatures integrated by bones (Fahy *et al.* 2017) and, moreover, sampling availability. Furthermore, in this respect, by analysing infants' osteological remains there is risk that these may have died because of wrong infant feeding practices. Hence, the buried population may not be representative of the living community, producing a so-called 'osteological paradox' (Wood *et al.* 1992; Beaumont *et al.* 2015).

Collagen extracted from adult tooth dentine samples was the subsequent step considered to overcome the 'osteological paradox' (Dupras & Tocheri 2007). Tooth dentine does not remodel *in vivo* and, as such, measured isotopic ratios mostly reflect dietary intakes assumed during childhood, even in adult 'survived' individuals. Exact time ranges depend on the formation period of each tooth (Schour & Massler 1940; Haavikko 1970; Fanning & Brown 1971; Anderson *et al.* 1976; Smith 1991; Liversidge *et al.* 2006; AlQahtani *et al.* 2010, 2014). However, bulk teeth integrate an isotopic signal that is an average of the whole temporal range of formation. The methodological refinement, also as consequence of improvements in mass spectrometry, was that of sectioning tooth dentine incrementally. Given that dentine does not remodel, it assumes and retains isotopes gradually during the formation period of the tooth. Thus, dentine increments will mainly reflect temporal childhood diets in relatively small time intervals (Fuller *et al.* 2003). Multiple sectioning techniques have been used so far, sometimes differing very little (Fuller *et al.* 2003; Eerkens *et al.* 2011; Beaumont *et al.* 2013; Burt & Garvie-Lok 2013; Henderson *et al.* 2014; Czermak *et al.* 2018, 2020). Overall, this methodology requires more effort and is more time-consuming when compared to a population analysis. However, this is more effective and provides for a high degree of temporal resolution, albeit this is counterpoised by the fact that it can be usually applied to a selected population subset.

Horizontal 1mm width sectioning from crown to tooth apex is the most commonly used technique (Fig. 4b), and this has reached a resolution of circa six months for each increment (Beaumont *et al.* 2013; Beaumont & Montgomery 2015). More recently, a less invasive and precise technique was proposed by Czermak *et al.* (2020). This consists of micro-sampling a sequence of dentine cylinders (1mm diameter) from crown to apex (Fig. 5). A critique to the horizontal sectioning technique is, in fact, that this is not sensitive to the dentine formation shape (similar to an umbrella) and it may inglobe, especially along the roots, overlapping isotopic signals that integrate multiple life periods.

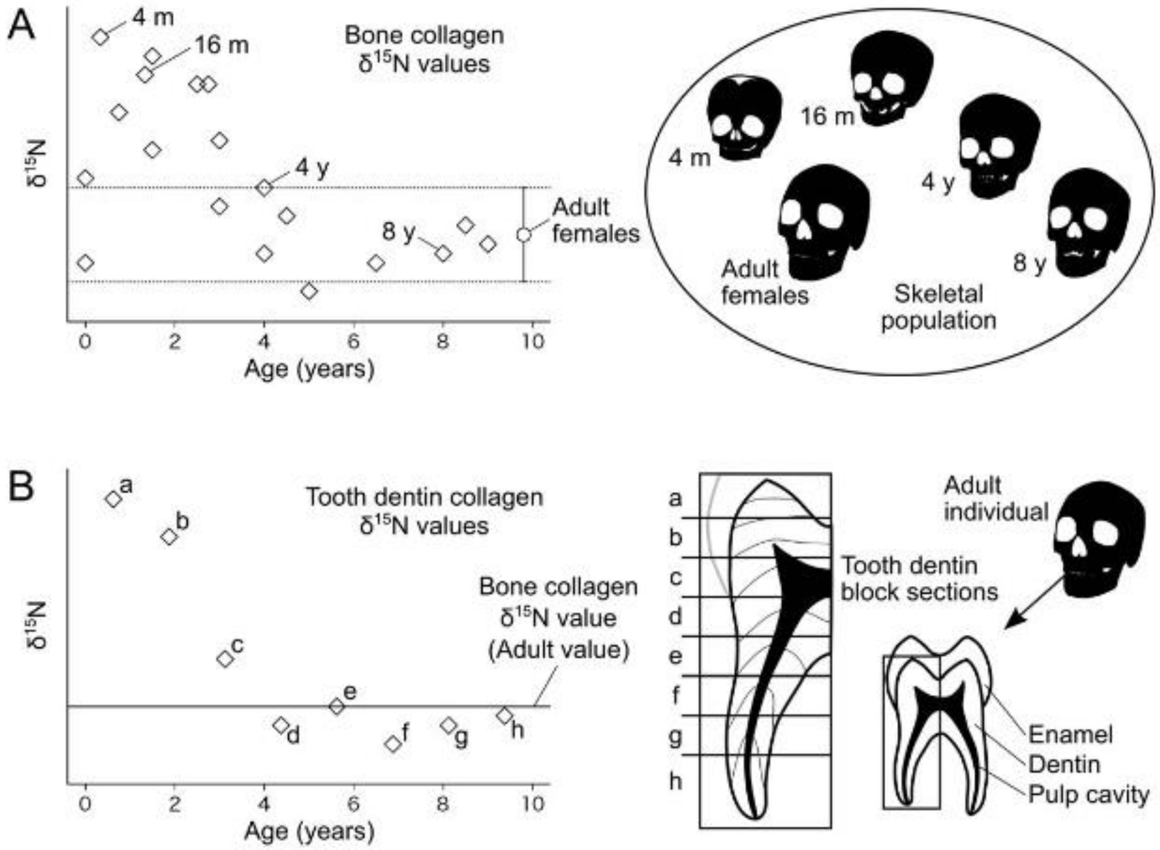


Fig. 4. Reference isotopic trends for infant feeding practices as observed in a) Bone collagen $\delta^{15}N$ values compared across an infant population; b) Incremental tooth dentine collagen $\delta^{15}N$ values in a single individual showing a temporal isotopic pattern. This figure is from Tsutaya & Yoneda (2015).

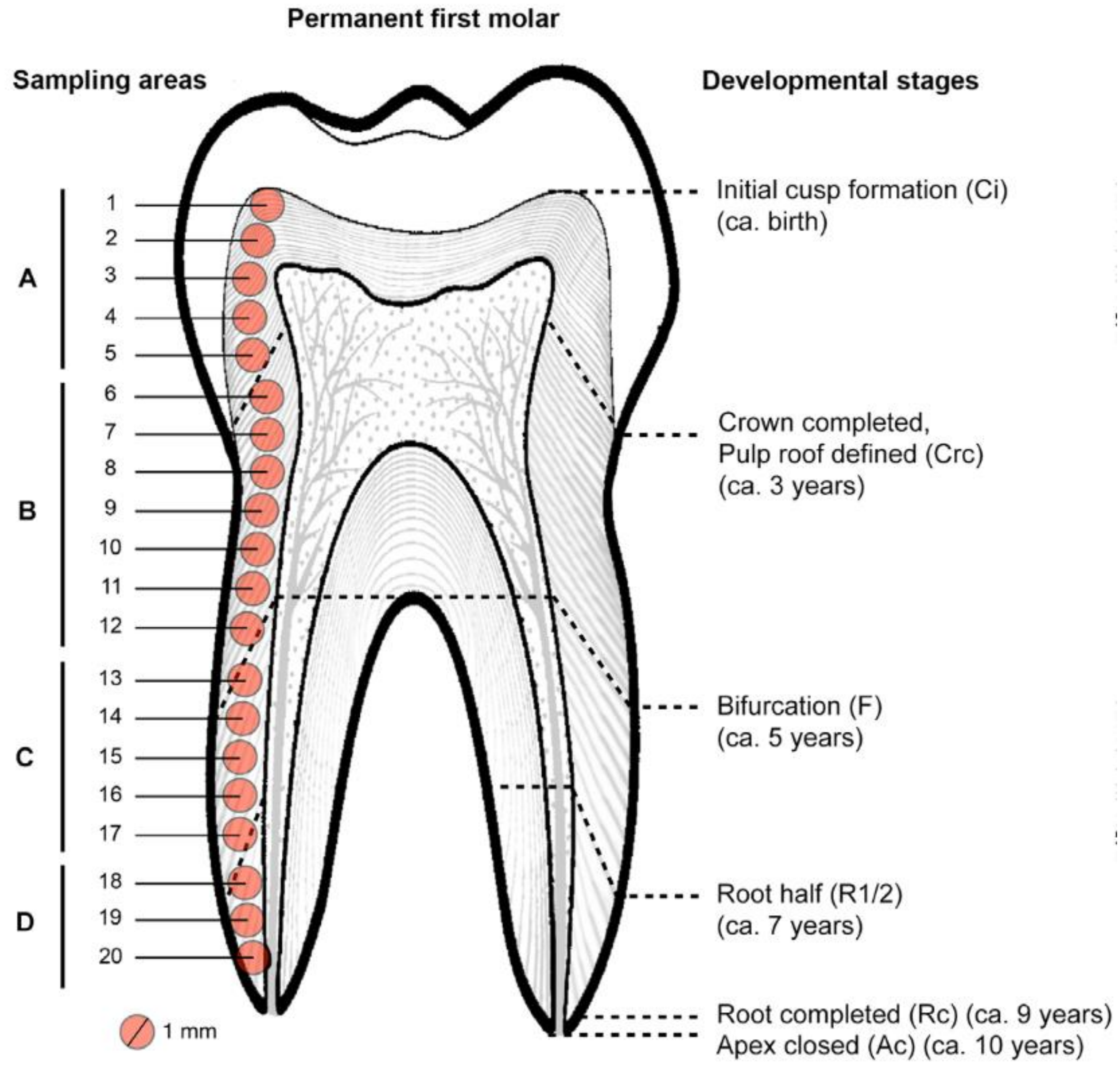


Fig.5. Incremental dentine analysis using 1mm-diameter cylinders. From Czermak *et al.* (2020).

2.3. Bioapatite and enamel $\delta^{13}C$, $\delta^{18}O$, and $^{87}Sr/^{86}Sr$ analysis: Improved dietary reconstruction and spatial mobility

Bones and teeth are composed of both an organic and a mineral part. The organic component includes collagen and this was discussed above. The mineral part is a carbonated calcium phosphate, also called hydroxyapatite. Chemical differences also exist between bone or dentine bioapatite and tooth enamel, given that the former presents more carbonate ione substitutes (CO_3^{2-}) and low crystallinity

(Lee-Thorp *et al.* 1989; Lee-Thorp 2008; Vallet-Regí & Arcos 2015). This leads to lower preservation of the *in vivo* isotopic ratios in bioapatite, as these can be affected by post-depositional soil contaminants (Lee-Thorp *et al.* 1989; Lee-Thorp 2008). For this reason, stable isotope analysis on tooth enamel is usually preferred in archaeological research, albeit it should still be considered that the isotopic signature reflects a pre-adulthood signal.

Given the presence of carbonate substitutes, it is possible to measure $\delta^{13}C$ ratios in bioapatite and enamel. Stable carbon isotopes in bioapatite follow a different metabolic route compared to carbon isotopes measured in collagen (Lee-Thorp 2008; Fernandes *et al.* 2012). In collagen, $\delta^{13}C$ values are routed for 74±4% from protein and the rest from carbohydrates and lipids, whereas in carbonate these reflect a diet carbon mix from all three macronutrients (Fernandes *et al.* 2012). Moreover, the diet-to-carbonate offset (10.1±0.5‰) is comparatively higher than in diet-to-collagen (4.8±0.5‰). Therefore, from an archaeological perspective, $\delta^{13}C_{carbonate}$ values can provide additional insights into the dietary analysis and in particular detect a main direct consumption of C_4 plants when the environment is C_3 or vice versa (e.g. Iacumin *et al.* 2014; Gugora *et al.* 2018; Dotsika & Michael 2018). A correlation between $\delta^{13}C_{collagen}$ and $\delta^{13}C_{carbonate}$ was proposed (Kellner & Schoeninger 2007), but this is limited to feeding experiments valid for that specific isotopic baseline and therefore not applicable in all archaeological populations.

As carbon isotopes are measured on the CO_3^{2-} ione substitutes, carbonated stable oxygen isotope ratios ($\delta^{18}O_c$) can also be measured on hydroxyapatite. However, oxygen isotopes are also present on the phosphate component of the hydroxyapatite (PO_4) and therefore can be measured separately ($\delta^{18}O_p$). Oxygen isotopic ratios in these two molecules cannot be directly compared, but need to be converted on the same reference scale (Chenery *et al.* 2012). However, oxygen isotopes that are measured either in carbonate or phosphate still do not reflect isotopic ratios found in water ($\delta^{18}O_w$), which is the original isotopic signal before entering into body tissues. Hence, an additional conversion is necessary to render isotopic values directly comparable with local baseline values (Luz *et al.* 1984; Daux *et al.* 2008; Pollard *et al.* 2011; Chenery *et al.* 2012). Oxygen isotopes can be measured relatively to the Vienna PeeDeeBelemnite (VPDB) or to the Vienna Standard Mean Ocean Water (VSMOW) standards and these can be converted using an established formula ($\delta^{18}O_{VSMOW} = \delta^{18}O_{VPDB} * 1.03092 + 30.92$).

Stable oxygen isotopes are used as a proxy to detect spatial mobility, especially as these can be sensitive to temperature and altitude variations (Longinelli 1984; Lightfoot & O'Connell 2016; Tuross *et al.* 2017; Pederzani & Britton 2019). When investigating this human lifeway, it is preferable to use a "non-mobile" *versus* "mobile" dichotomy instead of a "local" *versus* "non-local" one, as the former does not imply any social construct or personal identities. Moreover, it is also important to bear in mind that stable isotope analysis addresses spatial mobility relatively to the temporal signature of the sample. The underlying assumption that allows $\delta^{18}O$ values to be used for addressing past spatial mobility is that a non-mobile individual would only ingest water and consume food sources that originated locally (Longinelli 1984; Lightfoot & O'Connell 2016; Tuross *et al.* 2017; Pederzani & Britton 2019). As such, their stable oxygen isotope ratios should match with those from the local baseline. These reflect drinking water $\delta^{18}O$ ratios of local rainfalls, which provide nutrients to plants. Animals and humans then consume both water, plants and other animals, and therefore assume $\delta^{18}O$ values from these sources. However, the interpretation is complicated by the presence of diet-to-tissue offsets (i.e. $\delta^{18}O_w$ that are used in CO_3^{2-} ione substitutes and/or PO_4 molecules in hydroxyapatite), isotopic fractionation due to cooking activities (e.g. stewing and brewing), uncertainty in conversion formulas, sample diagenesis, lab pretreatment, and analytical errors in mass spectrometry (Longinelli 1984; Lightfoot & O'Connell 2016; Tuross *et al.* 2017; Pederzani & Britton 2019). For this reason, stable oxygen isotopes should be considered with conservative uncertainties and, possibly, paired with another mobility isotope proxy (e.g. $^{87}Sr/^{86}Sr$ ratios).

Strontium atoms are present in hydroxyapatite as calcium substitutes (Bentley 2006). Four strontium isotopes can be observed in osteological materials, and in particular the ratio between radiogenic ^{87}Sr (decaying from ^{87}Rb) and stable ^{86}Sr is measured to address archaeological questions (Ericson 1985; Bentley 2006; Montgomery 2010). Commonly, $^{87}Sr/^{86}Sr$ ratios are measured to explore spatial mobility in humans and animals, but this also underlies a potential dietary application (Sealy *et al.* 1991; Lahtinen *et al.* 2021). Strontium isotopes originate in local geological features but they can be carried to different soils through water sources. Plants assume ^{87}Sr and ^{86}Sr isotopes via nutrients in the soils and water. Animals and humans obtain their strontium intake through ingested water, consumed plants and the eating of other animals. As seen, the process is extremely similar to the assumption of $\delta^{18}O$ values in osteological tissues. However, the main difference is that strontium isotopes are not impacted by diet-to-tissue offsets and therefore hydroxyapatite will reflect an average $^{87}Sr/^{86}Sr$ ratio that was carried by all consumed sources. Whenever measured $^{87}Sr/^{86}Sr$ ratios in a sample match with those measured in the local isotopic baseline, it is likely to infer that this individual consumed local food and water sources. However, this is still an indirect interpretation of spatial mobility and further socio-economic considerations should be taken into consideration. For example, whenever 'non-mobile wealthy people consumed significantly more aquatic resources than the rest of the population their strontium signature may mislead to a pseudo mobility pattern (Lahtinen *et al.* 2021). In fact, aquatic resources tend to move along water sources within long distances. Hence, they assume different strontium signatures as they consume organisms from multiple environments. For this reason, it is always advisable to employ multi-isotope analysis when addressing spatial mobility in past human populations, in order to constraint the sources of different isotopic signals.

3. BAYESIAN MODELLING AND ARCHAEOLOGICAL APPLICATIONS

The employment of Bayesian statistics is not a novelty in archaeology. For example, in radiocarbon, this has been used since the early 1990's to probabilistic calibrate dates (Bronk Ramsey 2009). Bayes' theorem is a mathematical methodology that is used to obtain probabilities of events. Bayesian statistic is then used to obtain a posterior distribution of these probabilities using prior probability distribution and data. Prior information is the probability distribution that would express one's beliefs about a given quantity before some evidence is considered. For example, in the case of radiocarbon, this is represented by relative dating proxies such as ceramic typology, archaeological layers, etc. These allow to restrict the chronology also providing for some constraint. Priors could also be non-informative, whenever these are too vague or include a large uncertainty that does not allow to constraint the information. A Bayesian model is then set by the parameterization of prior information and data, and this leads to a probabilistic outcome.

More recently, a series of innovative modelling options for archaeological data that employ Bayesian statistics were developed by the Max Planck Institute for the Science of Human History, Jena (Dr Ricardo Fernandes) and other international partners. These R-based modelling tools (R Core Team 2021) are available online at https://isomemoapp.com/ and offline via source codes available on github.com (https://github.com/Pandora-IsoMemo/iso-app; https://github.com/Pandora-IsoMemo/resources; https://github.com/Pandora-IsoMemo/drat). These are part of the Pandora (https://pandoradata.earth/) and IsoMemo initiative, which brings together networks of archaeological databases and 'Big Data' meta-analysis. However, even data at site or individual level (e.g. isotopic measurements from a single individual) can be modelled using some of the statistical options. Archaeological databases that have been compiled within this doctoral project (Cocozza & Fernandes 2021a; 2021b; Cocozza *et al.* 2022a) are partners of the initiative and as such could employ these modelling softwares. These were also used in selected case studies and meta-analyses also included in this dissertation (Cocozza *et al.* 2021, 2022b; Izdebski *et al.* 2022). IsoMemo spatiotemporal apps, ReSources, and OsteoBioR are the three main softwares that were used and are below briefly described relatively to their high-potential in archaeological applications.

3.1. IsoMemo App: 'Big Data' spatiotemporal meta-analyses

IsoMemo App includes multiple Bayesian and non-Bayesian spatiotemporal modelling tools for large compilations of archaeological data. IsoMemo App is available at https://isomemoapp.com/. These options can be used to generate several data meta-analyses concerning the distribution, spread and comparison of selected archaeological variables. Data can be imported via Pandora (https://pandoradata.earth/) or uploaded through an external spreadsheet. These datasets necessarily require metadata fields that express geographical coordinates, in order to be modelled on a spatial scale, and a "dependent" numeric variable (i.e. the main collected data). In addition, some of the tools also present temporal modelling options, which further require chronological information (either expressed as interval, or mean plus standard deviation, or single point). Aside from modelling, a spatial distribution of locations that are compiled in the dataset can be exported via the "interactive map" option as .png, .pdf, or .jpeg files. Most of the archaeological applications of IsoMemo App are published in Cocozza *et al.* (2022a) where Bayesian examples displayed the high potential of large volumes of data. In this case, isotopic data from CIMA, a medieval stable isotope database for Europe and its margins was used. This publication is part of this cumulative dissertation and discussed below in section 4.3. However, a brief description of the different tools also follows. All outputs can be exported as .png, .pdf, .svg, .tiff, and .geo-tiff.

AverageR is a Bayesian geo-statistical model that estimates the expected value of a "dependent" variable across space. In figure 6a, this is used to generate a spatial isoscape of domesticated herbivores δ^{13}C values distribution for medieval Europe. The example is presented in Cocozza *et al.* (2022a) in combination with herbivore δ^{15}N values. This has suggested that environmental differences (e.g. altitude and temperature) may have a larger impact on δ^{13}C and δ^{15}N faunal values than anthropic factors such as cereal manuring, forage, and penning. This is a clear example of how a 'Big Data' approach can reduce the noise coming from local factors to observe main trends. As an additional example, AverageR was used in Wilkin *et al.* (2020) to generate dietscapes of average millet consumption across Early and Late Mongolian Empire. This shows that the potential of this model is not limited to isotopes. AverageR can also be employed to produce a Bayesian reference baseline for further modelling options (e.g. LocateR, see below; Wang *et al.* 2021).

TimeR applies the same principles valid for AverageR. In addition, the expected value of a "dependent" variable is also modelled across time and specific time-slices can be selected. In figure 6b, Bayesian spatial estimates of $\delta^{15}N$ mean values for human bone collagen in 800 CE Europe are shown. The model was in this case used to compare $\delta^{13}C$ and $\delta^{15}N$ human values in 200, 500, and 800 CE across Europe (Cocozza *et al.* 2022a). The aim was that of exploring continental shifts in human diets from the Roman empire to the early Middle Ages. Results have attested temporal changes and suggested the presence of a large regional variability. This likely indicate that different historical developments have impacted at multiple rates dietary shifts across the territories of the former Roman empire. Moreover, Time-sliced models can be saved and either used as a reference baseline or compared in a separate model (e.g. OperatoR, see below). Furthermore, in TimeR it is also possible to select geographical coordinates and generate a temporal plot of the "dependent" variable in given locations as done in figure 6c. In this example, geographical coordinates for Rome were selected and $\delta^{13}C$ and $\delta^{15}N$ values were modelled on a temporal scale, from the Roman period to early Middle Ages. In addition, these were contrasted between biological sexes assessed anthropologically in individuals. This analysis revealed that stable isotopes here varied across time and no significant difference is observed between sexes. Interestingly, isotopic temporal variations seem to correlate with known historical events, such as the fall of the western part of the Roman empire (Ward-Perkins 2006). These can both be linked with dietary shifts and changes in farming economies.

OperatoR performs mathematical operations between two previously produced models on a spatial scale. For example, in a 'Big Data' compilation that possesses a high level of chronological characterisation, it is possible to save multiple time-sliced models set at different years in TimeR and then contrast these in OperatoR. This will generate a spatial model that quantifies shifts in the 'dependent' variable between the two set time periods. Figure 6d shows this for average human $\Delta^{15}N$ values for two time slices (500 CE versus 800 CE). In the original example published in Cocozza *et al.* (2022a), this also included $\Delta^{13}C$ values and was combined with abovementioned $\delta^{13}C$ and $\delta^{15}N$ models for 200, 500, and 800 CE Europe. These difference models more clearly indicated the existence of varying regional isotopic shifts.

SpreadR is a Bayesian tool modelling the temporal distribution of a 'dependent' variable across space. This suits better for non-isotopic variables, e.g. the appearance of a given technology. In figure 6e this is applied to archaeological pottery and fatty acids analysis from the Neolithic in Atlantic Europe. The example is from Cubas *et al.* (2020), who have hence estimated dates for the Neolithic dispersal in this part of Europe. This model requires, in addition to geographical coordinates, chronological information for each database entry, which will be modelled to show the spread of the variable in given locations. As an additional example, this was used in Jarosz *et al.* (2022) to show the late spread of agriculture in the Ryukyu Islands, Japan.

KernelR is a spatial kernel density estimator. This tool, together with KernelTimeR, which is instead a 3-dimensional spatiotemporal kernel density estimator, is not modelling the 'dependent' variable. What is modelled is, in fact, the density of data provided in a dataset. A potential use of these two models is that of detecting research gaps or, vice versa, to select locations and periods where to perform better meta-analyses. This was done in figure 6f, where data clusters for isotopic measurements from medieval Iberia were formally detected (unpublished). This will be used for a forthcoming dietary meta-analysis. Moreover, in KernelTimeR, it is possible to generate a temporal density model in given locations. In figure 6g, a Kernel density temporal distribution of $\delta^{13}C$ and $\delta^{15}N$ human samples from London (green) and York (orange) dated to 1-1500 CE was generated. This was contrasted in Cocozza *et al.* (2022a) with a Kernel density temporal distribution of $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ human samples from the same locations. This latter suggested the existence of research gaps in mobility studies comparatively to dietary analyses. The former seems to focus in locations and periods where given mobility is expected (e.g. Roman London *versus* Anglo-Saxon London).

LocateR is a tool that assigns a density value to each location for a given value of the 'dependent' variable on a previous produced spatial model. The model can be employed to show probable dwelling locations by producing a Bayesian stable oxygen, strontium, or sulphur isotopic baseline in AverageR and then provide the relative value measured in the sample in LocateR. For example, this was used to address animal mobility across the prehistoric Yellow River basin in Wang *et al.* (2021). In figure 6h, a probability density map for place of origin for a Scandinavian individual buried in Repton, UK, was generated. The individual was part of the Great Heathen Army that invaded England in the late 9th century (Biddle & Kjølbye-Biddle 1992, 2001). Interestingly, the model points towards a higher probability that the original dwelling place of this individual is Ireland or the same Britain. This finds a counterpart in historical sources that mention the heterogeneity of the army and infers a potential link with Norse Dublin (Biddle & Kjølbye-Biddle 1992, 2001).

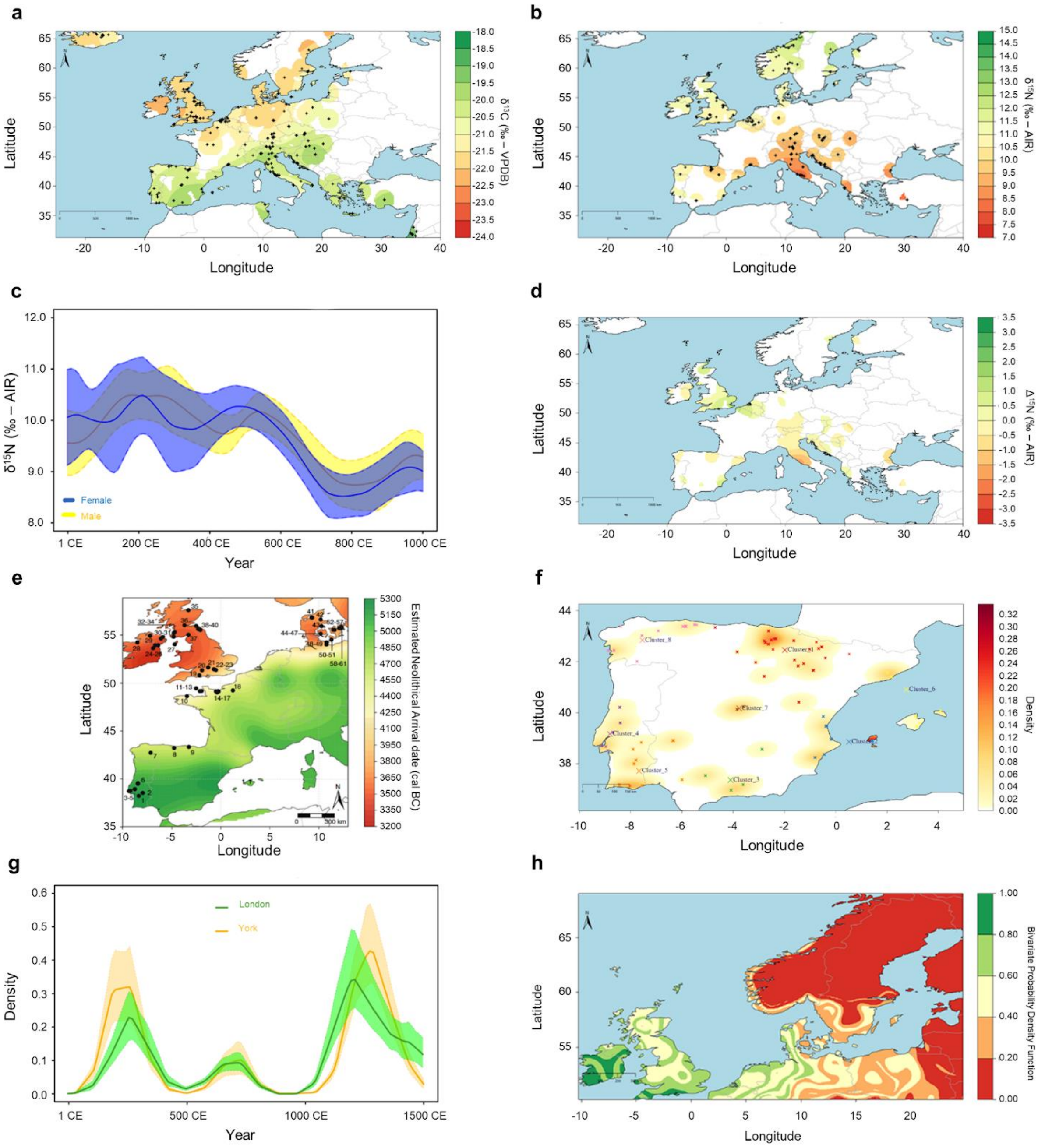


Fig. 6. Example outputs obtained using IsoMemo App modelling tools: **a**) Average domesticated herbivores $\delta^{13}C$ values distribution for medieval Europe (AverageR); **b**) Bayesian spatial estimates of $\delta^{15}N$ mean values for human bone collagen in 800 CE Europe (TimeR); **c**) Average human $\delta^{15}N$ values temporal distribution in 1-1000 CE Rome selected by biological sex (TimeR); **d**) Average human $\Delta^{15}N$ for two time slices (500 CE versus 800 CE) (OperatoR); **e**) Map of Atlantic Europe showing estimated dates for the Neolithic dispersal (SpreadR); **f**) Kernel Density spatial distribution and formal clustering detection for isotopic data from medieval Iberia (KernelR); **g**) Kernel density temporal distribution of $\delta^{13}C$ and $\delta^{15}N$ human samples from London (green) and York (orange) dated to 1-1500 CE (KernelTimeR). **h**) Probability density map for place of origin for a Scandinavian individual buried in Repton, UK (LocateR). Models **a-d**, and **g-h** are from Cocozza *et al.* (2022a) and are based on the CIMA compilation of isotopic measurements from Medieval Europe and its margins. Model **e** is from Cubas *et al.* (2020). Model **f** is unpublished, but it still employs data from CIMA.

3.2. ReSources: Dietary reconstruction through Bayesian Mixing Models

ReSources is an app available at https://isomemoapp.com/. This is an upgraded version of Food Reconstruction Using Isotopic Transferred Signals (FRUITS, Fernandes *et al.* 2014) and it is a Bayesian dietary mixing model. These are used to obtain an absolute quantification of dietary contributions. In the case of ReSources, this can be used to quantify both caloric and macronutrient (protein, carbohydrates, lipids) contributions obtained from different food sources composing past human diets. The model is mostly parameterized by using bulk stable isotopes as proxies, but recently, also Compound Specific Stable Isotope Analysis on Amino-Acids measurements were modelled (Soncin *et al.* 2021). Additional applications can be potentially explored using a variety of bioarchaeological proxies. Multiple Bayesian modelling options can also be used in ReSources, which depend on different research questions, dataset size, and quality and resolution of the archaeological information. Summary .csv, .xlsx, and .json files can be exported as well as .jpeg, .png, and .pdf plot outputs.

Recent research has used FRUITS/ReSources to reconstruct diets in past populations relatively to broad food groups (Fernandes *et al.* 2015; Bownes *et al.* 2017; Varano *et al.* 2020). These are often grounded on chemical classifications (e.g. C_3 *versus* C_4 plants), trophic categories (e.g. Herbivores *versus* Omnivores), or habitat divisions (e.g. Terrestrial *versus* Marine). This follows an issue of isotopic equifinality among different food sources that fall within the same group, rendering undistinguishable the dietary signal source. However, an important update in ReSources concerns the possibility of including additional non-isotopic prior information that constrains the model and increases the precision of the dietary output. This is a fundamental multi-disciplinary procedure that allows the definition of a dietary model with the inclusion of zooarchaeological, archaeobotanical, anthropological, archaeological, and even written evidence.

In figure 7, this is shown for a high-resolution dietary reconstruction for Imperial (200 CE), late antique (500 CE), and early medieval (800 CE) Rome. Isotopic 'Big Data' from CIMA (Cocozza *et al.* 2022a) and IsoArcH (Salesse *et al.* 2018) were modelled in TimeR at different time slices (200, 500, 800 CE). Data included $\delta^{13}C$ and $\delta^{15}N$ isotopic measurements for humans, animals, and plant individuals relatively to the city of Rome. A high-resolution reconstruction was aimed for the first time including very specific food groups that usually possess similar isotopic values (e.g. wheat *versus* barley *versus* legumes, usually included within a broad 'C_3 plants' category). This was made possible through the inclusion of Bayesian priors obtained from archaeobotanical (Sadori & Susanna 2005; Caracuta & Fiorentino 2009; van der Noort *et al.* 2009; Murphy *et al.* 2013; Buonincontri *et* *al.* 2017; Robinson & Rowan), historical (Montanari 1988; Garnsey & Scheidel 1998), and zooarchaeological (King 1999; Minniti 2005; MacKinnon 2019) evidence on Roman and early medieval central and southern Italy. The left side of the figure shows, in fact, how the model without the inclusion of this prior information would not be able to distinguish between different food group contributions. On the right side instead, dietary caloric intake is extremely precise due to priors (fig. 7d). These revealed a decrease of wheat and pork consumption during the late antique and early medieval periods, in favour of more barley, legumes, and sheep/goat contributions. These were also compared with modern Italian intakes, normalised relatively to the same food groups (http://www.fao.org/faostat/en/#data/FBS).

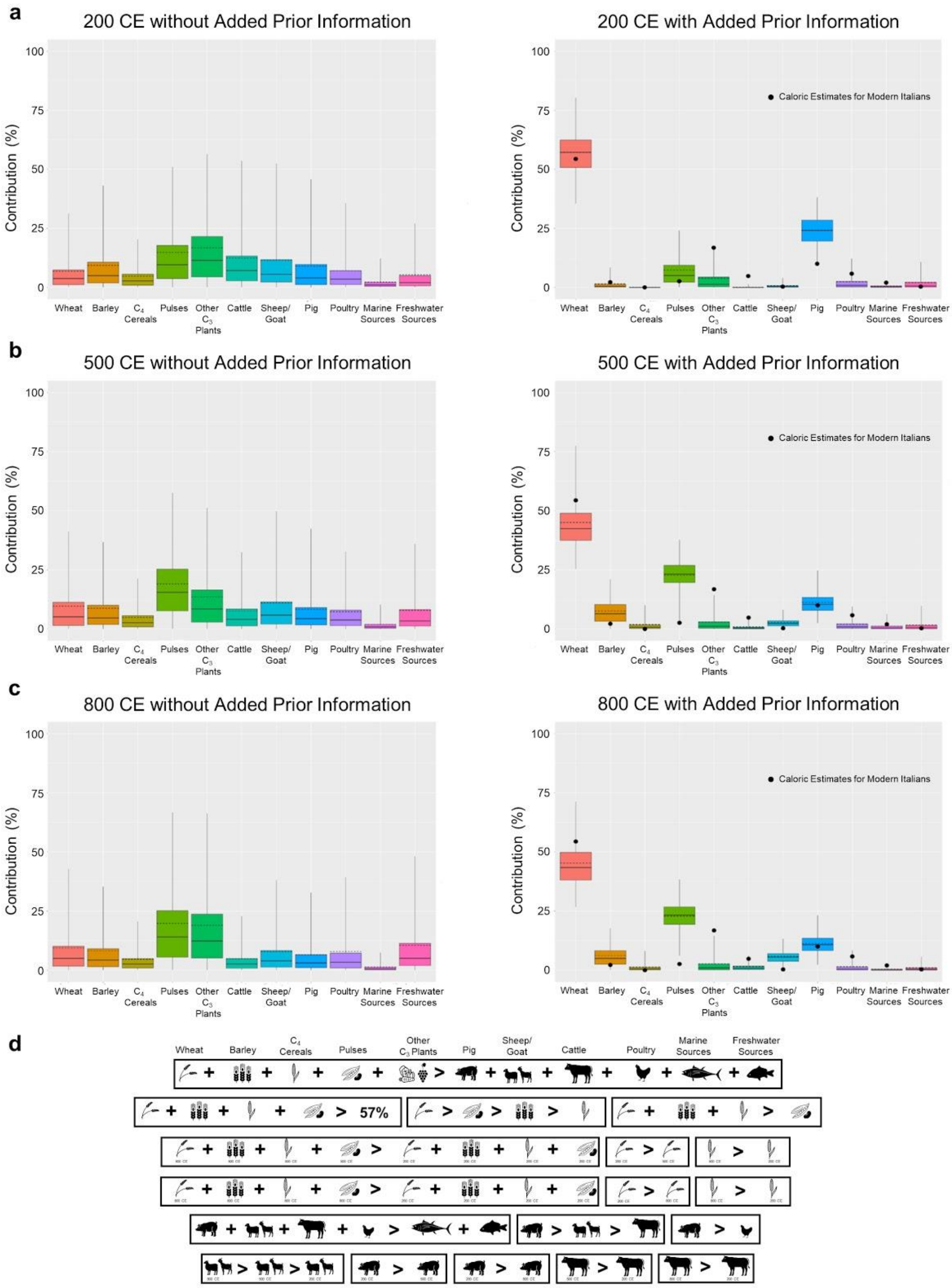


Fig. 7. 200 CE (a), 500 CE (b), and 800 CE (c) dietary estimated models of main food sources caloric contribution for the city of Rome without (left) and with (right) added prior dietary information (d). Black circles within plots correspond to modern dietary estimates for Italians. This figure is from (Cocozza *et al.* 2022a) and information on model parameterization can be found therein.

3.3. OsteoBioR: A Bayesian model for comparing multi-tissue isotopic measurements

OsteoBioR is a software available at https://isomemoapp.com/ that allows modelling multiple intra-individual isotopic measurements on a common temporal scale. Once a common scale is provided, isotopic measurements can be compared at intra- and inter-individual level. Summary .csv, .xlsx, and .json files can be exported as well as .jpeg, .png, .svg, .tiff, and .pdf plot outputs.

Collagen extracted from bone samples reflects different temporal isotopic signatures depending on the typology of osteological material. Ribs integrate an isotopic signal of circa 3-5 years on average and a similar turnover rate seems to apply to humeruses (Fahy *et al.* 2017). On the other hand, femurs appear to retain an average signal of up to 10 years before death (Hedges *et al.* 2007) and cranium fragments are likely also integrating a late childhood/adolescence signature (Fahy *et al.* 2017). At this resolution, multi-bone isotopic analysis may provide information only in case of significant dietary changes through the adult life of an individual.

More precise temporal ranges are instead provided by teeth. These do not remodel and as such they retain isotopic values assumed during their formation period (Gage *et al.* 1989). Formation periods vary depending on tooth type (Schour & Massler 1940; Haavikko 1970; Fanning & Brown 1971; Anderson *et al.* 1976; Smith 1991; Liversidge *et al.* 2006; AlQahtani *et al.* 2010, 2014), and, including also deciduous teeth, these cover a broad temporal range from *in utero* to late adolescence/early adulthood. When carrying out incremental dentine analysis on strategic tooth samples (e.g. permanent first, second, and third molars) it is possible to reconstruct the temporal isotopic evolution of an individual from birth to circa 20 years at the resolution of circa 6-months intervals. Oscillations in isotopic values can reflect dietary shifts, infant feeding practices, physiological stress, and even potential mobility patterns. This latter assumes a change in the isotopic baseline that composes the diet of the individual.

However, an underestimated methodological issue involves the intra- and inter-individual incomparability of isotopic measurements obtained from different tissues or increments. Bone turnover rates vary among people as impacted by genetic factors, biological sex, and even age (Fahy *et al.* 2017). The same factors also affect temporal differences in tooth formation periods (Schour & Massler 1940; Haavikko 1970; Fanning & Brown 1971; Anderson *et al.* 1976; Smith 1991; Liversidge *et al.* 2006; AlQahtani *et al.* 2010, 2014). In regards to dentine increments, an additional problem arises as sections do not possess the exact same length and/or these are often combined to provide measurable material. In addition, it should also be noticed that these reflect the average of overlapping isotopic values retained during the interval of formation of the same increment.

For the reasons mentioned above, samples rarely present comparable isotopic signals among individuals or different intra-individual tissues. Albeit the former is not an issue when addressing broad population studies, the latter has to be considered for a high-resolution investigation of temporal dietary shifts. The Bayesian software OsteoBioR provides therefore for a common temporal scale that considers all these temporal uncertainties. Once all isotopic measurements are presented on the same scale, these can be finally compared to address high-resolution archaeological questions. In figure 8 this appears clear as isotopic measurements are modelled into six-months intervals. Hence the first modelled increment does not represent a precise moment in life, yet an average within a temporal interval, e.g. [0-0.5]. If all increments are on the same scale, and all other individuals also follow this approach, it is possible to compare isotopic values for each interval and, consequentially, temporal diets. In the example from figure 8, BN144, a female Roman individual from Bainesse, UK, shows a potential prolonged exclusive breastfeeding patter up to [0.5-1.0] year (Cocozza *et al.* 2021). This is extremely interesting, because this is what the Greek physician Damastes recommended for female individuals (reported in *Soranus, Gyn., 2.48*) and also finds a parallel in another female individual from the same site (BN213). A temporal decrease in $\delta^{15}N$ values up [4.0-4.5] years at least, indicates a probable weaning completion around that age. This goes in contrast with medical recommendations by ancient physicians that suggested a weaning completion between two or three years.

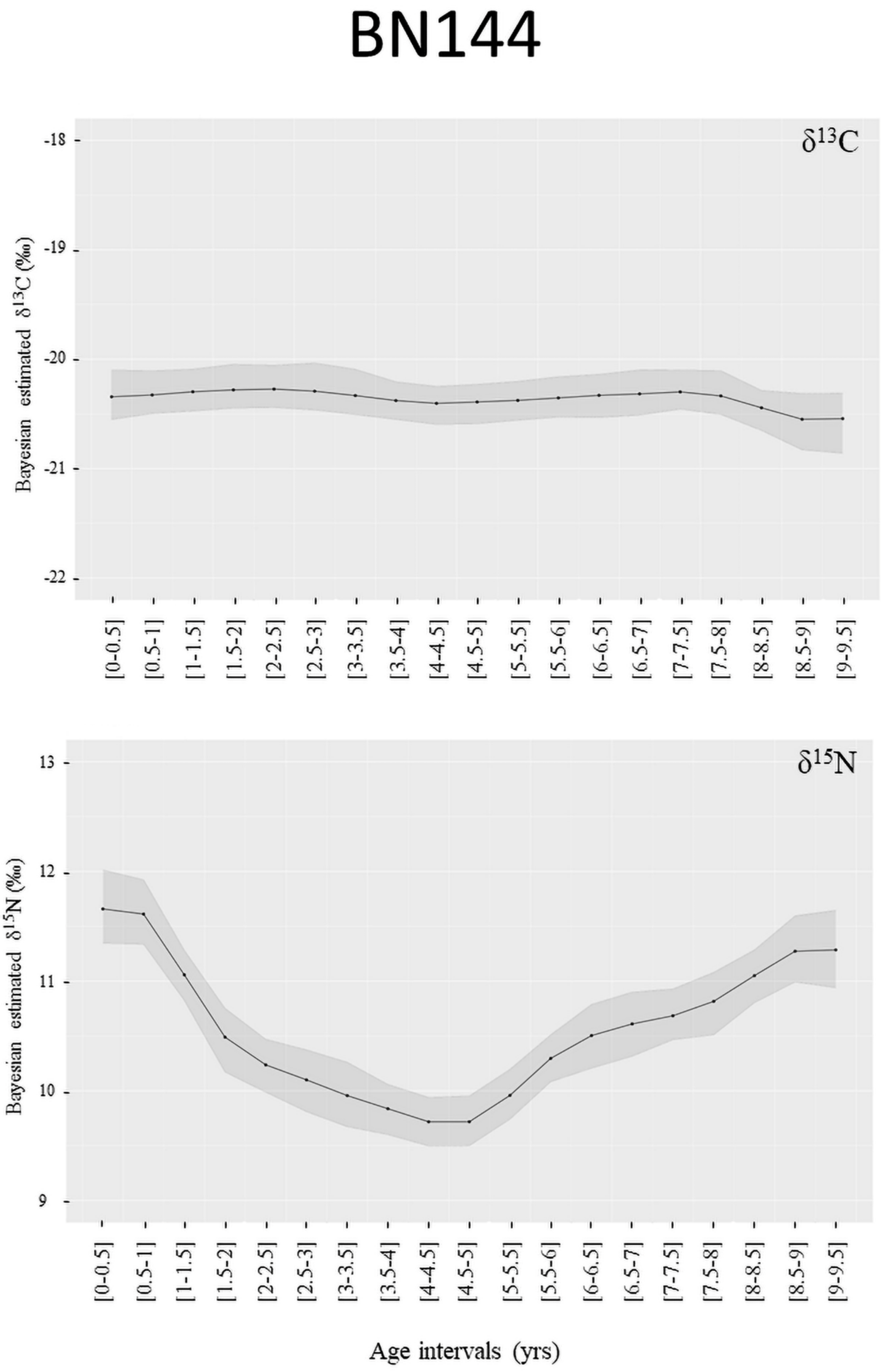


Fig. 8. Bayesian temporal modelling of a first molar incremental dentine $\delta^{13}C$ and $\delta^{15}N$ for a Roman individual from Bainesse, UK (Cocozza *et al.* 2021).

3.4. The Potential of Bayesian Modelling: A 'Big Data' meta-Analysis of dietary shifts in Longobard Italy

As observed in the examples above, Bayesian modelling options can be employed when 'Big Data' set on spatiotemporal coordinates is available. In this paragraph, a potential dietary meta-analysis is presented with the aim of illustrating the importance of database compilations and their statistical meta-analyses. The CIMA database (Cocozza *et al.* 2022a) is the main source of this meta-analysis, that concerns dietary shifts in Longobard Italy. As mentioned in the introduction, an unsolved research question involves a dramatic increase in C_4 cereal (likely millet or sorghum) consumption in early medieval northern Italy. Whereas this is not observable in all sites (e.g. Marinato 2018; Amorim *et al.* 2018; Riccomi *et al.* 2020), the 'Big Data' analysis will show whether this phenomenon represents a real human lifeway shift.

Montanari (1988) suggested that this increase in the consumption of so-called 'minor cereals' is explainable through a break, during Late Antiquity, with the former Roman system of cereal cultivation and the shifting from a wide market economy to a local subsistence production. This likely raised wheat and barley prices, that were the main cereals in Roman times. Therefore, as more economic (probably untaxed) cereals, C_4 became the main staple food for north Italian populations. Castiglioni & Rottoli (2013) also mention potential environmental factors and botanical characteristics of millet and sorghum, such as durability, growing rates, soil adaptations in the Po valley, and the requirement of smaller pieces of land comparatively to C_3 cereals. These factors would fit with the previous socio-economic interpretation, also adding an archaeobotanical explanation for this practice. Iacumin *et al.* (2014) agree with the previous interpretations and also argues that the political instability in the Late Antiquity may have impacted on the choice of cultivating these cereals. In fact, the continuous passage of armies and subsequently pillaging and ravaging actions, probably led poorer classes to prefer fast-growing and less resource-intense crops.

Within this scenario, Longobards (568-774) appear to be a passive presence. Iacumin *et al.* (2014) suggest that, as representing the dominant class, they fed with high-value cereals such as wheat and barley. However, a possible cultural impact given by the same Longobards in this pattern is still possible. Figure 9 shows a temporal plot for $\delta^{13}C$ and $\delta^{15}N$ values set in north-eastern Italy, where the amount of data is sufficient for this analysis. Preliminary results here indicate a correlation between a $\delta^{13}C$ average increase and the Longobard domination. The absence of a parallel $\delta^{15}N$ increase suggests that this is related to the consumption of C_4 cereals.

Whether this follows dietary traditions brought in by the arrival of the new population, or this was part of an economic agenda, a possible acculturation pattern cannot be ruled out. Longobards are assumed to originate in northern Germany and, in circa five centuries they settled in the Pannonian (i.e. Hungarian) plains (Jarnut 1982). Isotopic studies on Longobards before they set in this region are limited to one cemetery from Czech Republic, where a main C_3-based diet is attested (Plecerová *et al.* 2020). A comparison with other Migration Period populations from modern Germany also show a clear C_3-based dietary signal (Wiedemann & Bocherens 1997; Schutkowski *et al.* 1999; Strott *et al.* 2008; Hakenbeck *et al.* 2010). In the Pannonian area, a massive consumption of C_4 cereals was instead observed in Huns, Avar, and Gepid populations before and during the arrival of the Longobards (Hakenbeck *et al.* 2017). The only Longobard cemetery in Hungary that has been analysed using isotopes is Szólád (Alt *et al.* 2014). However, even here the majority of the population appear to possess a main C_3-based diet, but some of the individuals show higher $\delta^{13}C$ values that indicate a direct and significant consumption of C_4 plants. It is hence possible that Longobards became knowledgeable of millet/sorghum cultivation in the Hungarian plains. This does not necessarily mean that they assumed a new dietary tradition. Given that northern Italy faced a centuries-long crisis derived from wars, famines, and plagues, Longobard rulers may have adopted an extensive cultivation of C_4 cereals to provide fast subsistence to the poorer population. Additional data set in precise chronological ranges and further funerary studies can improve this preliminary analysis, in particular to investigate whether a proper ethnic-based dietary difference existed.

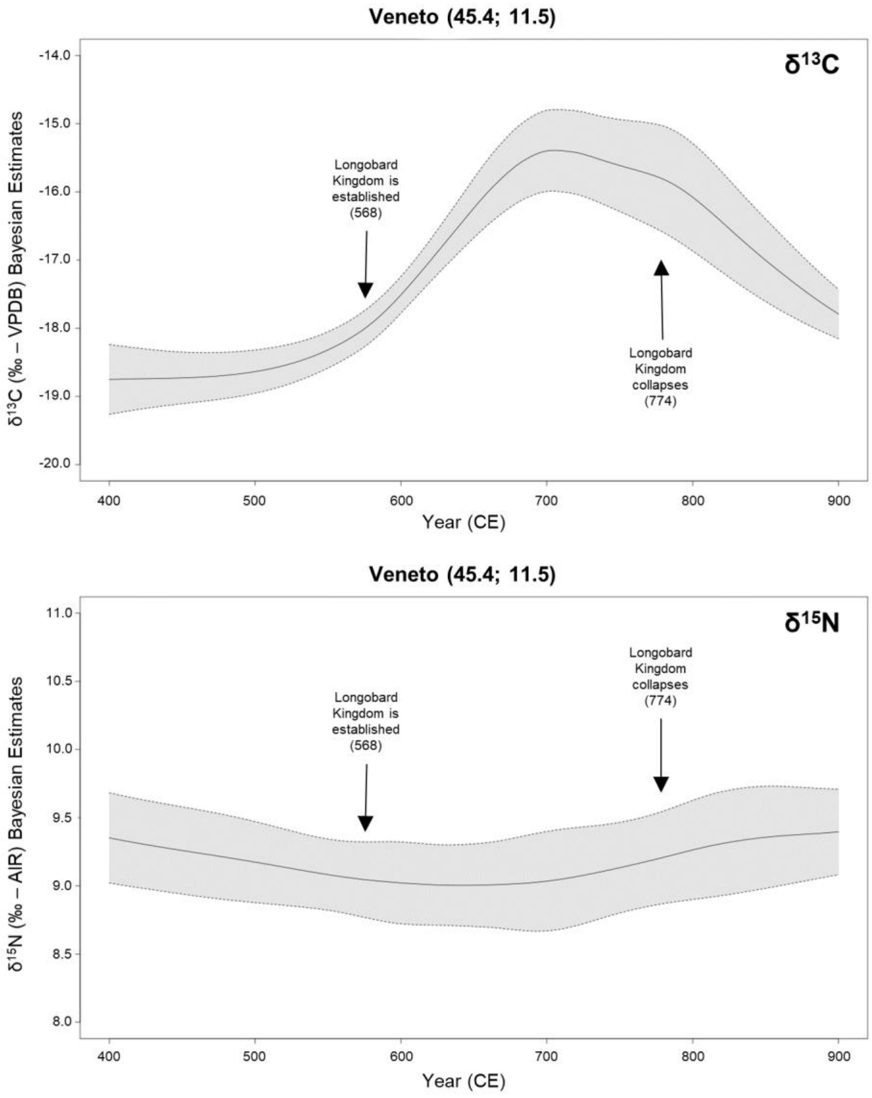


Fig. 9. Bayesian temporal estimates of $\delta^{13}C$ and $\delta^{15}N$ values for the Veneto region (coordinates set at 45.4; 11.5) between 400 and 900 CE. Data from CIMA (Cocozza *et al.* 2022a), figure unpublished.

3.5. The Potential of Bayesian Modelling: Reconstructing a high-resolution osteo-biography

All the modelling options discussed in this chapter can be combined to reach an extremely high level of resolution of human lifeways reconstruction, even in single individuals. In this paragraph, an undergoing research aiming to reconstruct the osteobiography of an unknown individual shows the potentiality of this approach. In 2019, during the excavation of a Roman villa in Sorrento (Italy), a grave containing an adult human (CDS1) was found. The grave was part of a small rural cemetery that was set within the ruins of a villa, in conjunction with a chapel dedicated to Saint Fortunata. However, this chapel had never been explored through an excavation and documentary sources on its foundation are missing. The skeleton presented a low level of osteological completeness and preservation, hence biological sex could not be assesses through established methods (Acsádi & Neméskeri 1970; Ferembach *et al.* 1980; Rösing *et al.* 2007). Age at death was defined using dental wear (Brothwell 1981) and revealed CDS1 as an approximate 25-35 year old individual. Moreover, traces of mechanical stress (enthesopathies) on the right femur are an indication of hard physical work. Therefore, in order to reconstruct this individual's osteo-biography multiple samples were recovered and subjected to different biochemical techniques. These include radiocarbon, stable carbon, nitrogen, and oxygen isotope analysis (on bone, bioapatite, incremental dentine, and enamel), aDNA, and proteomics. Results are then interpreted in the light of the known historical and archaeological context.

This study is still undergoing and results are preliminary. Proteomics and aDNA results are not available yet (June 2022). However, radiocarbon allowed to set this individual within the 8th century CE, when Sorrento was part of the Byzantine duchy of Naples. Interestingly, this matches with the spread of the cult of Saint Fortunata in the gulf of Naples, whose relics were translated in the second half of the 8th century (Vitolo 1990). This could likely set a reference chronology for the chapel. Bulk stable carbon and nitrogen isotope modelled results extracted from a rib fragment revealed a main C_3-based terrestrial diet with a low inclusion of animal protein and high in cereals and plant carbohydrates (Fig. 10). Incremental dentine analysis on a first, second, and third molar allowed to model isotopic values from birth up to circa 17 years (Fig. 11). Unfortunately, tooth roots were not well preserved and as such this could not be extended further. This has showed a weaning process going from six months up to two years of age. This latter is strikingly consistent with Roman and Byzantine recommendations (Fulminante 2015). After this period, some oscillations are present, indicating dietary shifts or shifts in the isotopic food baseline. This latter hypothesis is extremely fascinating and consistent with stable oxygen isotope results measured on the enamel of the same first, second, and third molars. In fact, despite an assumed low status of the individual as suggested by dietary and palaeopathological results, the analysis shows a high level of childhood spatial mobility (Fig. 12).

A possible reasonable justification for childhood high spatial mobility in a low status early medieval individual may be related to servitude and slavery, which did not disappear in Italy since the Roman period (McCormick 2002, 2016; Rotman 2009; MacMaster 2015). Byzantine law regulated that children conceived from a slave were born with the slave status, even if one of the parents was the master (Rotman 2009). As such, it is attested the existence of more or less regular neonate slave movements, patronised by their masters to ensure good health with correct breastfeeding and weaning practices (MacMaster 2015, 92-93). Moreover, as a child, it is possible that CDS1 was relegated to domestic mansions. In this case, Byzantine sources report the travelling of wealth men followed by their domestic household (MacMaster 2015, 64-78). Other explanations are still possible, but this scenario fits strikingly with isotopic results and the historical context.

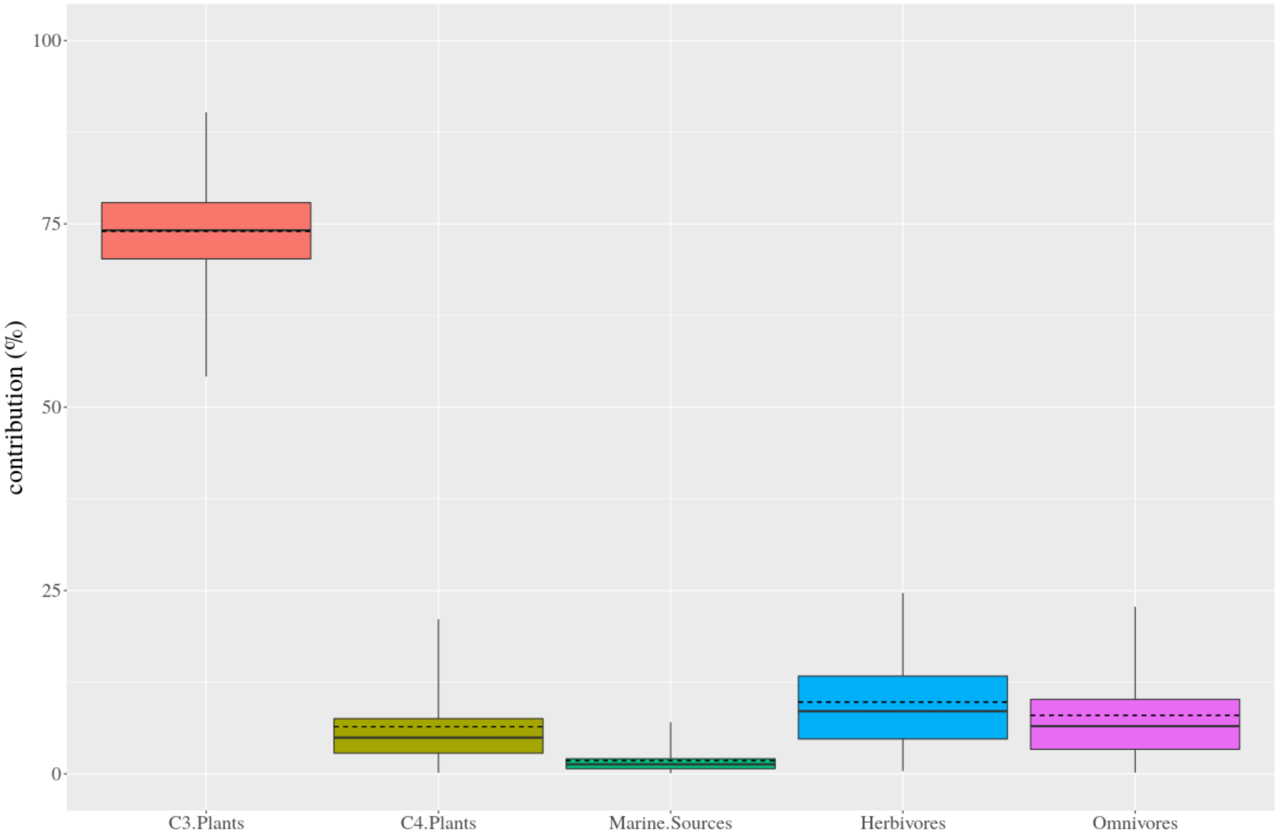


Fig. 10. Bayesian estimates of caloric contribution from main food groups for CDS1 (unpublished).

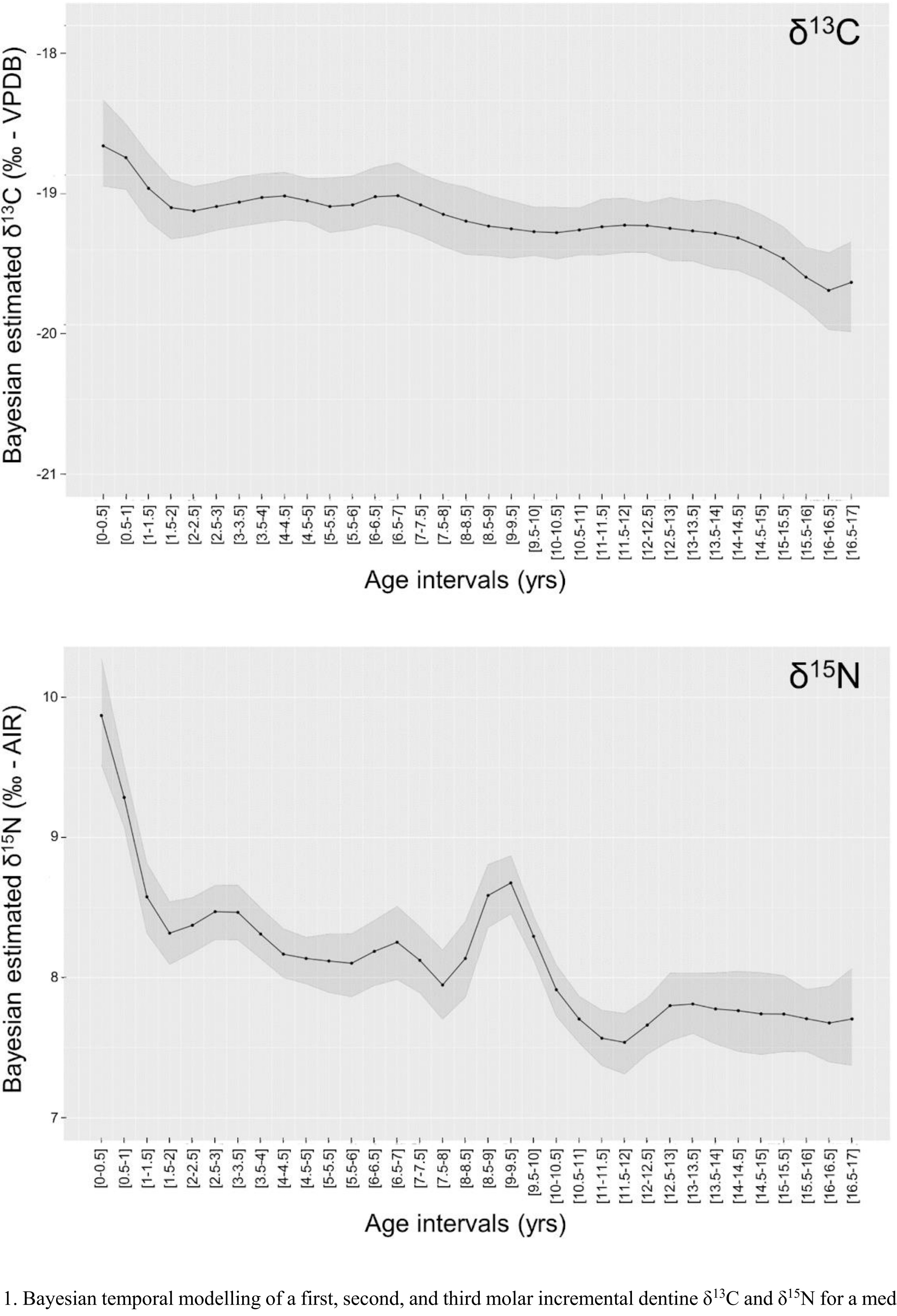
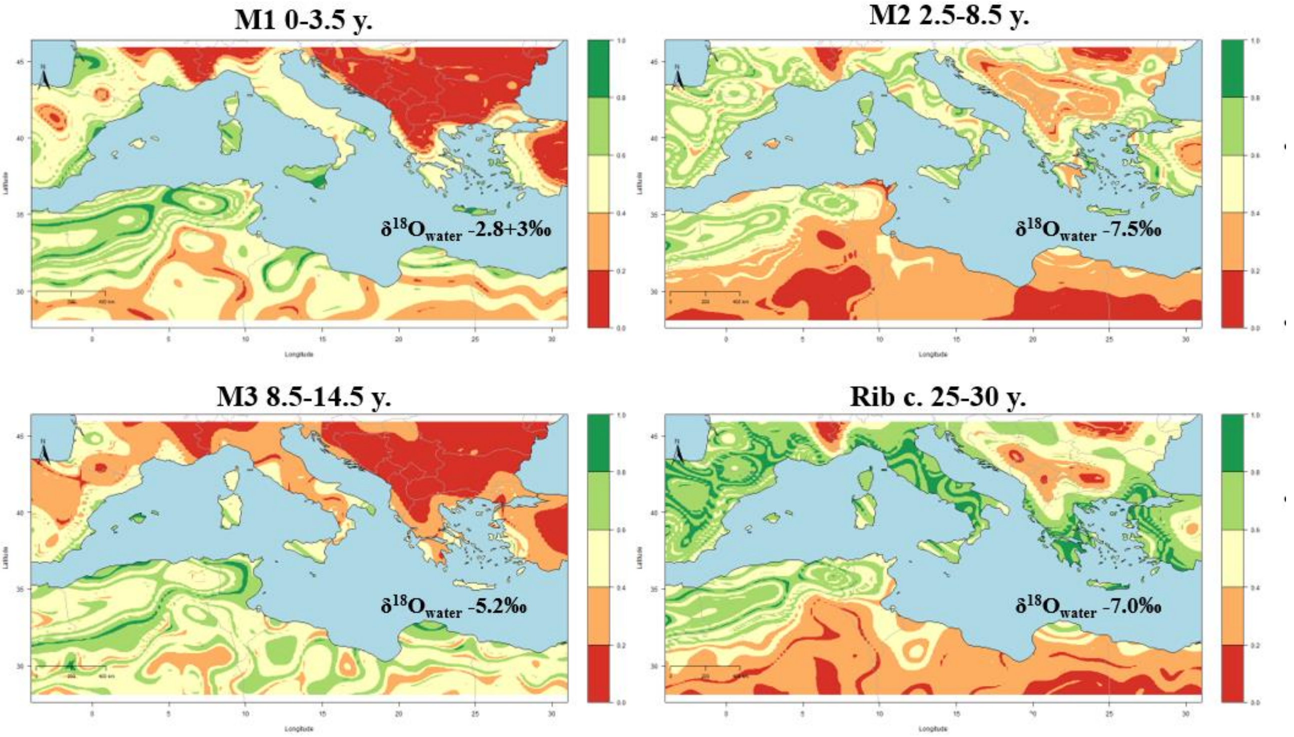


Fig. 11. Bayesian temporal modelling of a first, second, and third molar incremental dentine $\delta^{13}C$ and $\delta^{15}N$ for a medieval individual from Sorrento (Unpublished).



M1 0-3.5 y.

M2 2.5-8.5 y.

M3 8.5-14.5 y.

Rib c. 25-30 y.

Fig. 12. Probability density maps for place of origins of CDS1 in different samples and age stages (M1= first molar; M2 = second molar; M3 = third molar) (unpublished). As a baseline, the Regionalized Cluster-based Water Isotope Prediction model (RCWIP) from the International Atomic Energy Agency (IAEA) was used (Terzer *et al.* 2013). In the first molar, a 3‰ offset has been considered due to breastfeeding stable oxygen fractionation (Roberts *et al.* 1988). For all models, a 2‰ uncertainty was used, taking into account diet-to-tissue offsets, isotopic fractionation due to cooking activities (e.g. stewing and brewing), uncertainty in conversion formulas, sample diagenesis, lab pretreatment, and analytical errors in mass spectrometry (Longinelli 1984; Lightfoot & O'Connell 2016; Tuross *et al.* 2017; Pederzani & Britton 2019).

4. SCIENTIFIC PUBLICATIONS COMPOSING THIS CUMULATIVE DISSERTATION

The compilation of three archaeological databases and meta-analyses, new isotopic analysis from selected case studies, and broader research with a methodological focus compose this cumulative dissertation. These will be briefly presented and summarised below in the following order: Database articles (Cocozza & Fernandes 2021a; b; Cocozza *et al.* 2022a); Selected case studies employing Bayesian modelling of isotopic data (Cocozza *et al.* 2021, 2022b); A meta-analysis of paleoecological 'Big Data' assessing mortality in Europe during the Black Death (Izdebski *et al.* 2022). Complete databases can be found as an Appendix in the CD that is attached to this dissertation. This also includes supplementary information and figures for each article. These scientific publications can be read at the end of this dissertation, or in their online version at publishers' websites.

Before introducing these publications, a brief discussion on the creation of archaeological databases is presented here. Database production requires a research goal, a metadata and data structure, the set of specific inclusion criteria, and a repository to make the dataset publicly available. Whereas the main aim is usually that of creating a data archive, more research-oriented goals can be achieved through data meta-analyses. This is especially valid for databases produced following a distributive approach. For this reason, the creation of a well-defined and high-resolution metadata and data structure becomes a fundamental step of a database production. This should consist of specific metadata entries that characterise data across several variables. In archaeological databases, these usually consist of more or less characterised pieces of information on sites, chronological range, and location, but also social, religious, and cultural variables. Once this is done, data is collected via a literature review and inserted in the database. However, a data selection must be also carried out, in order to assure the quality of the database. This has to respect predefined criteria that provide for data consistency and are in line with the scopes of the database. Finally, a database should be made publicly available through online data repositories, so that the academic community can easily use this data for new research purposes. A database should also be constantly updated, once new data is available following novel research in the field.

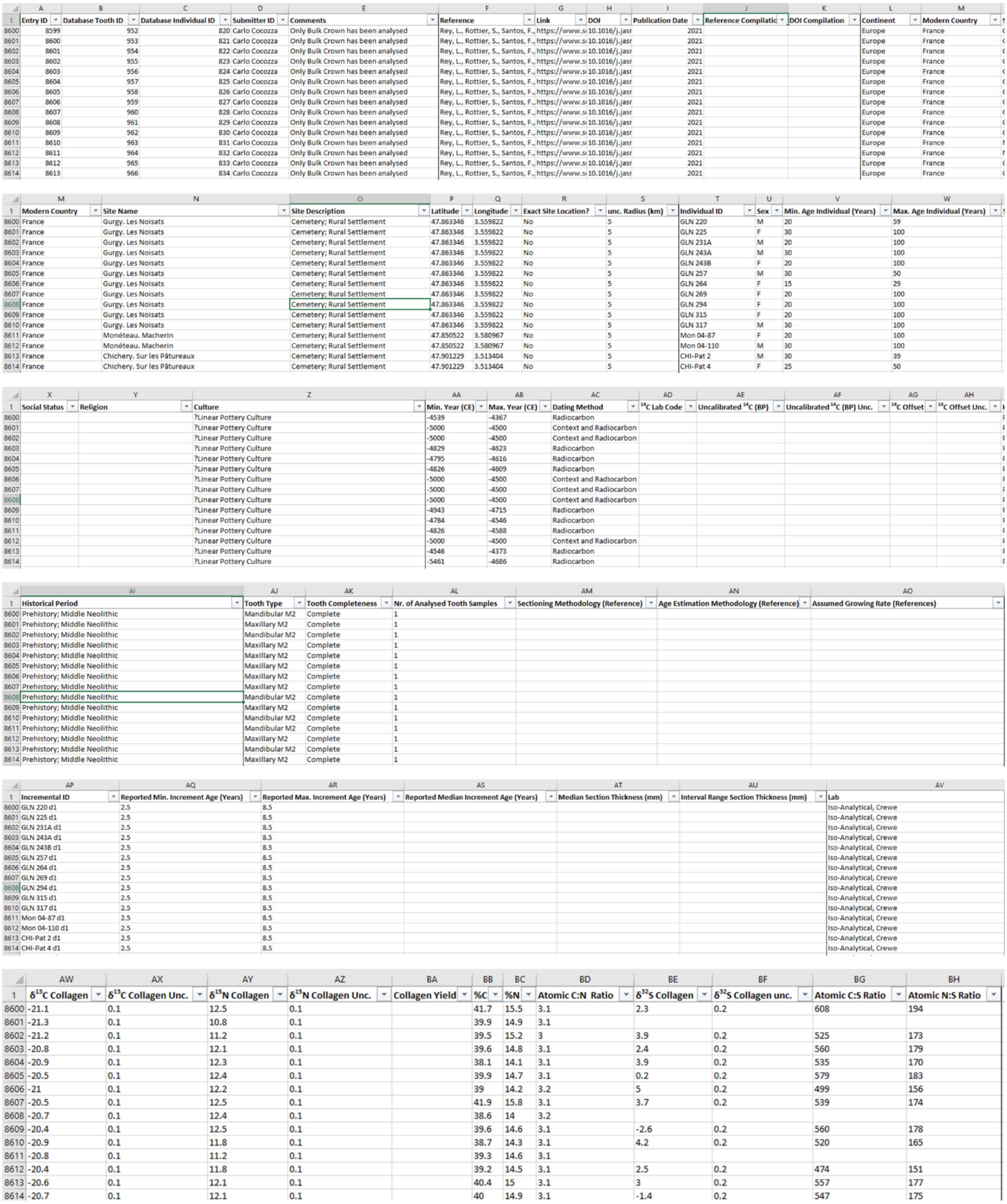
4.1. Amalthea: A database of isotopic measurements on archaeological and forensic tooth dentine increments (Cocozza & Fernandes 2021a)

Amalthea (https://doi.org/10.48493/sak5-9487) is a global database of incremental dentine δ^{13}C and δ^{15}N measurements. This data compilation is available at “Hebe: a data repository for the study of past human childhood” (https://pandoradata.earth/organization/hebe-data-repository-for-the-study-of-past-childhood). This data community is listed in Pandora (https://pandoradata.earth/) and has the aim of creating a networking community of data collectors that are interested in past childhood. Amalthea is regularly updated and, in the last available version (15.12.2021), also δ^{34}S measurements on dentine increments are included, as new research is following this direction (e.g. Rey *et al.* 2021).

Amalthea includes more than 15.000 isotopic measurements spanning from the sixth millennium BCE to current days. Data was recovered from more than 60 scientific publications detected through web search engines (e.g. Google Scholar) and academic repositories (e.g. researchgate). However, neither temporal or spatial constraints apply to this database. The only criterion followed for data selection is that isotopic ratios have to be measured on single tooth dentine increments obtained from human individuals. Increments can have different thickness (this is then reported in specific metadata fields) and may also not be part of a complete tooth sequence. Collagen quality criteria such as %C, %N, and atomic C:N ratios (Ambrose, 1990; DeNiro, 1985; Guiry & Szpak, 2021; van Klinken, 1999), wherever reported in the original publication, are included in the database. However, even if these fall outside common accepted ranges, isotopic measurements were still included as they provide data for future meta-analyses concerning tooth diagenesis and collagen preservation.

Each database entry reflects a dentine increment and, to this, a numeric progressive ID is assigned. Moreover, increments from the same tooth receive a single tooth ID. Given that on some occasions multiple teeth from the same individual are measured, an additional ID is given at individual level. This tripartite classification is paired with original IDs assigned in publications, which are reported in specific metadata fields. Each entry is then defined by geographical coordinates (which reflect site location plus an uncertainty radius expressed in kilometres) and a chronological range. This latter follows a hierarchical approach for which, whenever a direct dating (e.g. via radiocarbon) of the sample or individual is not provided, the chronological interval is defined by archaeological dating of site, region, or even culture. Additional metadata fields that include anthropological, archaeological, and historical information provide for a high level of characterisation of the database. Furthermore, information on samples, sectioning technique, age assignment, and assumed growth rate (references) is provided. Eventually, extensive bibliographic information on the original publication from which data is collected and fields for data citations are also present.

Amalthea, other than providing for a comparative archive of incremental dentine stable isotope data, can be used for broader meta-analyses. The high level of metadata characterisation (Fig. 13) will allow comparing and contrasting childhood diets and infant feeding practices on spatiotemporal variables. The latter is a current topic in bioarchaeology and a global meta-analysis can show the impact of cultural variables on such a biological need. This meta-analysis of data, that includes also late Roman and medieval individuals, is currently undergoing. Additional data that is produced by new studies, will be included in Amalthea in future updates and this may refine this research.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Entry ID	Database Tooth ID	Database Individual ID	Submitter ID	Comments	Reference	Link	DOI	Publication Date	Reference Compilatic	DOI Compilation	Continent	Modern Country
8600	8599	952	820	Carlo Cocozza	Only Bulk Crown has been analysed	Rey, L., Rottier, S., Santos, F.,	https://www.s	10.1016/j.jasr	2021			Europe	France
8601	8600	953	821	Carlo Cocozza	Only Bulk Crown has been analysed	Rey, L., Rottier, S., Santos, F.,	https://www.s	10.1016/j.jasr	2021			Europe	France
8602	8601	954	822	Carlo Cocozza	Only Bulk Crown has been analysed	Rey, L., Rottier, S., Santos, F.,	https://www.s	10.1016/j.jasr	2021			Europe	France
8603	8602	955	823	Carlo Cocozza	Only Bulk Crown has been analysed	Rey, L., Rottier, S., Santos, F.,	https://www.s	10.1016/j.jasr	2021			Europe	France
8604	8603	956	824	Carlo Cocozza	Only Bulk Crown has been analysed	Rey, L., Rottier, S., Santos, F.,	https://www.s	10.1016/j.jasr	2021			Europe	France
8605	8604	957	825	Carlo Cocozza	Only Bulk Crown has been analysed	Rey, L., Rottier, S., Santos, F.,	https://www.s	10.1016/j.jasr	2021			Europe	France
8606	8605	958	826	Carlo Cocozza	Only Bulk Crown has been analysed	Rey, L., Rottier, S., Santos, F.,	https://www.s	10.1016/j.jasr	2021			Europe	France
8607	8606	959	827	Carlo Cocozza	Only Bulk Crown has been analysed	Rey, L., Rottier, S., Santos, F.,	https://www.s	10.1016/j.jasr	2021			Europe	France
8608	8607	960	828	Carlo Cocozza	Only Bulk Crown has been analysed	Rey, L., Rottier, S., Santos, F.,	https://www.s	10.1016/j.jasr	2021			Europe	France
8609	8608	961	829	Carlo Cocozza	Only Bulk Crown has been analysed	Rey, L., Rottier, S., Santos, F.,	https://www.s	10.1016/j.jasr	2021			Europe	France
8610	8609	962	830	Carlo Cocozza	Only Bulk Crown has been analysed	Rey, L., Rottier, S., Santos, F.,	https://www.s	10.1016/j.jasr	2021			Europe	France
8611	8610	963	831	Carlo Cocozza	Only Bulk Crown has been analysed	Rey, L., Rottier, S., Santos, F.,	https://www.s	10.1016/j.jasr	2021			Europe	France
8612	8611	964	832	Carlo Cocozza	Only Bulk Crown has been analysed	Rey, L., Rottier, S., Santos, F.,	https://www.s	10.1016/j.jasr	2021			Europe	France
8613	8612	965	833	Carlo Cocozza	Only Bulk Crown has been analysed	Rey, L., Rottier, S., Santos, F.,	https://www.s	10.1016/j.jasr	2021			Europe	France
8614	8613	966	834	Carlo Cocozza	Only Bulk Crown has been analysed	Rey, L., Rottier, S., Santos, F.,	https://www.s	10.1016/j.jasr	2021			Europe	France

	M	N	O	P	Q	R	S	T	U	V	W
1	Modern Country	Site Name	Site Description	Latitude	Longitude	Exact Site Location?	unc. Radius (km)	Individual ID	Sex	Min. Age Individual (Years)	Max. Age Individual (Years)
8600	France	Gurgy. Les Noisats	Cemetery; Rural Settlement	47.863346	3.559822	No	5	GLN 220	M	20	59
8601	France	Gurgy. Les Noisats	Cemetery; Rural Settlement	47.863346	3.559822	No	5	GLN 225	F	30	100
8602	France	Gurgy. Les Noisats	Cemetery; Rural Settlement	47.863346	3.559822	No	5	GLN 231A	M	20	100
8603	France	Gurgy. Les Noisats	Cemetery; Rural Settlement	47.863346	3.559822	No	5	GLN 243A	M	30	100
8604	France	Gurgy. Les Noisats	Cemetery; Rural Settlement	47.863346	3.559822	No	5	GLN 243B	F	20	100
8605	France	Gurgy. Les Noisats	Cemetery; Rural Settlement	47.863346	3.559822	No	5	GLN 257	M	30	50
8606	France	Gurgy. Les Noisats	Cemetery; Rural Settlement	47.863346	3.559822	No	5	GLN 264	F	15	29
8607	France	Gurgy. Les Noisats	Cemetery; Rural Settlement	47.863346	3.559822	No	5	GLN 269	F	20	100
8608	France	Gurgy. Les Noisats	Cemetery; Rural Settlement	47.863346	3.559822	No	5	GLN 294	F	20	100
8609	France	Gurgy. Les Noisats	Cemetery; Rural Settlement	47.863346	3.559822	No	5	GLN 315	F	20	100
8610	France	Gurgy. Les Noisats	Cemetery; Rural Settlement	47.863346	3.559822	No	5	GLN 317	M	30	100
8611	France	Monéteau. Macherin	Cemetery; Rural Settlement	47.850522	3.580967	No	5	Mon 04-87	F	20	100
8612	France	Monéteau. Macherin	Cemetery; Rural Settlement	47.850522	3.580967	No	5	Mon 04-110	M	30	100
8613	France	Chichery. Sur les Pâtureaux	Cemetery; Rural Settlement	47.901229	3.513404	No	5	CHI-Pat 2	M	30	39
8614	France	Chichery. Sur les Pâtureaux	Cemetery; Rural Settlement	47.901229	3.513404	No	5	CHI-Pat 4	F	25	50

	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH
1	Social Status	Religion	Culture	Min. Year (CE)	Max. Year (CE)	Dating Method	^{14}C Lab Code	Uncalibrated ^{14}C (BP)	Uncalibrated ^{14}C (BP) Unc.	^{14}C Offset	^{14}C Offset Unc.
8600			?Linear Pottery Culture	-4539	-4367	Radiocarbon					
8601			?Linear Pottery Culture	-5000	-4500	Context and Radiocarbon					
8602			?Linear Pottery Culture	-5000	-4500	Context and Radiocarbon					
8603			?Linear Pottery Culture	-4829	-4623	Radiocarbon					
8604			?Linear Pottery Culture	-4795	-4616	Radiocarbon					
8605			?Linear Pottery Culture	-4826	-4609	Radiocarbon					
8606			?Linear Pottery Culture	-5000	-4500	Context and Radiocarbon					
8607			?Linear Pottery Culture	-5000	-4500	Context and Radiocarbon					
8608			?Linear Pottery Culture	-5000	-4500	Context and Radiocarbon					
8609			?Linear Pottery Culture	-4943	-4715	Radiocarbon					
8610			?Linear Pottery Culture	-4784	-4546	Radiocarbon					
8611			?Linear Pottery Culture	-4826	-4588	Radiocarbon					
8612			?Linear Pottery Culture	-5000	-4500	Context and Radiocarbon					
8613			?Linear Pottery Culture	-4546	-4373	Radiocarbon					
8614			?Linear Pottery Culture	-5461	-4686	Radiocarbon					

	AI	AJ	AK	AL	AM	AN	AO
1	Historical Period	Tooth Type	Tooth Completeness	Nr. of Analysed Tooth Samples	Sectioning Methodology (Reference)	Age Estimation Methodology (Reference)	Assumed Growing Rate (References)
8600	Prehistory; Middle Neolithic	Mandibular M2	Complete	1			
8601	Prehistory; Middle Neolithic	Maxillary M2	Complete	1			
8602	Prehistory; Middle Neolithic	Mandibular M2	Complete	1			
8603	Prehistory; Middle Neolithic	Maxillary M2	Complete	1			
8604	Prehistory; Middle Neolithic	Maxillary M2	Complete	1			
8605	Prehistory; Middle Neolithic	Maxillary M2	Complete	1			
8606	Prehistory; Middle Neolithic	Maxillary M2	Complete	1			
8607	Prehistory; Middle Neolithic	Maxillary M2	Complete	1			
8608	Prehistory; Middle Neolithic	Mandibular M2	Complete	1			
8609	Prehistory; Middle Neolithic	Maxillary M2	Complete	1			
8610	Prehistory; Middle Neolithic	Mandibular M2	Complete	1			
8611	Prehistory; Middle Neolithic	Mandibular M2	Complete	1			
8612	Prehistory; Middle Neolithic	Maxillary M2	Complete	1			
8613	Prehistory; Middle Neolithic	Mandibular M2	Complete	1			
8614	Prehistory; Middle Neolithic	Maxillary M2	Complete	1			

	AP	AQ	AR	AS	AT	AU	AV
1	Incremental ID	Reported Min. Increment Age (Years)	Reported Max. Increment Age (Years)	Reported Median Increment Age (Years)	Median Section Thickness (mm)	Interval Range Section Thickness (mm)	Lab
8600	GLN 220 d1	2.5	8.5				Iso-Analytical, Crewe
8601	GLN 225 d1	2.5	8.5				Iso-Analytical, Crewe
8602	GLN 231A d1	2.5	8.5				Iso-Analytical, Crewe
8603	GLN 243A d1	2.5	8.5				Iso-Analytical, Crewe
8604	GLN 243B d1	2.5	8.5				Iso-Analytical, Crewe
8605	GLN 257 d1	2.5	8.5				Iso-Analytical, Crewe
8606	GLN 264 d1	2.5	8.5				Iso-Analytical, Crewe
8607	GLN 269 d1	2.5	8.5				Iso-Analytical, Crewe
8608	GLN 294 d1	2.5	8.5				Iso-Analytical, Crewe
8609	GLN 315 d1	2.5	8.5				Iso-Analytical, Crewe
8610	GLN 317 d1	2.5	8.5				Iso-Analytical, Crewe
8611	Mon 04-87 d1	2.5	8.5				Iso-Analytical, Crewe
8612	Mon 04-110 d1	2.5	8.5				Iso-Analytical, Crewe
8613	CHI-Pat 2 d1	2.5	8.5				Iso-Analytical, Crewe
8614	CHI-Pat 4 d1	2.5	8.5				Iso-Analytical, Crewe

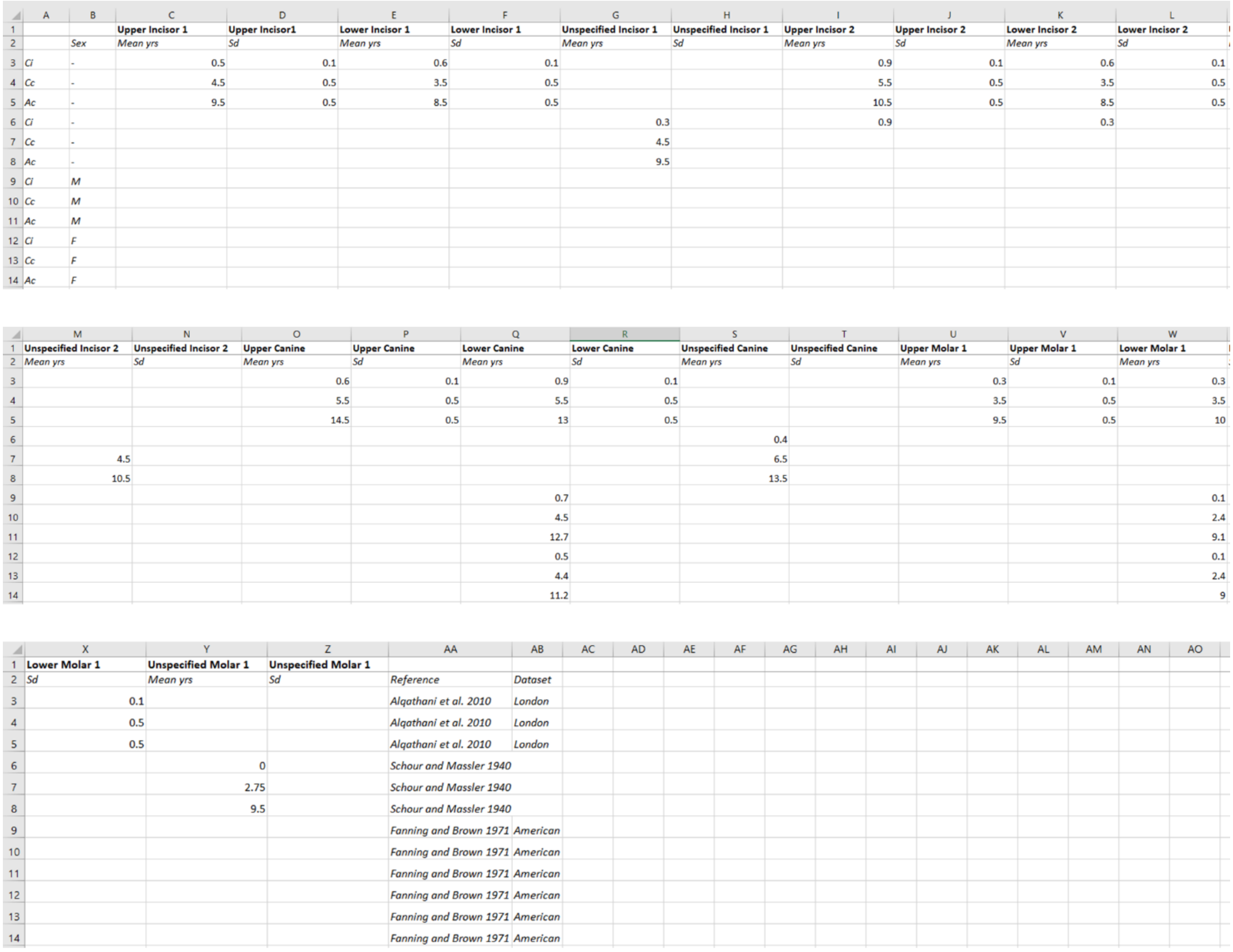
	AW	AX	AY	AZ	BA	BB	BC	BD	BE	BF	BG	BH
1	δ^{13}C Collagen	δ^{13}C Collagen Unc.	δ^{15}N Collagen	δ^{15}N Collagen Unc.	Collagen Yield	%C	%N	Atomic C:N Ratio	δ^{32}S Collagen	δ^{32}S Collagen unc.	Atomic C:S Ratio	Atomic N:S Ratio
8600	-21.1	0.1	12.5	0.1		41.7	15.5	3.1	2.3	0.2	608	194
8601	-21.3	0.1	10.8	0.1		39.9	14.9	3.1				
8602	-21.2	0.1	11.2	0.1		39.5	15.2	3	3.9	0.2	525	173
8603	-20.8	0.1	12.1	0.1		39.6	14.8	3.1	2.4	0.2	560	179
8604	-20.9	0.1	12.3	0.1		38.1	14.1	3.1	3.9	0.2	535	170
8605	-20.5	0.1	12.4	0.1		39.9	14.7	3.1	0.2	0.2	579	183
8606	-21	0.1	12.2	0.1		39	14.2	3.2	5	0.2	499	156
8607	-20.5	0.1	12.5	0.1		41.9	15.8	3.1	3.7	0.2	539	174
8608	-20.7	0.1	12.4	0.1		38.6	14	3.2				
8609	-20.4	0.1	12.5	0.1		39.6	14.6	3.1	-2.6	0.2	560	178
8610	-20.9	0.1	11.8	0.1		38.7	14.3	3.1	4.2	0.2	520	165
8611	-20.8	0.1	11.2	0.1		39.3	14.6	3.1				
8612	-20.4	0.1	11.8	0.1		39.2	14.5	3.1	2.5	0.2	474	151
8613	-20.6	0.1	12.1	0.1		40.4	15	3.1	3	0.2	557	177
8614	-20.7	0.1	12.1	0.1		40	14.9	3.1	-1.4	0.2	547	175

Fig.13. Metadata and data structure for Amalthea.

4.2. Tooth formation age dataset for early childhood bioarchaeological and medical studies (Cocozza & Fernandes 2021b)

As mentioned previously, an important methodological issue, that concerns the analysis of childhood diets and infant feeding practices by means of dentine incremental stable isotope measurements, is the difficulty of assigning precise age intervals to tooth sections. Tooth formation periods vary across individuals according to population genetics and biological sex (Schour & Massler 1940; Haavikko 1970; Fanning & Brown 1971; Anderson *et al.* 1976; Smith 1991; Liversidge *et al.* 2006; AlQahtani *et al.* 2010, 2014). Moreover, growth rates oscillate at intra-tooth level (Kawasaki *et al.* 1979) and cannot be simplified as constant for incremental age calculations as suggested by Beaumont & Montgomery (2015). Commonly, the London Atlas of Human Tooth Development and Eruption by AlQahtani *et al.* (2010) is employed as a reference for standard formation periods of teeth used in archaeological research to detect breastfeeding and weaning timings (Beaumont & Montgomery 2015). However, the Atlas is based on modern measurements from multi-ethnic individuals from London and this can present a bias relative to its application to ancient populations.

In order to use an operational reference valid for all ancient populations that can be used in the global meta-analysis of infant feeding practices, the tooth formation ages database (https://doi.org/10.48493/p5g4-ps12) was therefore created. This dataset is also hosted at "Hebe: a data repository for the study of past human childhood" (https://pandoradata.earth/organization/hebe-data-repository-for-the-study-of-past-childhood). The database collects formation periods (mean and standard deviation) from the literature (Fig. 14). This included different populations. Measurements on teeth commonly used for investigating infant feeding practices, i.e. first molars (M1), first and second incisors (I1; I2), and canines (C) were collected. Separate fields identify whether the tooth type that is measured in the original publication is mandibular (lower), maxillary (upper), or unspecific as differences in formation times may be impacted by position. Reported formation periods are relative to crown initiation (ci), crown completion (cc) and root apex completion (ac). Whenever different periods are measured according to biological sex in the original scientific publication, this is also identified in the database. Eventually bibliographic information and the population that was measured originally is also flagged. A data meta-analysis has then allowed calculating weighted means and standard deviation that could be applied operatively to ancient populations.



	A	B	C	D	E	F	G	H	I	J	K	L
1			**Upper Incisor 1**	**Upper Incisor1**	**Lower Incisor 1**	**Lower Incisor 1**	**Unspecified Incisor 1**	**Unspecified Incisor 1**	**Upper Incisor 2**	**Upper Incisor 2**	**Lower Incisor 2**	**Lower Incisor 2**
2		*Sex*	*Mean yrs*	*Sd*	*Mean yrs*	*Sd*	*Mean yrs*	*Sd*	*Mean yrs*	*Sd*	*Mean yrs*	*Sd*
3	*Ci*	-	0.5	0.1	0.6	0.1			0.9	0.1	0.6	0.1
4	*Cc*	-	4.5	0.5	3.5	0.5			5.5	0.5	3.5	0.5
5	*Ac*	-	9.5	0.5	8.5	0.5			10.5	0.5	8.5	0.5
6	*Ci*	-					0.3		0.9		0.3	
7	*Cc*	-					4.5					
8	*Ac*	-					9.5					
9	*Ci*	*M*										
10	*Cc*	*M*										
11	*Ac*	*M*										
12	*Ci*	*F*										
13	*Cc*	*F*										
14	*Ac*	*F*										

	M	N	O	P	Q	R	S	T	U	V	W
1	**Unspecified Incisor 2**	**Unspecified Incisor 2**	**Upper Canine**	**Upper Canine**	**Lower Canine**	**Lower Canine**	**Unspecified Canine**	**Unspecified Canine**	**Upper Molar 1**	**Upper Molar 1**	**Lower Molar 1**
2	*Mean yrs*	*Sd*	*Mean yrs*	*Sd*	*Mean yrs*	*Sd*	*Mean yrs*	*Sd*	*Mean yrs*	*Sd*	*Mean yrs*
3			0.6	0.1	0.9	0.1			0.3	0.1	0.3
4			5.5	0.5	5.5	0.5			3.5	0.5	3.5
5			14.5	0.5	13	0.5			9.5	0.5	10
6							0.4				
7	4.5						6.5				
8	10.5						13.5				
9					0.7						0.1
10					4.5						2.4
11					12.7						9.1
12					0.5						0.1
13					4.4						2.4
14					11.2						9

	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO
1	**Lower Molar 1**	**Unspecified Molar 1**	**Unspecified Molar 1**															
2	*Sd*	*Mean yrs*	*Sd*	*Reference*	*Dataset*													
3	0.1			*Alqathani et al. 2010*	*London*													
4	0.5			*Alqathani et al. 2010*	*London*													
5	0.5			*Alqathani et al. 2010*	*London*													
6		0		*Schour and Massler 1940*														
7		2.75		*Schour and Massler 1940*														
8		9.5		*Schour and Massler 1940*														
9				*Fanning and Brown 1971*	*American*													
10				*Fanning and Brown 1971*	*American*													
11				*Fanning and Brown 1971*	*American*													
12				*Fanning and Brown 1971*	*American*													
13				*Fanning and Brown 1971*	*American*													
14				*Fanning and Brown 1971*	*American*													

Fig. 14. Data and metadata structure for the tooth formation age dataset.

4.3. Presenting the Compendium Isotoporum Medii Aevi, a multi-isotope database for Medieval Europe (Cocozza et al. *2022a)*

The *Compendium Isotoporum Medii Aevi* (CIMA, https://doi.org/10.48493/s9nf-1q80) is a large collection of isotopic measurements from medieval Europe and its margins. CIMA is a partner of the IsoMemo network that creates a gathering of isotopic databases covering all continents and periods. CIMA is hosted at "MATILDA: A repository for Medieval bioAnThropologIcaL DatAbases" (https://pandoradata.earth/organization/matilda-a-repository-for-medieval-bioanthropological-databases), a data community that gathers biomolecular archaeology and biological anthropology collectors on the medieval world. Given that a higher level of metadata characterisation can be achieved by answering specific research questions, CIMA has implemented a further network system that allows additional isotopic datasets on medieval Europe to be included and referenced in the database itself. High-resolution meta-analyses at different scales can therefore be pursued following regional collections. Eventually, CIMA will still include the whole existing data on medieval isotopes with main archiving purposes. For example, it is undergoing a collaboration with IsoIberMed (Dr Michelle Alexander and Dr Maite García-Collado), a medieval isotopic database specifically created for Iberia. This database will be uploaded in the MATILDA data community and the successive updates of the CIMA dataset will then reference IsoIberMed for data entries relative to Iberia. Clearly, references to original scientific publication from which the data is obtained are still maintained. From IsoIberMed a data meta-analysis aiming to investigate spatiotemporal dietary shifts in medieval Iberia is planned. Further collaborations on other geographical regions have been activated or are planned for the future. The CIMA network has the aim of filling research gaps and increasing the knowledge on medieval human lifeways.

CIMA includes more than 50,000 isotopic measurements on humans, animals, and plants for more than 25,000 database entry IDs. This enormous amount of data is recovered from more than 370 data sources that included scientific articles, monographies, reports, and dissertations also in different European languages. This compilation required circa six months for collecting all the data and an additional year to obtain its publication together with Bayesian meta-analysis examples. Although CIMA is an isotopic database, this publication is a clear example of the infinite potentiality of combining 'Big Data' and probabilistic models for archaeological proxies (Fig. 6-7, 9). Figure 15 show the spatial distribution of data included in the database.

Several isotopic ratios ($\delta^{13}C$, $\delta^{15}N$, $\delta^{34}S$, $\delta^{18}O$, and $^{87}Sr/^{86}Sr$) also differentiated according to different proxies (e.g. $\delta^{13}C_{collagen}$ *versus* $\delta^{13}C_{carbonate}$) were selected as the main data. In addition, collagen quality parameters (DeNiro 1985; Ambrose 1990; van Klinken 1999; Guiry & Szpak 2021) are added wherever reported. When these do not fit within commonly accepted ranges, data is not excluded as they can provide information on preservation and diagenesis. It is however still possible to filter data successively, according to selected criteria for addressing a meta-analysis of past human lifeways. Data was included as following three criteria: 1) Spatial, i.e. isotopic data measured from individuals found in geographic European archaeological sites; 2) Temporal, i.e. isotopic data measured from individuals set in a chronological range of 500-1500 CE; 3) Material, i.e. isotopic data measured on hard tissues (bones and teeth, plus antlers and rostra for given animals) and organic remains in the case of plants. However, additional data obtained from non-European regions that present some historical cultural continuity with medieval Europe (e.g. Greenland, or the Mediterranean basin) and/or data that was slightly outside the chronological range were still included.

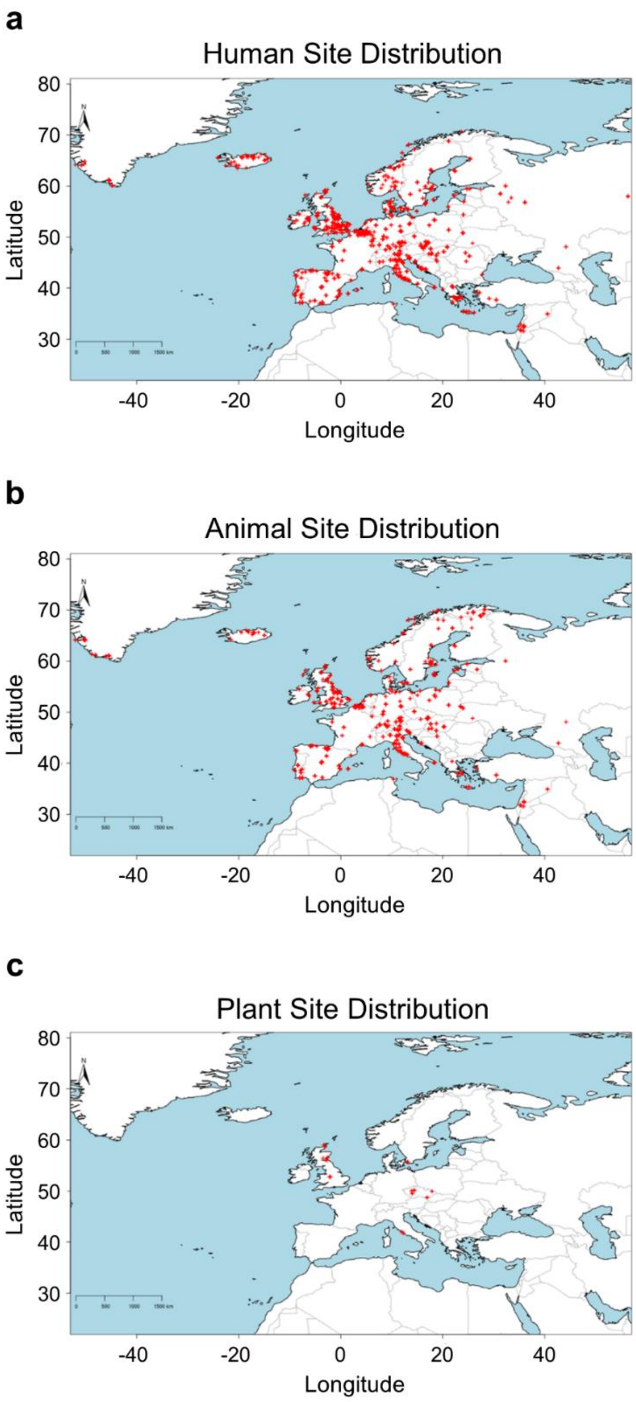
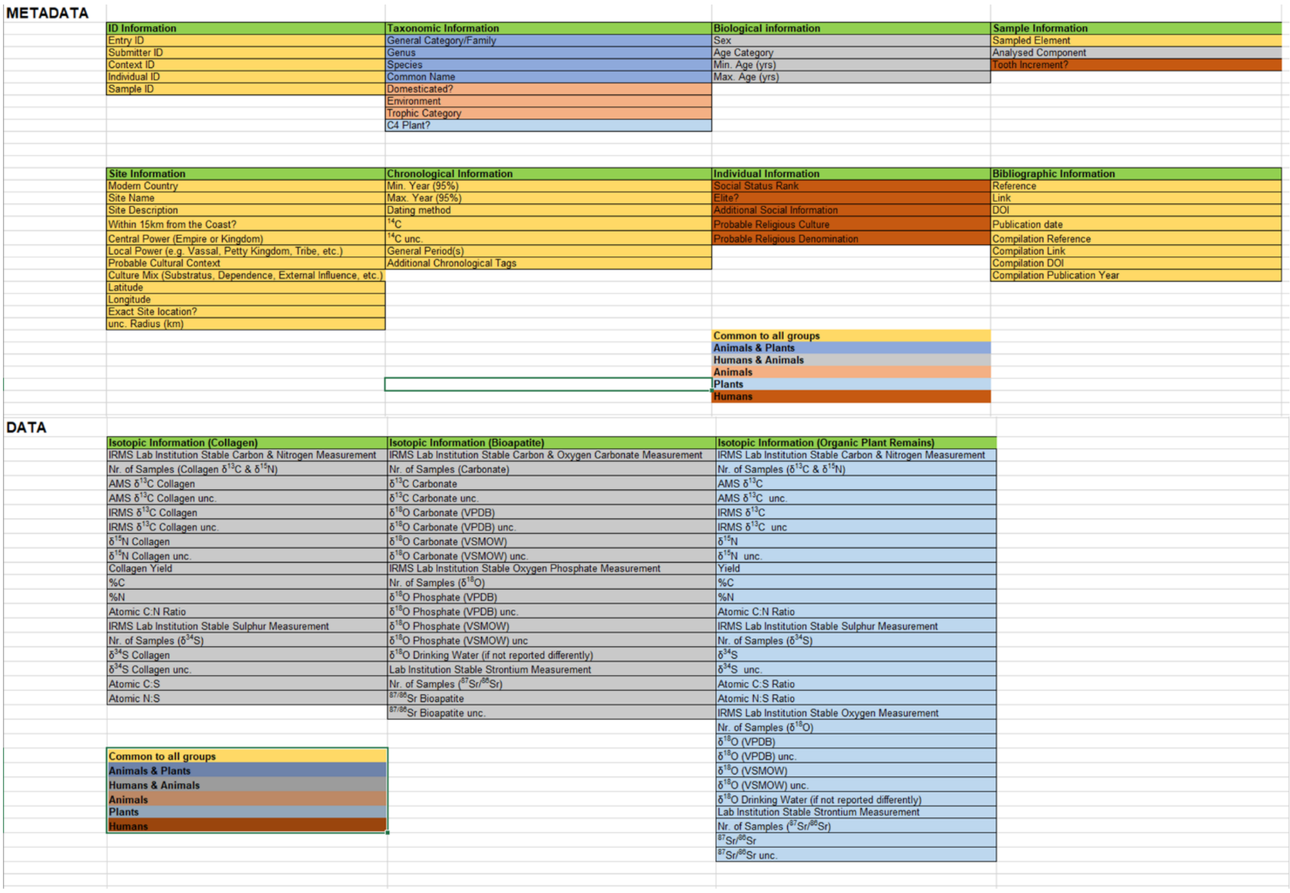


Fig. 15. Spatial distribution of medieval sites that are included in CIMA for humans (a), animals (b) and plants (c). From (Cocozza *et al.* 2022a).

CIMA also presents a high-level of metadata characterisation (Fig. 16) that follows the complexity of medieval Europe. Entries are flagged with a progressive numeric ID. Human, animal, and plant collections are compiled in separate datasets and they present their own independent sequence. Subsequently, a series of IDs as reported in original publications are included in the metadata structure, in order to identify data and ensure the quality of the collection. These include archaeological, analytical and anthropological IDs. Subsequently, measurements are described relatively to biological information on the individual (e.g. sex, age at death, taxa, habitat, trophic level). Samples are also identified relatively to osteological (or plant) material and elements that were analysed. A palimpsest of information on the archaeological site, including name, description, and political entities provide further variables to be subjected to meta-analyses. Each data entry is then furnished with geographical coordinates and chronological indication. As in Amalthea, coordinates include a field for an uncertainty radius expressed in kilometres, whereas chronological ranges follow a hierarchical approach. Radiocarbon dates on sample/individual are included and, whenever these were not available, the chronological interval can refer to the site, the region, or the culture, respectively. Further metadata fields include information on cultural proxies (e.g. religion, or status) and bibliographic references to the original publication. Fields specifically implemented for data citations within or outside the CIMA network are also present.



METADATA

ID Information	Taxonomic Information	Biological information	Sample Information
Entry ID	General Category/Family	Sex	Sampled Element
Submitter ID	Genus	Age Category	Analysed Component
Context ID	Species	Min. Age (yrs)	Tooth Increment?
Individual ID	Common Name	Max. Age (yrs)	
Sample ID	Domesticated?		
	Environment		
	Trophic Category		
	C4 Plant?		

Site Information	Chronological Information	Individual Information	Bibliographic Information
Modern Country	Min. Year (95%)	Social Status Rank	Reference
Site Name	Max. Year (95%)	Elite?	Link
Site Description	Dating method	Additional Social Information	DOI
Within 15km from the Coast?	^{14}C	Probable Religious Culture	Publication date
Central Power (Empire or Kingdom)	^{14}C unc.	Probable Religious Denomination	Compilation Reference
Local Power (e.g. Vassal, Petty Kingdom, Tribe, etc.)	General Period(s)		Compilation Link
Probable Cultural Context	Additional Chronological Tags		Compilation DOI
Culture Mix (Substratus, Dependence, External Influence, etc.)			Compilation Publication Year
Latitude			
Longitude			
Exact Site location?			
unc. Radius (km)			

Common to all groups
Animals & Plants
Humans & Animals
Animals
Plants
Humans

DATA

Isotopic Information (Collagen)	Isotopic Information (Bioapatite)	Isotopic Information (Organic Plant Remains)
IRMS Lab Institution Stable Carbon & Nitrogen Measurement	IRMS Lab Institution Stable Carbon & Oxygen Carbonate Measurement	IRMS Lab Institution Stable Carbon & Nitrogen Measurement
Nr. of Samples (Collagen δ^{13}C & δ^{15}N)	Nr. of Samples (Carbonate)	Nr. of Samples (δ^{13}C & δ^{15}N)
AMS δ^{13}C Collagen	δ^{13}C Carbonate	AMS δ^{13}C
AMS δ^{13}C Collagen unc.	δ^{13}C Carbonate unc.	AMS δ^{13}C unc.
IRMS δ^{13}C Collagen	δ^{18}O Carbonate (VPDB)	IRMS δ^{13}C
IRMS δ^{13}C Collagen unc.	δ^{18}O Carbonate (VPDB) unc.	IRMS δ^{13}C unc
δ^{15}N Collagen	δ^{18}O Carbonate (VSMOW)	δ^{15}N
δ^{15}N Collagen unc.	δ^{18}O Carbonate (VSMOW) unc.	δ^{15}N unc.
Collagen Yield	IRMS Lab Institution Stable Oxygen Phosphate Measurement	Yield
%C	Nr. of Samples (δ^{18}O)	%C
%N	δ^{18}O Phosphate (VPDB)	%N
Atomic C:N Ratio	δ^{18}O Phosphate (VPDB) unc.	Atomic C:N Ratio
IRMS Lab Institution Stable Sulphur Measurement	δ^{18}O Phosphate (VSMOW)	IRMS Lab Institution Stable Sulphur Measurement
Nr. of Samples (δ^{34}S)	δ^{18}O Phosphate (VSMOW) unc	Nr. of Samples (δ^{34}S)
δ^{34}S Collagen	δ^{18}O Drinking Water (if not reported differently)	δ^{34}S
δ^{34}S Collagen unc.	Lab Institution Stable Strontium Measurement	δ^{34}S unc.
Atomic C:S	Nr. of Samples (^{87}Sr/^{86}Sr)	Atomic C:S Ratio
Atomic N:S	$^{87/86}$Sr Bioapatite	Atomic N:S Ratio
	$^{87/86}$Sr Bioapatite unc.	IRMS Lab Institution Stable Oxygen Measurement
		Nr. of Samples (δ^{18}O)
		δ^{18}O (VPDB)
		δ^{18}O (VPDB) unc.
		δ^{18}O (VSMOW)
		δ^{18}O (VSMOW) unc.
		δ^{18}O Drinking Water (if not reported differently)
		Lab Institution Stable Strontium Measurement
		Nr. of Samples (^{87}Sr/^{86}Sr)
		^{87}Sr/^{86}Sr
		^{87}Sr/^{86}Sr unc.

Common to all groups
Animals & Plants
Humans & Animals
Animals
Plants
Humans

Fig. 16. Data and metadata structure for CIMA.

This high level of metadata characterisation allows data filtering to pursue several meta-analyses. In the scientific publication presenting CIMA, the potential of this large volume of isotopic data is expressed by some examples that also include the combination with a Roman database (Salesse *et al.* 2018). These are partially presented already in figure 6-7, and 9 in this dissertation as they employed Bayesian modelling options described above. For example, a wide compilation of δ^{13}C and δ^{15}N isotopic data obtained from plants and animals had the potential of investigating past farming practices and palaeoenvironmental shifts on different spatiotemporal scales. Similarly, the same δ^{13}C and δ^{15}N values measured on humans can allow addressing shifts in human diets. Different isotopic values can either indicate the consumption of different food sources across societies, or varying farming economies (and climatic changes) that impact isotopic baselines. The two factors are often correlated by historical variables, as simplified in fig. 17, relatively to the late antique period. 'Big Data' from δ^{13}C and δ^{15}N human values could also be employed, together with those from the baseline and additional historical, archaeological, and anthropological information to produce a high-resolution Bayesian dietary mixing model for ancient Rome. Spatial mobility could also be addressed using data from the CIMA compilation. For example, this was used to show research gaps in spatial mobility studies, the temporal density of migration patterns, or to detect dwelling places for individuals that had a historical background worth investigating.

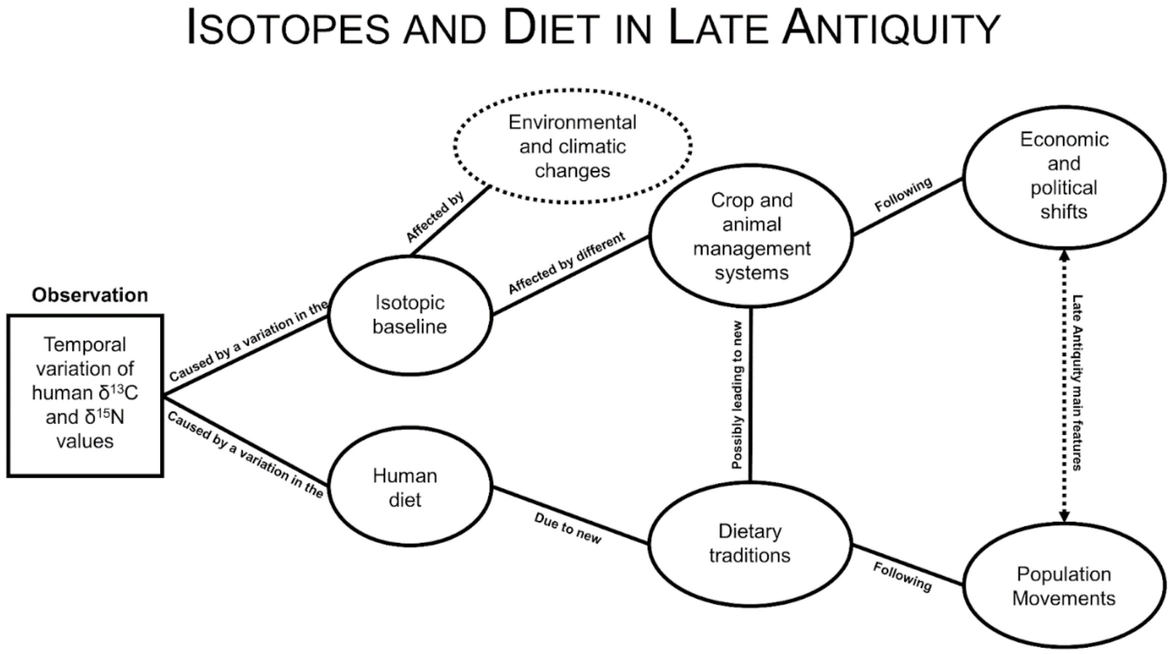


Fig. 17. Diagram simplifying how isotopic temporal variations in humans may reflect different diets or different farming practices/environmental changes (unpublished).

4.4. Palaeoecological data indicates land-use changes across Europe linked to spatial heterogeneity in mortality during the Black Death pandemic (Izdebski et al. *2022)*

Although this publication does not involve stable isotopes, a ‘Big Data’ and Bayesian modelling approach was used to detect plague-related human lifeways in late medieval Europe. Mortality rates were in fact linked with shifts in land-use changes after the first Black Death wave. Whenever pollen data suggested a constant (or even an increase) crop presence, this likely indicates that a given region was not impacted by a high death toll. On the other hand, wherever pollen data inferred a shift from cultivations towards pasturing and reforestation, this probably demonstrates a demographic decrease.

Results showed a large regional variability over the mortality rate of the Black Death in Europe. This contradicts the dogma of a devastating impact of the plague across Europe, killing up to half its population (Benedictow 2006; Aberth 2022). This estimation is overly exaggerated as likely based on written sources from a few western European regions and extended to the entire continent. Moreover, it is also probable that a relatively high death toll affected urban centres, where certainly most medieval scholars that reported these events resided. In this study, the impact of Black Death mortality was instead explored in rural zones through a quantitative approach. This revealed an extremely variable impact across Europe. Interestingly, in regions where written sources on this pandemic are limited, such as central and eastern Europe, even a demographic increase is attested. This has proved that Black Death mortality was far more spatially heterogeneous than previously thought. Cultural, ecological, economic, societal, and climatic proxies may have determined this phenomenon at different scales.

4.5. Investigating infant feeding strategies at Roman Bainesse through Bayesian modelling of incremental dentine isotopic data (Cocozza et al. *2021)*

In this selected case study, infant feeding practices from a Late Roman site in Britain were explored using incremental dentine stable isotope analysis and Bayesian modelling. The model OsteoBioR was presented here and showed how this could be used to render directly comparable isotopic measurements obtained from dentine increments. Moreover, this analytical technique was applied for the first time in a context from the Roman Empire. Results were therefore compared with known medical recommendations from ancient physicians and these also exhibited some striking consistency.

The site of Bainesse was a commercial hub founded near the Roman fort of *Cataractonium*, in northern England, in the late 1st century CE (Wilson 2002; Speed & Holst 2019). The town was founded strategically on the Swale river and along Dere Street, the main Roman road linking *Eboracum* (York) to Hadrian's Wall. More than 200 individuals were excavated from the Roman funerary area during construction works. Most were radiocarbon dated, suggesting a chronological range between the late 1st and early 5th centuries CE (Moore *et al.* 2019). Anthropological and palaeopathological studies have evidenced a high infant mortality rate, especially concentrated between one and six years of life (Holst *et al.* 2019) (Fig. 18). Therefore, a preliminary investigation on infant feeding practices was carried out on five selected 'survived' individuals to observe potential correlations. First molars were sampled and subjected to incremental dentine stable isotope analysis.

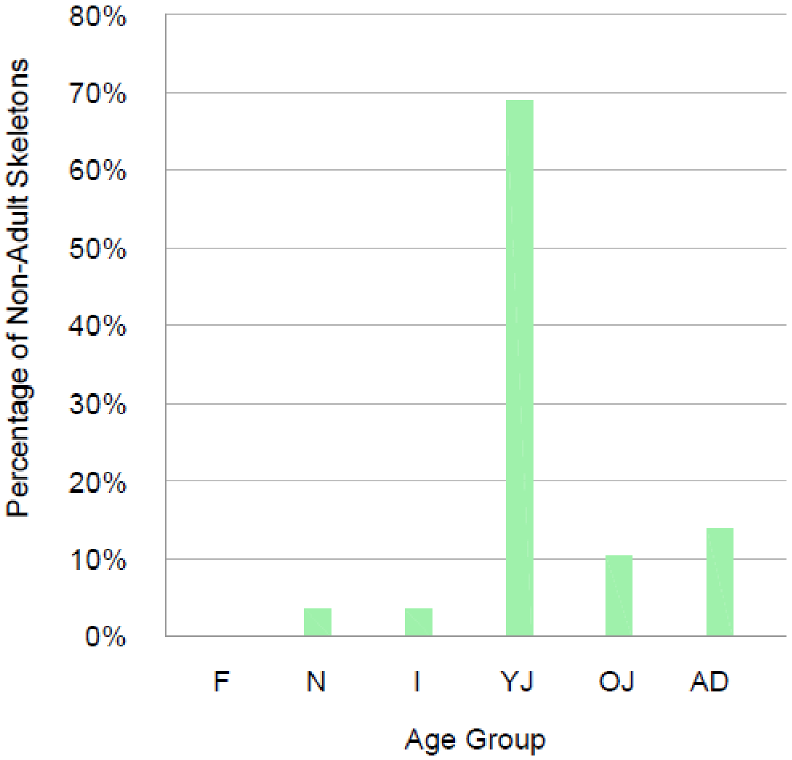


Fig.18. Graph showing age distribution of the Bainesse Cemetery non-adults. From (Holst *et al.* 2019).

Modelled isotopic results have shown that exclusive breastfeeding ceased no earlier than six months of age, which is what main Roman written sources suggest. In two female individuals, this seems to be protracted up to one year, and this finds an interesting counterpart in sex-based recommendations given by the physician *Damastes* (reported in *Soranus,* Temkin 1956). However, ancient sources recommend a weaning completion between two and three years, but in Bainesse no uniform weaning completion was observed. Some individuals even appear to have been completely weaned around four or five years of age. A possible explanation involves the high level of infant mortality noticed on the site across this life-stage. Hence, families likely prolonged the weaning process to provide more nutrients to the infant. Moreover, also individual familiar traditions and socio-economic status may have impacted this process.

Additionally, it was noted a likely post-weaning trend around the age of seven. In fact, infants seem to show a higher consumption of animal protein around that life stage and this was suggested to be linked with a potential rise in the status of the child. This seems also confirmed by historical evidence that inferred how the age of seven was an important step in the life of a child (Eyben 1972). Whether medical and philosophical treatises from Rome and an overall Mediterranean culture were known in Bainesse it is hard to tell. However, it is possible that the commercial vocation of the settlement and the nearby military outpost may have introduced some knowledge directly from the centre of the Roman empire.

4.6. A Bayesian multi-proxy contribution to the socioeconomic, political, and cultural history of Late Medieval Capitanata (southern Italy) (Cocozza et al. *2022b)*

Stable carbon, nitrogen, and oxygen isotope analysis was carried out on more than 150 human and faunal samples from the region of Capitanata, Apulia, southern Italy. These were recovered during past archaeological campaigns from the sites of Tertiveri, Montecorvino, and San Lorenzo in Carminiano, and are dated to the late medieval age (broadly 1000-1500 CE). During this period, Byzantines, Normans, Staufen, and Angevins ruled the region. Isotopic data was Bayesian modelled to increase the resolution of the dietary and spatial mobility analysis. This allowed exploring farming economies, transhumance, and migrations as linked with known historical developments and archaeological evidence.

The sites of Tertiveri (Clemens & Zimmer 2014, 2016; Clemens & Matheus 2018; Matheus 2018; Clemens & Muntoni 2020) and Montecorvino (Giuliani & Favia 2007; Favia *et al.* 2009a, 2012, 2014, 2015a; b) were two fortified bishoprics set on the Apennine hills. The largest dataset in this analysis was recovered from Tertiveri (113 human individuals, plus 5 faunal samples). Within this dataset, also an alleged Bishop and two individuals buried according to an Islamic rite were recovered (Teegen 2018). Muslim individuals likely date to 1296-1300, when the site was granted by the Angevin king of Naples to the Muslim knight ‘Abd al-‘Azīz from Lucera (Engl 2018). Montecorvino had a more urban and productive character, as attested by archaeological evidence. From this site, 17 human individuals and a larger faunal dataset (n=15) were sampled. San Lorenzo in Carminiano was a wide rural settlement set in the Tavoliere plain, and most of the local economy appears grounded on crafting activities, animal husbandry - in particular pigs - and cereal production (Caracuta & Fiorentino 2009; Favia *et al.* 2009b; De Venuto 2013)(Caracuta et al., 2012; De Venuto, 2013; Favia et al., 2009). From this site only four human samples and two deer samples from the same specimen were measured.

The temporal resolution of the analysis was not high enough to allow multi-period comparisons across the Byzantine, Norman, Staufen, and Angevin phases. However, intra- and inter-site comparisons provided some interesting results. In particular, in Tertiveri two main population dietary clusters were detected. One, that also includes the bishop, displays a higher consumption of marine resources which reveals the existence of trade routes that connect the Adriatic coast to the Apennine area. Moreover, previous archaeobotanical and archaeological evidence discarded the presence of C_4 cereals (millet or sorghum) as a cultivated crop in the region, whereas isotopic results indicated a moderate consumption in Tertiveri. This could be linked to seasonal transhumance routes, given certain C_4 characteristics such as durability and fast ripening. Overall, isotopic data showed that in medieval Capitanata, human diets were mainly composed of C_3 plants (which include wheat, barley and legumes), pork and ovicaprine products. The consumption of such food sources likely reflected a regional farming economy that involved a wide cereal production, intensive pig husbandry, and transhumance. Faunal isotopic results also show a ^{15}N-enrichment in comparison to other coeval southern Italian sites explored through isotopes (Torino *et al.* 2015; Rolandsen *et al.* 2019), and this argues toward an intensive manuring and animal feeding. These agricultural practices are consistent with a demographic increase observed in the archaeological record relative to the late medieval periods. ‘Mobile’ individuals were also identified in Tertiveri and, with the exception of a Muslim individual whose stable oxygen signature suggests Mediterranean mobility, their probable origins were in the alpine region. This was associated with historical events involving German elites and Angevin soldiers moving to the region in the thirteenth century.

5. CONCLUSION

This cumulative dissertation includes multiple scientific publications with the aim of exploring spatiotemporal shifts in human lifeways across late Roman and medieval Europe. Among others, moving populations, collapsing political entities, new economic structures, cultural clashes, the spread of monotheistic religions, and even climatic changes and pandemics marked this age as an extremely heterogeneous period in European history. For this reason, synchronic and diachronic shifts in human lifeways are expected to reflect these events. Moreover, due to a large palimpsest of historical and archaeological available information, these can be detected at relatively high resolution.

In this project, human lifeways were approached through 'Big Data' collections, meta-analyses, Bayesian modelling, and newly generated measurements of stable isotope ratios. Also non-isotopic proxies were employed. Using this transdisciplinary, multi-proxy, and multi-scale approach, changes in human subsistence practices, infant feeding strategies, and spatial mobility were detected both at regional level (e.g. archaeological sites) and following broader spatiotemporal coordinates. However, given the extremely wide topic and global restrictions associated with the Coronavirus disease (COVID-19) pandemic, this cumulative doctoral dissertation was limited to address only a few selected case studies and focus on the production of archaeological databases and their meta-analyses. Database production allowed setting a starting point for future late Roman and medieval research. Some of these works can also be of use for archaeologists carrying out research on different topics, such as sample diagenesis, or further chronological and geographical horizons.

An important point within this work is the multi-scale approach. Depending on the research question, an analysis can be carried out at different scales. These can all provide for different resolutions and interpretative limitations. For example, it is possible to carry out multiple bioarchaeological analyses of given individuals to reconstruct their osteo-biography. This will provide information on human lifeways that were based on single personal choices and can differ from choices endorsed by the majority of other individuals composing a larger social group. This latter can then be compared with other social groups from the same site and the analysis may reveal the existence of a shared system of choices concerning human lifeways. The same comparison can subsequently be made among sites, across regions, and so on to larger interpretative scales. The wider the scale, the higher is the possibility of observing how human lifeways shifted (or did not) across a more restricted number of historical variables. A ‘Big Data’ meta-analysis reduces in fact the impact of diverging behaviours on the final interpretation, hence allowing the detection of main trends. Future machine learning programs and artificial intelligence implementations will likely allow refining historical correlations. However, this is valid whenever a chosen scale is adequate to the amount and typology of data that is available.

The collection of isotopic databases, such as CIMA (Cocozza *et al.* 2022a) and Amalthea (Cocozza & Fernandes 2021a)**,** follows this philosophy. As a general rule, data collections can highlight research gaps and provide for large data archives that can be used to compare new measurements. However, both compilations can provide for large scale spatiotemporal data meta-analyses concerning diet, farming economies, spatial mobility and infant feeding practices. New Bayesian modelling options were also proposed in this dissertation as a main methodology to perform these statistical spatiotemporal meta-analyses. Preliminary results have shown potential links between shifts in human lifeways trends and historical developments during the late Roman and medieval ages. For example, shifting human dietary practices compared across imperial, late antique, and early medieval Rome were associated with demographic decrease, collapse of the political and economic Roman structure, and new adaptive farming economies. A large regional variability was also observed, suggesting that different climates, environments, political agenda, socio-economic systems, and cultural traditions had different impacts on human communities. This was also noticed by applying Bayesian modelling tools to a non-isotopic archaeological indicator. In (Izdebski *et al.* 2022), ‘Big Data’ paleoecological remains from late medieval Europe showed the varying impact of Black Death mortality across regions. Additional data meta-analyses using CIMA and Amalthea are already planned and/or undergoing. These include a high-resolution investigation of dietary shifts in Medieval Iberia across several socio-cultural variables, and a global meta-analysis of early childhood diets. A meta-analysis of tooth formation periods for samples commonly used to detect weaning timings was also included in this dissertation and provided for an operational reference to be used in future research (Cocozza & Fernandes 2021b).

Bayesian modelling options could also be employed in selected case studies involving infant feeding practices (Cocozza *et al.* 2021), human diets, farming economies, and spatial mobility (Cocozza *et al.* 2022b) at site level. These case-studies revealed smaller intra- and inter-site variations that suggested the existence of multiple local variables influencing human lifeways. For example, in

Roman Bainesse (UK), some striking correlation between ancient medical recommendations and infant feeding practices as revealed through isotopes, suggested that the former could have been known, even at the northern frontier of the Roman empire. This is likely linked to military and commercial mobility in the area. However, the completion age of weaning varied across individuals and this still indicates that given choices could be influenced by other factors. This was associated with family traditions and/or socio-economic status. In Tertiveri (Italy), a moderate consumption of C_4 plants (likely millet) detected through isotopes is an interesting anomaly in respect to what is observed from other archaeological indicators in the region. This was connected to a local economy based on transhumance routes. Therefore, in selected case studies it is possible to address local socio-economic variables and even individual choices. Both would be obscured in a meta-analysis that involves a relatively larger scale. Thus, it is fundamental to always set the scale of the analysis as relative to specific research questions that are to be investigated.

Overall, this dissertation proved that, at different scales and using multiple proxies, human lifeways in late Roman and medieval Europe were extremely heterogeneous. This was expected at site level, as many local variables and single human choices can influence subsistence practices, farming economies, infant feeding strategies, and mobility patterns. However, preliminary ‘Big Data’ Bayesian meta-analyses carried out on large volumes of isotopic data and combined with known evidence obtained from zooarchaeology, archaeobotany, anthropology, and written sources have revealed this point as valid even on a wider scale. This is not necessarily an *a priori* consequence of differences in the local scale, given that large human trends would overshadow smaller local differences. More likely, this instead confirms that human societies are impacted as a whole by main historical developments and environmental differences. This indicates hence that human lifeways do not only respond to biological inputs. At the state of the arts, it is hard to estimate which historical and/or environmental variables impacted late Roman and Medieval human lifeways the most. A direction to follow will be that of including into the analysis machine learning software applied to ‘Big Data’. Future research concerning Roman and Medieval Europe and its margins is therefore suggested to employ a similar multi-scale and multi-proxy transdisciplinary approach to investigate human lifeways.

ACKNOWLEDGEMENTS

First and foremost, my biggest thanks go to my parents for supporting me during the hard times that we all faced in the last years. They have always invested in my education and now that I am finally at the end of it I am sure I can repay their love and support. I dedicate this dissertation to them. This dissertation is also in memory of Mario Russo, an archaeologist who dedicated his own life to reconstruct, preserve, and give value to the cultural heritage of Sorrento and its margins, my homeland.

For these three years, I must thank Prof. Wolf-Rüdiger Teegen for accepting me into a doctoral program and providing me contacts, support, and precious advice. I also have to thank Prof. Carola Metzner-Nebelsick for additional support when Prof. Teegen could not be present. Additionally, I thank lab technicians and colleagues at the isotope lab of Max Planck Institute for the Science of Human History in Jena and at the iCONa Lab of the Università della Campania in Caserta for their technical support and important methodological discussions. In particular, I wish to thank Mary Lucas, Erin Scott, Dr Jana Ilgner, Dr Simona Altieri, and Dr Maria Rosa di Cicco. Moreover, I must thank Prof. Carmine Lubritto for welcoming me at the iCONa Lab in Caserta, so that I could carry out my last stable isotope measurements when restrictions applied for travelling back to Germany. Finally, last but not least, I must and I wish to thank Dr Ricardo Fernandes. Ricardo taught me how to go deeper in the basic principles of stable isotopes and bioarchaeological research, considerably improving my skills. Most importantly, other than a supervisor, he became a friend.

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SCIENTIFIC PUBLICATIONS IN INTERNATIONAL PEER-REVIEWED JOURNALS

In this section, I list and present scientific publications composing this cumulative dissertation. Complete article citations, online links, and author contributions are provided. Publications are included here as post-prints (i.e. final version of the manuscript before final formatting). Supplementary information and databases are available as an Appendix in the CD that is attached to this dissertation.

1. **Cocozza, C.** & R. Fernandes (2021). Amalthea: A Database of Isotopic Measurements on Archaeological and Forensic Tooth Dentine Increments. *Journal of Open Archaeology Data*, **9**.

Link: https://openarchaeologydata.metajnl.com/article/10.5334/joad.75/

Author contributions

Carlo Cocozza: Co-designed the study, defined the meta-data structure, collected the data and wrote the original draft; Ricardo Fernandes: Co-designed the study and edited the original draft.

2. **Cocozza, C.** & R. Fernandes (2021). Tooth formation age dataset for early childhood bioarchaeological and medical studies. *Data in Brief*, **36**: 107141. DOI: 10.1016/j.dib.2021.107141

Link: https://www.sciencedirect.com/science/article/pii/S235234092100425X

Author contributions

Carlo Cocozza: Collected the data and wrote the manuscript; Ricardo Fernandes: Defined the data structure, performed data analysis, and edited the manuscript.

3. Cocozza, C., E. Cirelli, M. Groß, W.R. Teegen & R. Fernandes (2022). Presenting the Compendium Isotoporum Medii Aevi, a Multi-Isotope Database for Medieval Europe. *Scientific Data* (Accepted).

Author contributions

Carlo Cocozza: collected the data, co-designed meta-data structure, wrote the manuscript and performed the modelling; Enrico Cirelli: oversaw data collection in respect to historical and archaeological aspects and co-wrote the manuscript; Marcus Groß: developed modelling apps and co-wrote the manuscript; Wolf-Rüdiger Teegen: oversaw data collection in respect to anthropological, zooarchaeological and archaeobotanical aspects and co-wrote the manuscript; Ricardo Fernandes: designed meta-data structure, supervised data collection, and co-wrote manuscript.

4. Izdebski, A., P. Guzowski, R. Poniat, L. Masci, J. Palli, C. Vignola, M. Bauch, **C. Cocozza**, R. Fernandes, F. C. Ljungqvist, T. Newfield, A. Seim, D. Abel-Schaad, F. Alba-Sánchez, L. Björkman, A. Brauer, A. Brown, S. Czerwiński, A. Ejarque, M. Fiłoc, A. Florenzano, E. D. Fredh, R. Fyfe, N. Jasiunas, P. Kołaczek, K. Kouli, R. Kozáková, M. Kupryjanowicz, P. Lagerås, M. Lamentowicz, M. Lindbladh, J. A. López-Sáez, R. Luelmo-Lautenschlaeger, K. Marcisz, F. Mazier, S. Mensing, A. M. Mercuri, K. Milecka, Y. Miras, A. M. Noryśkiewicz, E. Novenko, M. Obremska, S. Panajiotidis, M. L. Papadopoulou, A. Pędziszewska, S. Pérez-Díaz, G. Piovesan, A. Pluskowski, P. Pokorny, A. Poska, T. Reitalu, M. Rösch, L. Sadori, C. Sá Ferreira, D. Sebag, M. Słowiński, M. Stančikaitė, N. Stivrins, I. Tunno, S. Veski, A. Wacnik & A. Masi (2022). Palaeoecological data indicates land-use changes across Europe linked to spatial heterogeneity in mortality during the Black Death pandemic. *Nature Ecology & Evolution*, **6**: 297-306. DOI: 10.1038/s41559-021-01652-4.

Link: https://www.nature.com/articles/s41559-021-01652-4

Author contributions

A.I., A.M. and P.G. designed the study. A.I. drafted the paper with contributions from M.B., R.Fer., G.P., A.M., T.N., P.G., R.P., F.C.L. and C.V.; A.M., L.M., J.P. and C.V. created the pollen database, with the support of J.A.L.S. (Spain), P.L. (Sweden) and T.R. (Estonia). A.I., R.P., R.Fer. and **Carlo Cocozza** carried out the analyses. A.S., D.A.S., F.A.S., L.B., A.Bra., A.Bro., S.C., A.E., M.F., A.F., E.D.F., R.Fyf., N.J., P.K., K.K., R.K., M.K., M.Lam., M.Lin., R.L.L., K.Mar., F.M., S.M., A.M.M., K.Mil., Y.M., A.M.N., E.N., M.O., S.P., M.L.P., A.Pęd., S.P.D., G.P., A.Plu., P.P., A.Pos., M.R., L.S., C.S.F., D.S., M.Sło., M.Sta., N.S., I.T., S.V. and A.W. provided palynological data and contributed to the text and the interpretation.

5. Cocozza, C., R. Fernandes, A. Ughi, M. Groß & M.M. Alexander (2021). Investigating infant feeding strategies at Roman Bainesse through Bayesian modelling of incremental dentine isotopic data. *International Journal of Osteoarchaeology*, **31**: 429-439. DOI: 10.1002/oa.2962

Link: https://onlinelibrary.wiley.com/doi/full/10.1002/oa.2962

Author contributions

Carlo Cocozza: Analysed the data, wrote the manuscript and performed the modelling; Ricardo Fernandes: Co-wrote the manuscript and supervised the modelling; Alice Ughi: Co-analysed the data and co-wrote the manuscript; Michelle M. Alexander: Co-analysed the data, co-wrote the manuscript and supervised the study.

6. Cocozza, C., W.R. Teegen, I. Vigliarolo, P. Favia, R. Giuliani, I.M. Muntoni, D. Oione, L. Clemens, M. Groß, P. Roberts, C. Lubritto & R. Fernandes (2022). A Bayesian multi-proxy contribution to the socioeconomic, political, and cultural history of Late Medieval Capitanata (southern Italy). *Scientific Reports*, **13**: 4078. DOI: 10.1038/s41598-023-30706-9

Link: https://www.nature.com/articles/s41598-023-30706-9

Author contributions

Carlo Cocozza: Co-designed the study, analysed the data, wrote the manuscript and performed the modelling; Wolf-Rüdiger Teegen: Co-designed the study, provided for anthropological analysis and interpretation, and co-wrote the manuscript; Ilaria Vigliarolo: Provided for anthropological analysis and interpretation, and co-wrote the manuscript; Pasquale Favia: Provided for archaeological materials and interpretation, and co-wrote the manuscript; Roberta Giuliani: Provided for archaeological materials and interpretation, and co-wrote the manuscript; Italo Maria Muntoni: Provided for archaeological materials and interpretation; Domenico Oione: Provided for archaeological materials and interpretation; Lukas Clemens: Provided for archaeological materials and interpretation, and co-wrote the manuscript; Marcus Groß: developed modelling apps and co-wrote the manuscript; Patrick Roberts: Provided for lab capabilities and edited the manuscript; Carmine Lubritto: Provided for lab capabilities and edited the manuscript; Ricardo Fernandes: Co-designed the study, supervised the modelling, and edited the manuscript.

AMALTHEA: A DATABASE OF ISOTOPIC MEASUREMENTS ON ARCHAEOLOGICAL AND FORENSIC TOOTH DENTINE INCREMENTS

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ABSTRACT

Amalthea is a global database of stable isotope measurements on tooth increments from archaeological and modern individuals spanning more than 7,000 years. The dataset includes c. 15,000 isotopic measurements from more than 700 individuals. In addition to isotopic data the database also includes information on the archaeological context and osteological features of recorded individuals. This database allows for the reconstruction of individual iso-biographies. In particular, the database allows for meta-studies on childhood diet and nutrition across time and space. The database is a collaborative effort and will be regularly updated.

KEYWORDS: Tooth Sections; Dentine Collagen; Carbon and Nitrogen Stable Isotopes; Childhood Diet and Physiology

(1) OVERVIEW

Context

Amalthea is a global database of carbon and nitrogen stable isotope measurements on human tooth dentine sections previously reported in archaeological and forensic scientific publications. The database is made available via Hebe, a data repository for the study of past human childhood (https://pandoradata.earth/organization/hebe-data-repository-for-the-study-of-past-childhood). Hebe is itself integrated within the Pandora and IsoMemo Big Data initiatives.

Stable isotope analysis has now been employed for more than four decades to the reconstruction of past human diets and nutritional status [1][2]. A relatively recent development has been the measurement of stable isotopes on tooth sections allowing for a high-temporal reconstruction of human diets within the formation period of different teeth [3]. This makes this technique particularly relevant for the study of past childhood diets and nutrition, allowing for the reconstruction of infant feeding practices and the timing of breastfeeding and weaning [4]. Malnutrition and metabolic imbalances are known to impact stable isotope values and their study has also been the subject of previous archaeological research [5]. Given the higher temporal resolution achievable using isotopic measurements on tooth sections, the method has been employed to investigate historical famines [6][7].

The temporal reconstruction of diet and nutritional status using isotopic measurements on tooth sections is made possible since tooth dentine retains the isotopic signature of its formation [8] whereas other skeletal tissues may undergo remodelling [9]. The approximate tooth dentine growth rates are also known (4-8μm per day [10]) making it possible to approximately associate a temporal interval within the lifetime of an individual to each sampled tooth section, although some limitations may apply [11]. Improvements in sampling methods and the reduction of the amount of sample necessary for stable isotope analyses have permitted the achievement of temporal resolutions of only a few months [7]. Human tooth sectioning for stable isotope analysis began in 2003 [12] and the method for higher-resolution sampling was established in 2011 [13] and later on subject to further technical improvements [3][14][15][16][17]. Given the research potential of the technique, there has been a growing number of scientific publications in which its use is reported, especially during the last three years (Fig. 1).

Spatial coverage

The dataset has a global coverage with site distribution shown in Fig. 2.

Temporal coverage

The dataset has a temporal range from 5600 B.C.E. to 2020 C.E. (fig. 3).

(2) METHODS

Steps

We made a global collection of previously published carbon and nitrogen stable isotope measurements ($\delta^{13}C$ and $\delta^{15}N$) on tooth sections. We included all $\delta^{13}C$ and $\delta^{15}N$ measurements on dentine sections, regardless of the number of measured sections and their thickness. Data retrieved from collected publications also included information on the osteological description of the sampled individuals, archaeological contexts, tooth sectioning methods, geographical coordinates of the archaeological site and its dating range. Geographical coordinates, whenever not directly reported within publications, were estimated using Google Maps. For the latter we report an uncertainty radius in kilometres.

Sampling strategy

Relevant publications were located using the web search engine Google Scholar (search up to February 2021). Different combinations of key words such as “analysis”, “dentin/dentine”, “human”, “increment/incremental”, “isotope/isotopic”, “section/sections” were used. We also located any additional relevant data sources following the references given within each collected publication.

Quality control

Among the collected data we included the standard parameters (collagen yield, %C, %N, atomic C/N ratios) for assessment of dentine collagen preservation [18]. In some instances, these were not reported in the original source or their values were outside of the recommended ranges. The latter data entries were still included in the dataset since these can be employed in future studies of tooth diagenesis.

Constraints

Our dataset lists measurement results obtained using different tooth sectioning methods which is reflected on the variety of reported tooth thicknesses and temporal resolutions. Moreover, in several cases the entire tooth was not sectioned and, for older individuals, it is not clear whether secondary dentine forming in a later period was removed. In addition, sample typology and position affects the incremental age assignment, due to different formation periods, and imprecise tooth determinations in either sampling or publication can be another potential constraint. This limits to an extent the research potential although recent modelling developments allow for a larger inter-comparability of dietary histories obtained from isotopic results obtained through different sectioning methods [4].

Another constraint is the sampling distribution of our dataset. Although global in reach (fig. 2), most of the isotopic research on tooth sections has been reported for Europe (fig. 3). As new isotopic data on tooth sections becomes available we will add this to our datasets. We also welcomed direct contributions from other researchers.

(3) DATASET DESCRIPTION

Amalthea consists of a single spreadsheet file (Amalthea.xlxs) and a bibliography (Amalthea-bibliography.docx) deposited at the data platform of the Pandora initiative (https://pandoradata.earth/) within the Hebe repository (https://pandoradata.earth/organization/hebe-data-repository-for-the-study-of-past-childhood). The spreadsheet file consists of columns representing the different metadata categories (see below). Each row represents a tooth increment for which $\delta^{13}C$ and $\delta^{15}N$ measurements were reported.

We collected data from 58 publications for a total of 746 individuals, 886 different teeth, 7,997 increments, and 15,994 isotopic measurements. A summary description of the datasets for tooth typology, sex of the sampled individuals (determined through osteological analysis), and spatial and temporal coverage is shown in Fig. 3.

The fields of the Amalthea database are organized into thematic units described below.

Data identifiers

Each row within Amalthea has a unique identifier which follows an integer sequence. This identified each tooth increment within the database (Entry ID). In addition, there are identifiers to identify each individual (Database Individual ID) to which the tooth increment corresponds and each analysed tooth for an individual (Database Tooth ID). The data submitter is also identified (Submitter ID) and a field for additional comments is also available (Comments).

Bibliography

Each data source is cited using the Harvard citation style (Reference). Whenever available, a link to the source (Link) and a digital object identifier (DOI) are given. Also included is the year of publication (Publication Date). We expect that future data additions to Amalthea may include contributions from other researchers. Respective data files can be assigned individual DOIs prior to the inclusion of the new data into the Amalthea master file. Thus within this master file we also included fields for references (Reference compilation) and DOIs (DOI compilation) to previous compilations.

Site description

Several fields are employed to describe the site and its geographical location from which the tooth material is reported to have originated (Continent; Modern Country; Site Name; Site Description). Geographical coordinates (Latitude, Longitude) are reported using decimal GPS coordinates. A database field is used to establish if an exact site location is reported in the original data source (Exact Site Location?). If not, a radius of uncertainty (unc. Radius (km)) in kilometres is given.

Description of Individual

Most of the collected data is from skeletal remains recovered during archaeological excavations which typically would have been subject to osteological analysis. We report the original skeleton identified as given in the original data sources (Individual ID) plus the biological sex (Sex) and a numeric range for age at death (Min. Age Individual (Years); Max. Age Individual in (Years)). When available, other contextual information such as the socioeconomic status (Social Status), likely religion (Religion), and cultural assignment (Culture) are given.

Chronology

A numeric CE/BCE date range (Min. Year (CE); Max. Year(CE)) is given for each individual. Negative values are used for BCE dates. Whenever direct dating of skeletal material is available this is reported (e.g. from biographical written sources or by radiocarbon dating). If this is not available, the known range for the site's chronology is given instead. The type of employed dating is also reported (Dating Method). Whenever radiocarbon dates are employed, and if reported in original publication, we reported radiocarbon lab code (^{14}C lab code), uncalibrated mean value for date (Uncalibrated ^{14}C (BP)) plus its standard deviation (Uncalibrated ^{14}C (BP) Unc.). Traditional historical periods tags are also given (Historical Period).

Sampling methods

We describe the sample typology, specifying whether the sample is a deciduous/permanent and/or mandibular/maxillary tooth (Tooth Type). Also reported is if a tooth was found fully formed and preserved (Tooth Completeness) and the number of isotopic analyses made on each tooth (Nr. of Analysed Tooth Samples). The latter can differ from the number of original tooth sections since some may have been combined to provide enough collagen for an isotopic measurement.

Bibliographic references are given for the sectioning protocol (Sectioning Methodology (Reference)), the method used for age assignment (Age Estimation Methodology (Reference)), and tooth growth rate (Assumed Growing Rate (References)).

Description of increments

We report the increment identifier as given in the original data source (Incremental ID) and, if available, which ages are assigned to each (Reported Min. Increment Age (Years); Reported Max. Increment Age (Years); Reported Median Increment Age (Years)). We also report data relative to the thickness of the increment (Median Section Thickness (mm); Interval Range Section Thickness (mm)).

Stable isotope and elemental measurements

For each dentine increment(s) the measurement result of carbon (δ^{13}C Collagen; δ^{13}C Collagen unc.) and nitrogen (δ^{15}N Collagen; δ^{15}N Collagen unc.) stable isotope ratios plus respective uncertainties are given. Also reported are the results for the indicators of collagen preservation, i.e. collagen yield (Collagen yield), percentage of elemental carbon (%C), percentage of elemental nitrogen (%N) and the carbon to nitrogen atomic ratio (Atomic C:N Ratio). The laboratory where the measurements were carried out is also identified (Lab).

Object name

Amalthea dataset 29.05.2021; Amalthea Bibliography 29.05.2021.

Data type

Secondary data

Format names and versions

.xlsx; .docx.

Creation dates

Records created from June 2020 to February 2021.

Dataset Creators

Ricardo Fernandes was responsible for the metadata structure while Carlo Cocozza collected the data.

Language

English.

License

Creative Commons Attribution-ShareAlike.

Repository location

https://www.doi.org/10.48493/sak5-9487

Publication date

05.03.2021.

(4) REUSE POTENTIAL

The data collected within the Amalthea database can be employed to reconstruct individual dietary histories and is particularly useful for the study of past children's diets and nutrition. Given that each tooth can be set in a formation period interval, the combination of different teeth such as the three permanent molars potentially allow the reconstruction of dietary inputs from birth to early adulthood. Some limitations still exist as concerning the age assignation of increments and alignment of different teeth, but new modelling techniques are being employed to address such issues [4][11]. Our dataset can be used to carry out meta-analyses that compare children feeding practices across time and space and within varied cultural contexts. The data can also be combined with other existing isotopic datasets to compare, for instance, dietary differences among children and adults.

Our aim is to continuously update Amalthea as new relevant data is released. The database aims at being a collaborative research effort within the spirit of the Pandora communities and it welcomes new data submissions to the Hebe repository (https://pandoradata.earth/organization/hebe-data-repository-for-the-study-of-past-childhood). Individual data contributions can be deposited at Hebe and assigned a DOI so that data collection efforts are easily recognized. Individual datasets are combined in the Amalthea master file which also includes references to previous compilations.

ACKNOWLEDGEMENTS

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FIGURES

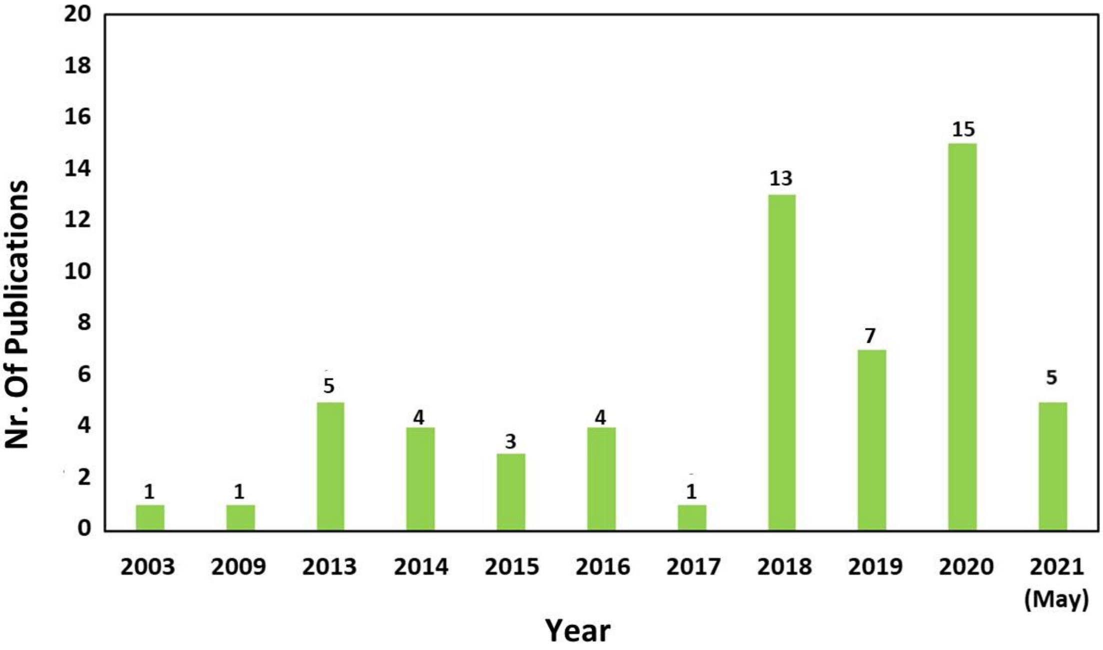

Fig. 1. Number of publications by year on isotopic analysis of tooth increments.

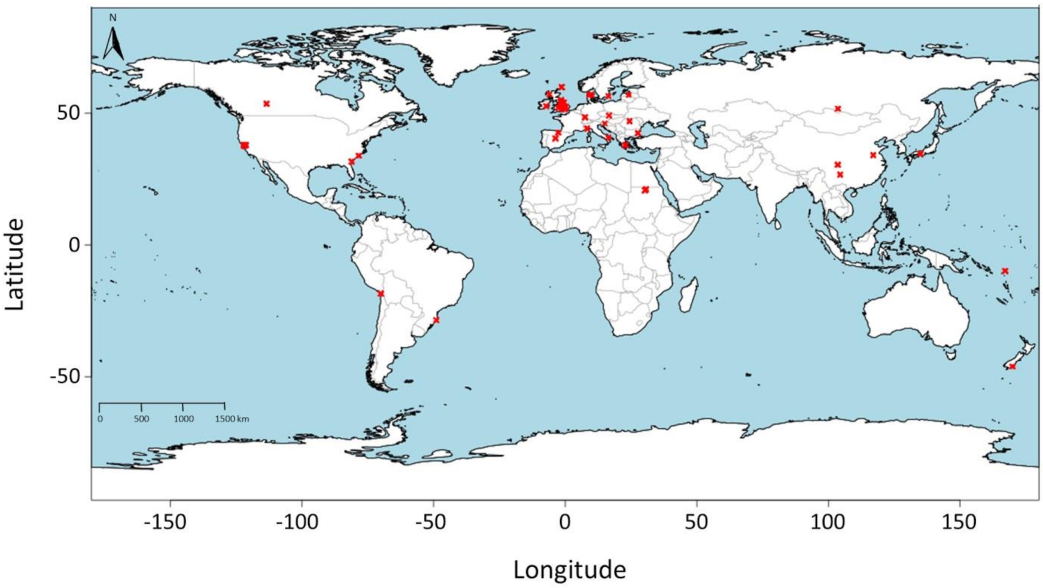

Fig. 2. Spatial distribution of sites reported in data sources for isotopic analyses of tooth increments.

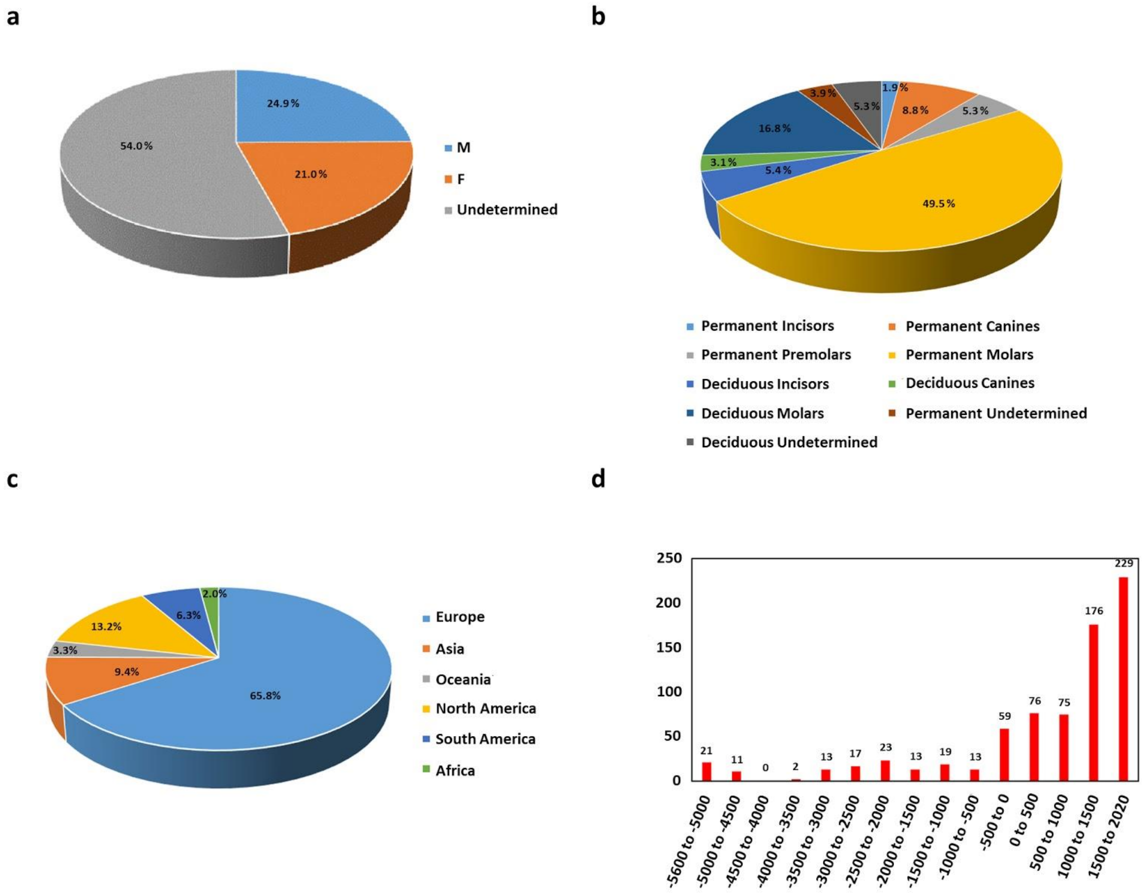

Fig. 3. Summary statistics for Amalthea dataset. a) Identified sex through osteological analysis; b) type of tooth; c) geographical distribution of investigated sites; d) distribution of chronology for investigated sites.

TOOTH FORMATION AGE DATASET FOR EARLY CHILDHOOD BIOARCHAEOLOGICAL AND MEDICAL STUDIES

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Abstract

We compiled data from histological sources on the formation ages for human mandibular and maxillary permanent first molars, lateral and central incisors and canines. From this we summarised the data by reporting weighted means for cusp initiation, crown completion and apex completion. This provides a reference for bioarchaeological and medical studies investigating early childhood. More specifically, this reference is a crucial element in the study of early childhood nutrition and *morbidity from osteological analysis and stable isotope analyses of teeth and their growth increments.*

Keywords

Database; Tooth Formation Ages; Dental Histology; Early Childhood; Cusp Initiation; Crown Completion; Apex Completion

Specifications Table

Subject	Social Sciences
Specific subject area	Human tooth formation ages are necessary for archaeological studies of the early diets and morbidity of past humans.
Type of data	Table
How data were acquired	Bibliographic: published data from dental histology papers Analysis: weighted means and standard errors
Data format	Secondary
Parameters for data collection	Cusp initiation, crown completion and apex completion ages for human permanent first molars, canines and incisors

Description of data collection	Data was collected through a review of scientific publications on dental histology listing formation ages for certain human teeth (see parameters). We summarized collected data by reporting weighted means and standard errors for each type of tooth
Data source location	Dental histology scientific publications (References in text)
Data accessibility	Repository name: Pandora (Hebe: Data repository for the study of past childhood) Data identification number: 10.48493/p5g4-ps12 Direct URL to data: https://pandoradata.earth/dataset/tooth-formation-age-dataset-for-early-childhood-bioarchaeological-and-medical-studies

Value of the Data

- This data collects human tooth formation ages for permanent first molars, canines and incisors. Such references are a requirement for dental research, particularly within an archaeological context.
- This data can be employed by archaeologists, physical anthropologists, palaeopathologists, paediatrics, and histologists.
- This data is a requirement for archaeological studies of childhood diet and morbidity using stable isotope and osteological analyses. The data can also be employed to improve the precision of age-at-death determinations for juvenile individuals found in archaeological contexts.

Data Description

Collected data consisted of previously reported means for tooth formation ages: a) cusp initiation (ci); b) crown completion (cc); and c) apex completion (ac). This data was originally collected for the crowns and roots of both upper and lower first molars (M1), lateral incisors (I2), central incisors (I1), and canines (C). These were calculated from measurements on more than 10,000 individuals from across the different studies and from different world regions [1,2,3,4,5,6,7]. Collected data and summary calculations are given within the same file in separate sheets. For collected data we report the original mean and standard deviation for ci, cc and ac according to tooth type and sex (male, female, unreported). In this respect, original publications provide for each study group summary statistics on measurements but did not report the individual results. Within the collected data sheet, we also identify the target population on which the study was made and provide the bibliographic references. We summarized this data by reporting weighted means and standard errors, weighted by the standard deviations given in the original data.

Experimental Design, Materials and Methods

We employed Google Scholar to identify previously published histological studies on tooth formation ages. Different combinations of key words such as “tooth”, “dentin/dentine”, “human”, “formation”, “development” were employed. To the best of our knowledge we identified all published studies concerning our tooth selection. We targeted data on human permanent first molars, canines and incisors since these are the most suitable within bioarchaeological research of early childhood nutrition and palaeopathology [8, 9]. Collected data is reported in an Excel spreadsheet file, as described in the previous section. This also includes, in a separate sheet, a data summary where weighted means and standard errors are reported. The data file is made available via the data platform of the Pandora initiative (https://pandoradata.earth/) and included within the Hebe data repository for the study of past childhood (https://pandoradata.earth/organization/hebe-data-repository-for-the-study-of-past-childhood).

CRediT Statement

Carlo Cocozza made the data search and collection. Ricardo Fernandes defined the data structure and performed data analysis. The article was co-written by Carlo Cocozza and Ricardo Fernandes.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships which have, or could be perceived to have, influenced the work reported in this article.

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PRESENTING THE COMPENDIUM ISOTOPORUM MEDII AEVI, A MULTI-ISOTOPE DATABASE FOR MEDIEVAL EUROPE

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Keywords: Database: Medieval Europe; Medieval Bioarchaeology; Stable Isotope Analysis; Bayesian Modeling; Human Diet; Animal Management; Human Spatial Mobility

ABSTRACT

Here we present the Compendium Isotoporum Medii Aevi (CIMA), an open-access database gathering more than 50 000 isotopic measurements for bioarchaeological samples located within Europe and its margins, and dating between 500 and 1500 CE. This multi-isotope ($\delta^{13}C$, $\delta^{15}N$, $\delta^{34}S$, $\delta^{18}O$, and $^{87}Sr/^{86}Sr$) archive of measurements on human, animal, and plant archaeological remains also includes a variety of supporting information that offer, for instance, a taxonomic characterization of the samples, their location, and chronology, in addition to data on social, religious, and political contexts. Such a dataset can be used to identify data gaps for future research *and to address multiple research questions, including those related with studies on medieval human lifeways (i.e. human subsistence, spatial mobility), characterization of paleo-environmental and -climatic conditions, and on plant and animal agricultural management practices. Brief examples of such applications are given here and we also discuss how the integration of large volumes of isotopic data with other types of archaeological and historical data can improve historical knowledge.*

BACKGROUND AND SUMMARY

The Middle Ages (c. 500 and 1500 CE) is a formative period of European history. It was marked by major transformations in political and economic systems, vast population movements, violent armed conflicts, climate change, development of religious movements, and technological innovations, albeit with regional variations[1–9]. The study of such historical phenomena has been predominantly based on written sources although these may vary in quality and representativity[10]. In particular, the lifestyles of lower socioeconomic classes are often mis- or under-represented given their illiteracy. Knowledge gaps can be reduced by isotopic analyses of human remains from which it becomes possible to build iso-biographies describing the diets and spatial mobility of single individuals from across socioeconomic, religious, and cultural spectra[11–29]. Isotopic analyses of animal and plant remains have also been employed in medieval contexts to reconstruct past climatic and environmental conditions plus to investigate economic and agricultural activities[30–43].

In the late 1970's, stable carbon isotope analysis of human remains was first employed for paleo-diet reconstruction[44,45]. Since then, the use of isotopic methods in archaeological research has expanded following several developments in isotope ratio mass spectrometry methods and lab pretreatment protocols that increased the number of measurable isotopic ratios across a wide variety of materials[46–48]. Such developments have allowed for a larger number of applications in archaeological research and for more accurate and precise assessments of past phenomena. The reconstruction of past human subsistence, nutrition and spatial mobility, the study of past animal and crop management practices, or the reconstruction of paleo-environments and -climates are just some examples that illustrate the importance of isotopic methods in archaeological research[49–57]. This is also evident from the exponential growth in recent decades in the number of archaeological publications reporting isotopic results[58]. Once collected and curated, amassed isotopic data can be subject to meta-analyses from which it is possible to investigate past human and natural phenomena at varying spatial and temporal scales[59–61].

Recent databases have partially compiled isotopic data for the European medieval world[62,63]. Here we present the open-access CIMA (Compendium Isotoporum Medii Aevi) database, the first isotopic database to comprise the full extent of the medieval period across the entirety of Europe and its margins. This database also includes for the first time all types of bioarchaeological remains (plants, animals, and humans) and isotopic measurements ($\delta^{13}C$, $\delta^{15}N$, $\delta^{34}S$, $\delta^{18}O$, and $^{87}Sr/^{86}Sr$) on bulk organic remains and on tooth increments. To address various historical questions, CIMA includes metadata that characterizes the political, religious, and social context of listed samples. Here we describe CIMA and briefly illustrate its research potential.

METHODS

The collection of published isotopic measurements for medieval Europe and its margins, began in November 2019 and was completed in May 2020. Since then regular updates have been made to the database following the publication of new data. Isotopic measurements were obtained from journal articles, book chapters, archaeological reports, and academic dissertations available in different languages (Portuguese, Italian, English, Spanish, French, Swedish, Dutch, and German). Publications were located through a web search using scientific search engines (e.g. Google Scholar) employing different combinations of keywords such as "Medieval", "Isotope" plus geographical or cultural tags (e.g. "Italy" or "Longobard"). We also relied on thorough readings of publications' bibliography through which several additional isotopic datasets were located.

Data collection was mostly limited to Europe for samples dated between c. 500 and 1500 CE. However, isotopic measurements from non-European regions presenting cultural or religious affinities with medieval Europe (e.g. Norse populations in Greenland or Christian Crusaders in Jordan or Palestine) were also added. In this compilation, we included isotopic measurements ($\delta^{13}C$, $\delta^{15}N$, $\delta^{34}S$, $\delta^{18}O$, and $^{87}Sr/^{86}Sr$) of human and animal bone and tooth collagen (including tooth increments), bone bioapatite and tooth enamel, and plant organic remains. We did not include single compound measurements but this is planned for future CIMA updates once more data becomes available.

The CIMA database includes meta-data on the historical, cultural, religious, and social context of the samples. This information was collected both from primary and secondary publications on sites and individuals. Each isotopic measurement has an internal ID (sequential integer assignment) together with original IDs, as per primary sources, on each individual sample plus also, when available, for archaeological context and site. In some instances, isotopic values were only reported as a population mean. Whenever possible we contacted publication authors to obtain individual measurements plus additional contextual information. If this was not possible, data entries were flagged (data fields list the number of measurements included in the mean calculation).

A detailed description of the database metadata structure is given in Supplementary Information file S1. To maintain data consistency, we had at times to perform data conversions. Examples of this are reported human osteological descriptions (e.g. osteologically determined ages are listed in the database using the Buikstra and Ubelaker system[64]). The assignment of political, cultural, social and religious values is based on the archaeological, historical, and chronological context as reported by academic publications. This often does not assign a specific individual to a certain religious or political group but rather places a burial population within a site or even regional context. In cases where such an assignment is ambiguous we include in the database the various possibilities (e.g. religious assignment may be listed as "pagan; Christian").

Each database entry is georeferenced using decimal coordinates ("Latitude"; "Longitude") relative to the WGS84 system. Whenever available we used the geographical coordinates as reported in the original publication. If these were not available, the archaeological site was located and georeferenced using Google Earth. It was not always possible to locate the geographic center of archaeological sites. In such cases we identified the smallest administrative unit and used its geographical center. The field "unc. Radius (km)" gives an estimate on the radius of uncertainty (in km) for the location of a site.

The chronology of each sample is given as a temporal interval ("Min. Year (95%)"; "Max. Year (95%)" in years CE). Also included are data fields ("General Period(s)"; "Additional Chronological Tags") that describe chronological categories as text strings. The temporal interval was assigned following a hierarchical approach. Whenever direct dating of samples was available this was used (e.g. from radiocarbon dating). Otherwise, and successively, we employed the dating of the burial context, burial site, and overall culture.

DATA RECORDS

CIMA is organized into three separate datasets according to sample categories (humans, animals, plants) made available as Excel and CSV files. It consists of 17,756 human, 4946 animal and 164 plant entries. Isotopic data was collected from 358 primary sources (full list given in Supplementary Information file S2). The total number of $\delta^{13}C$, $\delta^{15}N$, $\delta^{34}S$, $\delta^{18}O$, and $^{87}Sr/^{86}Sr$ measurements included in the database is 50,153. Most of the collected data originates from archaeological sites located in the UK (24.1%), followed by Italy (10.8%), Spain (9.6%), and Germany (8.0%). The spatial distribution of archaeological sites included in CIMA is shown in Fig. 1. This reveals a major data gap for France (3.1% of data) which is compounded by its size and importance in medieval European history. Additional summaries and descriptions of human, animal, and plant data can be found in Supplementary Information file S1 and S3.

The CIMA datasets (https://doi.org/10.48493/s9nf-1q80) are made available via the Pandora data platform (https://pandora.earth/) within the MATILDA data community (https://pandoradata.earth/organization/matilda-a-repository-for-medieval-bioanthropological-databases) that collects historical and archaeological data relevant for the study of medieval Europe. Depending on assigned roles, MATILDA data community members may create/edit datasets and assign to these new DOIs. It is both possible to store datasets and to provide links to external compilations having previously assigned DOIs. Under this setup, individual researchers, research groups, museums, and laboratories can easily make available their medieval isotopic data as individual datasets within the MATILDA data community. This data is then incorporated into the CIMA master files following the predefined metadata standards. These master files include reference data fields that identify both primary sources with original data ("Reference"; "Link"; "DOI"; "Publication date") plus data compilations ("Compilation Reference"; "Compilation Link"; "Compilation DOI"; "Compilation Publication Year"). Under this system it is possible to easily track and acknowledge both previous data production and data compilation efforts. CIMA and MATILDA are open to new memberships and data contributions from research groups and individuals performing isotopic research on medieval Europe.

Another feature made available via the Pandora platform is the possibility of creating data networks linking separate datasets. One such example is a network of isotopic datasets (https://pandoradata.earth/group/isomemo-group) which are part of the IsoMemo initiative (https://isomemo.com/). IsoMemo is a collaborative network of independent isotopic databases. It includes several archaeological isotopic databases allowing for comparative studies at various spatiotemporal scales[65–69].

TECHNICAL VALIDATION

The database lists standard measures ("Collagen Yield"; "%C"; "%N"; "Atomic C:N ratio"; "Atomic C:S ratio"; "Atomic N:S ratio") employed to assess collagen preservation and establish the reliability of isotopic measurements for dietary or mobility studies[70–73]. Measurements of preservation criteria falling outside of accepted ranges were kept in the database since these can be used in studies related to sample preservation. However, for dietary or mobility studies they should be filtered out prior to data analysis.

Carbon stable isotope ratios are typically measured using an isotope ratio mass spectrometer (IRMS). However, some publications report measurements made using accelerator mass spectrometry (AMS). These are usually produced during radiocarbon dating and employed to correct radiocarbon concentrations for isotopic fractionation that may take place during sample preparation (e.g. combustion, graphitization) and machine measurement. The AMS and IRMS $\delta^{13}C$ values may differ considerably although this varies across laboratories and sample preparation and measurement techniques[74,75]. In CIMA we employed separate fields to report IRMS ("IRMS $\delta^{13}C$ Collagen"; "IRMS $\delta^{13}C$ Collagen unc."; "$\delta^{13}C$ Carbonate"; "$\delta^{13}C$ Carbonate unc.") and AMS ("AMS $\delta^{13}C$ Collagen"; "AMS $\delta^{13}C$ Collagen unc.") $\delta^{13}C$ values. Uncertainty associated with isotopic measurements is marked in database fields using "unc.".

Oxygen isotopic ratios are frequently measured on carbonates although phosphate measurements are at times reported. In addition, these measurements may also be reported relative to a VPDB (Vienna Pee Dee Belemnite) or VSMOW (Vienna Standard Mean Ocean Water) standard. In some studies, for instance on spatial mobility, conversions are made to report $\delta^{18}O$ measurements relative to the same standard and molecular ions relying on experimental work[76–78]. In CIMA, $\delta^{18}O$ results are listed using the standard and molecular ion as given in original publication ("$\delta^{18}O$ Carbonate (VPDB)"; "$\delta^{18}O$ Carbonate (VPDB) unc."; "$\delta^{18}O$ Carbonate (VSMOW)"; "$\delta^{18}O$ Carbonate (VSMOW) unc."; "$\delta^{18}O$ Phosphate (VPDB)"; "$\delta^{18}O$ Phosphate (VPDB) unc."; "$\delta^{18}O$ Phosphate (VSMOW)"; "$\delta^{18}O$ Phosphate (VSMOW) unc."). In addition, conversions may be made to calculate the $\delta^{18}O$ of drinking water[76–78]. Some publications give only these values and are listed in CIMA using a separate field ("$\delta^{18}O$ Drinking Water (if not reported differently)").

USAGE NOTES

The CIMA compilation of medieval isotopic data can be employed for multiple research goals including: 1) paleoclimatic and paleoenvironmental studies; 2) investigating past human agricultural management practices; 3) and in the reconstruction of different aspects of past human lifeways such as diet, nutrition, and spatial mobility. In the following section we provide brief examples that illustrate this research potential and how data from this collection can be combined with non-isotopic data from the medieval period. We implemented an R-based toolkit to access online data records using a Shiny app interface (https://isomemoapp.com/)[79,80]. In addition, the app includes interactive dashboards for data modeling employing previously published Bayesian and non-Bayesian methods[59–61,81,82]. Further details on modeling methods employed in examples below are given in Supplementary Information File S4 and S5.

Stable carbon and nitrogen isotopic values from archaeological animal remains are a palimpsest of information on agricultural management practices (e.g. irrigation, manuring) and of how local vegetation is influenced by environmental/climatic conditions (e.g. precipitation, canopy effects, altitude, soil chemistry, etc.)[54,56,57,83]. To illustrate spatiotemporal isotopic variability in bone collagen for terrestrial animals from Medieval Europe we employed broad temporal (time bin 500 to 1000 CE versus 1000 to 1500 CE) and spatial (Europe plus sub-selections for England, Iberia, and Italy) divisions. The comparison was made for $\delta^{13}C$ and $\delta^{15}N$ IRMS values from domesticated herbivores (cattle/ovicaprids) and omnivores (pigs/chickens).

The diachronic comparison using violin plots for selected regions (Fig. 2) and the observed spatial patterns for all combined periods (Fig. 3) show that Italy and Iberia have roughly similar distributions for both bone collagen $\delta^{13}C$ and $\delta^{15}N$ values and that these differ from England when it comes to domesticated herbivores. In the case of herbivore bone collagen $\delta^{13}C$, observed patterns likely reflect a higher water abundance and greater canopy effect in northern Europe although some of the more highly elevated $\delta^{13}C$ values in southern Europe suggest animal consumption of C_4 plants such as millet or sorghum or, in the case of Muslim Iberia, of sugarcane production wastes[11,83–85]. The $\delta^{15}N$ values in England and Italy/Iberia are similar for omnivores but show narrower ranges for herbivores in England in spite of the considerably larger environmental variability in Iberia/Italy. Given that there are no visible temporal differences, this suggests that omnivores' feeding and crop/vegetation management practices differ considerably within medieval England[86].

The CIMA database allows for studies of the impacts that major historical developments had on different aspects of human lifeways such as diet. For instance, the collapse of the Western Roman Empire (476 CE), the splitting of its territories into separate kingdoms, and the subsequent territorial unification attempt during the Carolingian empire (800–887 CE) mark major historical transitions in Europe[6–8]. Different sources of historical and archaeological evidence point towards a higher diversification of farming and animal rearing in Late Roman to early medieval Europe, yet far from the intensive agricultural economy of the Roman Empire[84,87–90]. In concomitance, the arrival of migrating populations may have also shifted dietary habits[91].

We combined CIMA medieval isotopic data with Roman isotopic data from the IsoArcH database[92], to map and compare spatial distribution of human adult bone collagen carbon ($\delta^{13}C$ - IRMS) and nitrogen ($\delta^{15}N$) stable isotopes for three time slices: 200 CE, 500 CE, and 800 CE (Fig. 4). This revealed regional differences in human isotopic values that reflect differences in diet and/or local isotopic baselines plus diachronic shifts associated with historical transitions. For instance, the comparison of the 200 and 500 CE time slices shows that in some regions (e.g. Galicia in northern Spain, northern Italy, and northern Balkans) there were increases in $\delta^{13}C$ without major shifts in $\delta^{15}N$. This suggests larger consumption of C_4 cereals (e.g. millet and/or sorghum) and/or products from animals foddered on these. Such a dietary shift may be the result of new incoming dietary traditions (e.g. Suebi in western Iberian[20]) but it should also be noted that the collapse of the Roman economic and agrarian systems reduced access to wheat and barley while millet and sorghum became commonly consumed by the lower classes[84,85,93–95]. The comparison of the 500 CE and 800 CE time slices reveals regions with visible isotopic shifts. In northern Italy and the Balkans, the increase in $\delta^{13}C$ values shows that the cultivation of C_4 cereals increased through time[84,85,93–95]. In central Italy, there is a decrease in $\delta^{15}N$ values. Here a reduction in animal sizes and a general shift towards silvopastoralism is consistent with a decline in the consumption of terrestrial animal protein and/or a decrease in animal δ^{15}N values as consequence of free-roaming rearing practices[88,89].

Diachronic patterns in human lifeways may also be investigated for specific locations and offer insights into changes in medieval social structures. For instance, some historical sources suggest the existence of gender-based nutritional inequality in antiquity, although their extension beyond restricted communities (e.g. monastic) remains unknown[91,96,97]. Figure 5 shows temporal plots of adult human isotopic values classified according to osteological sex for the city of Rome between 1 and 1000 CE. Modeled results show that isotopic ranges for both sexes greatly overlap. The temporal plots show relatively constant δ^{13}C values and some variability in δ^{15}N values although there is an overall decrease after c. 500 CE. This likely reflects a combination of factors, including the end of the Roman proto-welfare system (Annona i.e. the yearly distribution of grain in Rome, which at times included pork98) and a reduction in the proportion of consumed pork in favor of ovicaprids as revealed by archaeofaunal studies[88,89,99].

The study of medieval diets is also explored using a variety of nonisotopic evidence (e.g. written sources, archaeofaunal, and archaeobotanical studies). The integration of these types of evidence using Bayesian methods allows for improvements in the precision of dietary reconstructions[100,101]. Figure 6 shows the comparison of Bayesian dietary estimates for three separate time slices (200, 500, and 800 CE). It also includes a comparison of modeling relying only on isotopic data and vague priors (left) and of modeling combining isotopic data with non-isotopic dietary prior constraints obtained from ethnographic, archaeofaunal, archaeobotanical, and ancient textual studies (right) (modeling details and results in Supplementary Information file S4, S5, and S6). Clearly the use of isotopic data alone does not allow for precise dietary estimates given the uncertainties in model parameters and issues of equifinality (varying proportions of food intakes resulting in the same human isotopic value). Instead, the incorporation of prior dietary information[101] resulted in a clear improvement in dietary precision that revealed diachronic trends and allowed for comparisons with modern day diets (Fig. 6, right, and Supplementary Information file S6).

The precision of modeled dietary estimates, and of other past phenomena, may also be improved by integrating data from multiple isotopic proxies. CIMA includes data from several isotopic proxies measured on human remains. Among these, are sulfur isotopic measurements (δ^{34}S) that can exhibit a large spatial and environmental variability[102]. Figure 7 shows the distribution of δ^{34}S, δ^{15}N, and δ^{13}C measurements on bone collagen included in CIMA from terrestrial herbivores, freshwater fish, and marine fish that passed elemental quality criteria (atomic ratios of C:N, C:S, and N:S)[70,72]. For the available data, the multi-proxy approach exhibits a clear separation among the taxa. However, the number of measurements available for marine fish (n=3) and freshwater fish (n=4) is small and lack representativity of the expected isotopic range. For instance, freshwater fish δ^{13}C values are atypically high, values closer to terrestrial herbivores would be expected, and all originate from an Icelandic volcanic lake[103]. Unavailable from publications, were records for δ^{34}S measurements in plants although these should be similar to those from collocated herbivores. These examples illustrate another important function of CIMA, to identify data gaps and set future research targets.

Isotopic data can also be employed to investigate human and animal spatial mobility patterns although here we only illustrate the former. In this respect, medieval Europe witnessed several population movements at various scales, from the mass migrations of the Germanic Migration Period (conventional 375–568 CE), to comparatively smaller scale movements following military conflicts, urbanization processes, and religious pilgrimages[1,6–8]. Isotopic studies of human mobility often explore spatial variability of water strontium ($^{87}Sr/^{86}Sr$) or oxygen ($\delta^{18}O$) isotopic ratios[17,104–107]. These can then be compared with measurements in human tissues with varying formation periods and turnover rates[53,55].

Most common isotope-based mobility studies determine if investigated individuals have isotopic signatures matching burial locations. We illustrate this for Roman and medieval individuals buried at sites in York and London. Their $^{87}Sr/^{86}Sr$ or $\delta^{18}O$ isotopic values measured on teeth are compared with a Bayesian reference baseline (modeling details in Supplementary Information file S4-S5). Individuals for which the values for one of these proxies did not match local values (overlap in 95% credible ranges) were classified as mobile or otherwise as non-mobile. Kernel density plots were then used to reveal the proportion of mobile vs. non-mobile individuals at each location (Fig. 8b and c). Also included in Fig 8 (a) are Kernel density plots for $\delta^{13}C$ and $\delta^{15}N$ bone/tooth collagen IRMS measurements for the same locations. These are more abundant than $^{87}Sr/^{86}Sr$ or $\delta^{18}O$ and may reveal data gaps resulting not only from sampling bias but also from sample availability which depends on past population numbers, burial practices, and taphonomic effects. The modeling results show the presence of mobile individuals at both London and York across the periods for which data is available. However, variations in height ratios of mobile versus non-mobile individuals reveal that in London there was a comparatively higher proportion of mobile individuals during the early Roman Period and during the continental migration of the fifth century CE.

In some cases it may be possible to determine the place of origin of a mobile individual by comparing $^{87}Sr/^{86}Sr$ and/or $\delta^{18}O$ values measured in a tooth formed at an early age with isotopic reference maps[61]. This assumes low mobility during the formation of the tooth and that the research areas may be somewhat constrained. Relying on $\delta^{18}O$ tooth data we employ this approach to estimate the place of origin for three individuals (REP-295, REP-511, REP-529) buried in Repton, UK and associated to the Scandinavian 'Great Heathen Army', invading Britain in the late ninth century[108–111]. Modeling results (Fig. 9) show that individuals from a double grave (REP-295 and REP-511) likely originated from Ireland, which is often associated with campaigns led by some of the leaders of the army, although other regions in the British Isles and the opposing continental coast are also possible. On the other hand, the remaining Repton individual (REP-529) was likely from Sweden, Norway, or the Baltic region.

We also investigated the place of origin of a young individual (SK27), buried in a high medieval leprosarium in Winchester, UK, together with a scallop shell typical of a pilgrim who completed a pilgrimage to Santiago de Compostela, was determined using both $^{87}Sr/^{86}Sr$ and/or $\delta^{18}O$ measurements. This individual was likely residing in northern England or in southern Scotland during tooth formation in accordance with previous reports (Fig. 9)[112].

CODE AVAILABILITY

The statistical analysis and modeling employed for examples given in the Usage Notes was done in R[79] and included R packages developed within the Pandora & IsoMemo initiatives[59–61,81,82]. Source code for spatiotemporal models (AverageR, TimeR, OperatoR, KernelTimeR, and LocateR) is available for download at GitHub (https://github.com/Pandora-IsoMemo/iso-app) together with the source code for ReSources (https://github.com/Pandora-IsoMemo/resources). These can be run locally (https://github.com/Pandora-IsoMemo/drat) as Shiny apps[80]. For modeling reproducibility, a full description of model options is given in Supplementary Information S5.

The MATILDA data community where CIMA is stored is part of the Pandora data platform that is based on the CKAN open source data management system (https://ckan.org/). This is hosted by the Max Planck Computing and Data Facility.

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AUTHOR CONTRIBUTIONS

Carlo Cocozza collected the data, co-designed meta-data structure, wrote the manuscript and performed the modeling; Enrico Cirelli oversaw data collection in respect to historical and archaeological aspects and co-wrote the manuscript; Marcus Groß developed modeling apps and co-wrote the manuscript; Wolf-Rüdiger Teegen oversaw data collection in respect to anthropological, zooarchaeological and archaeobotanical aspects and co-wrote the manuscript; Ricardo Fernandes designed meta-data structure, supervised data collection, and co-wrote manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

DATA CITATION

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FIGURES

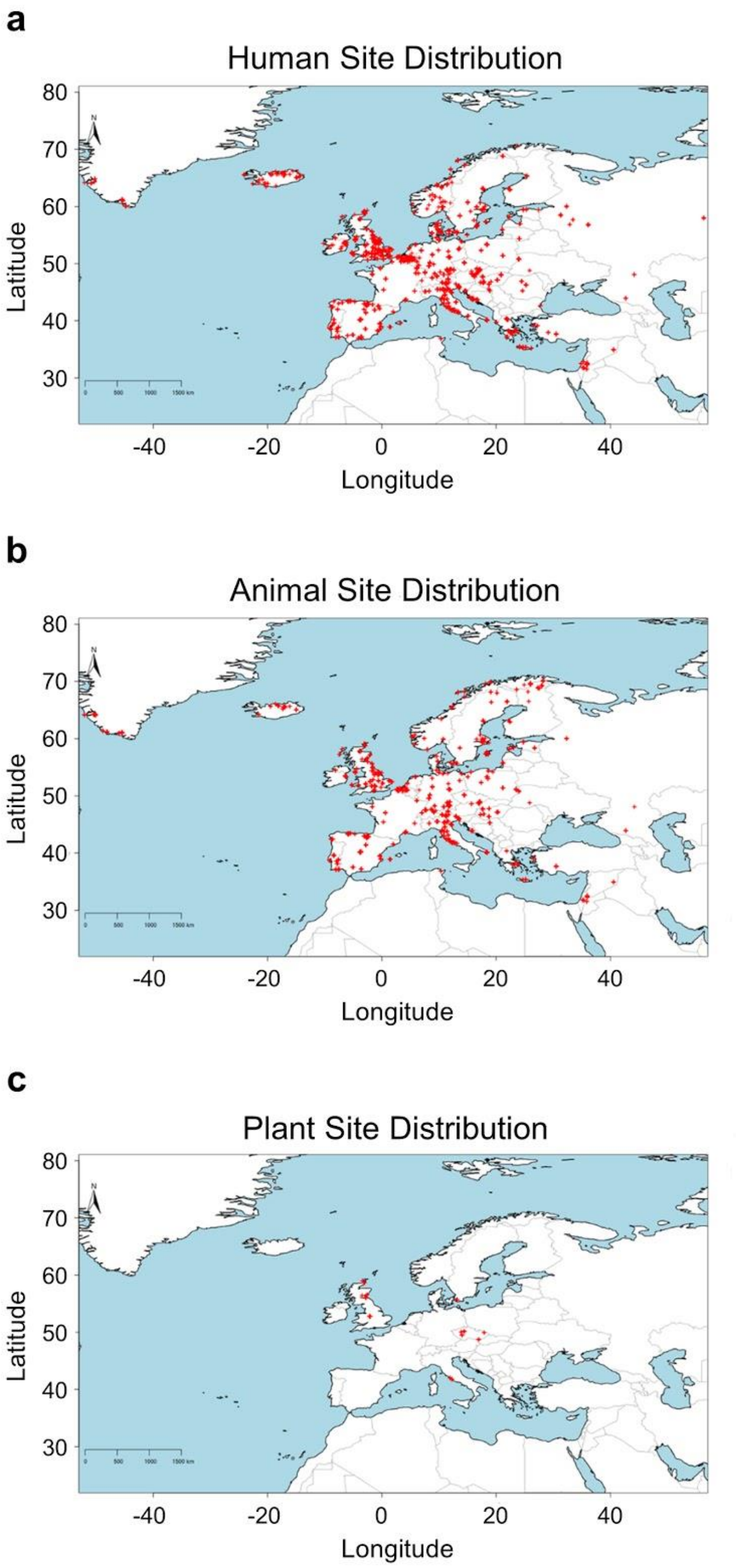

Fig. 1. Spatial distribution of human (a), animal (b), and plant (c) site locations for data compiled within CIMA.

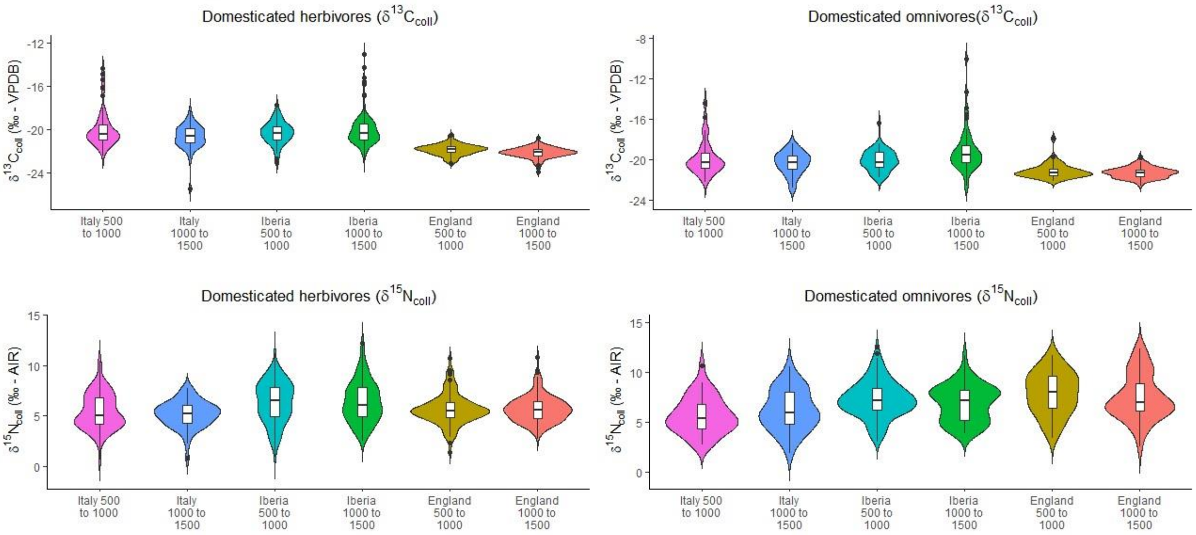

Fig. 2. Violin plots showing a temporal comparison of $\delta^{13}C$ and $\delta^{15}N$ bone collagen values from domesticated herbivores and omnivores in Italy, Iberia, and England.

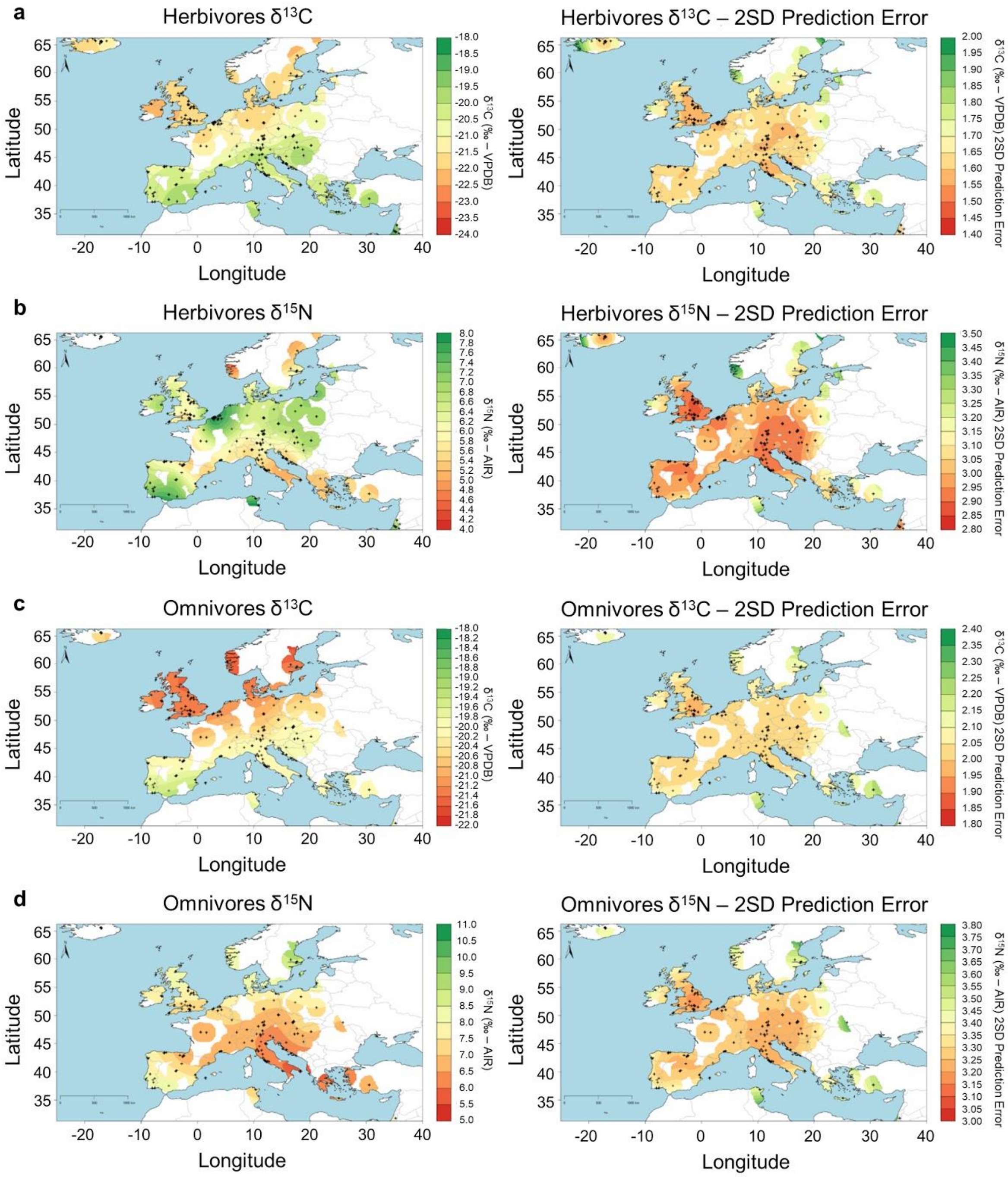

Fig. 3. Spatial comparison of predicted δ13C and δ15N mean and associated errors (double the square root of the sum of the standard error plus the square of the population standard deviation) for domesticated animals. a) δ13C herbivores; b) δ15N herbivores; c) δ13C omnivores; d) δ15N omnivores.

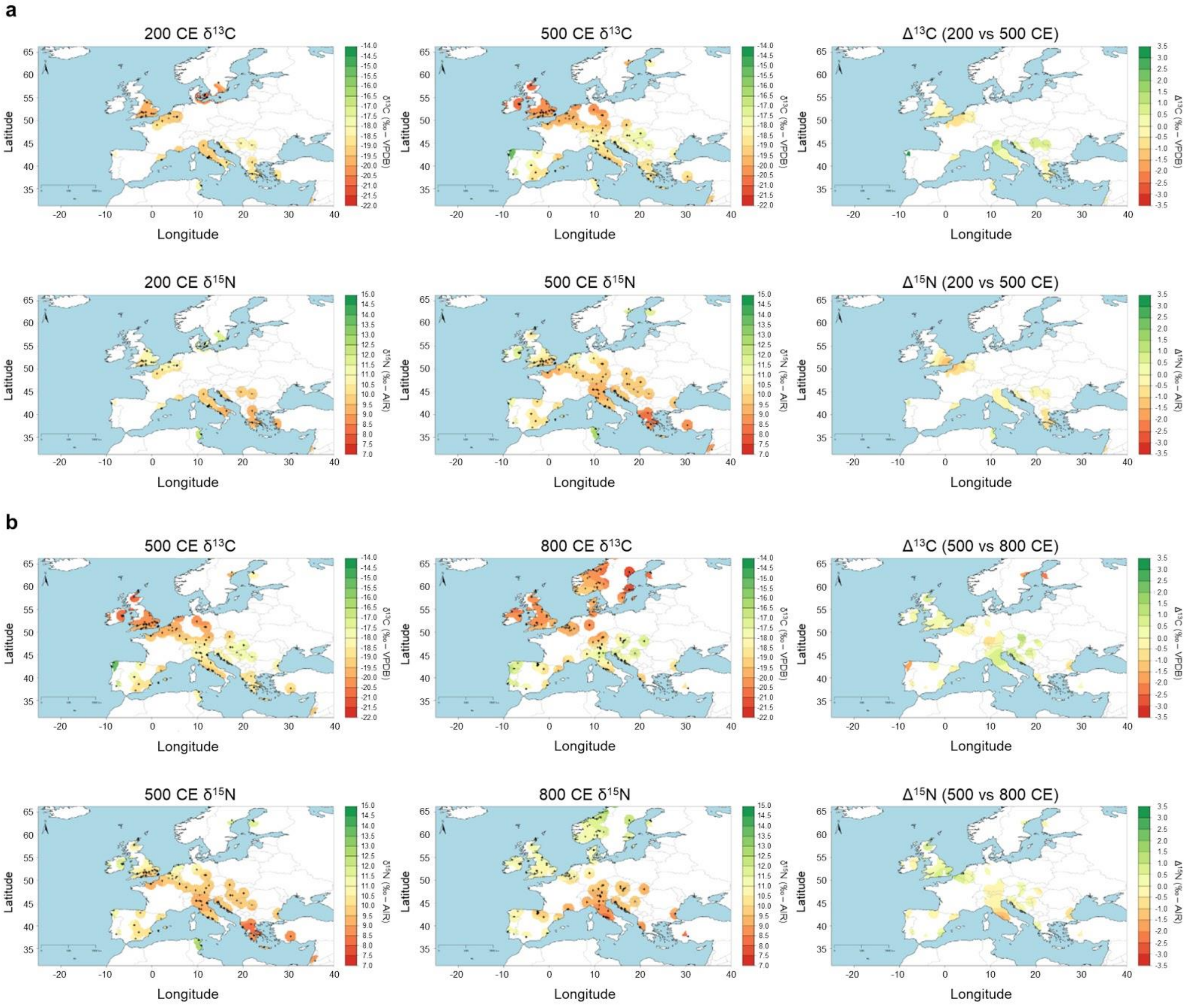

Fig. 4. a) Bayesian spatial estimates of δ^{13}C and δ^{15}N mean values for human bone collagen in 200 CE (left column) and 500 CE (middle column) and mapping of differences in isotopic values (Δ^{13}C and Δ^{15}N, right column). b) Bayesian spatial estimates of δ^{13}C and δ^{15}N mean values for human bone collagen in 500 CE (left column) and 800 CE (middle column) and Bayesian mapping of differences in isotopic values (Δ^{13}C and Δ^{15}N, right column).

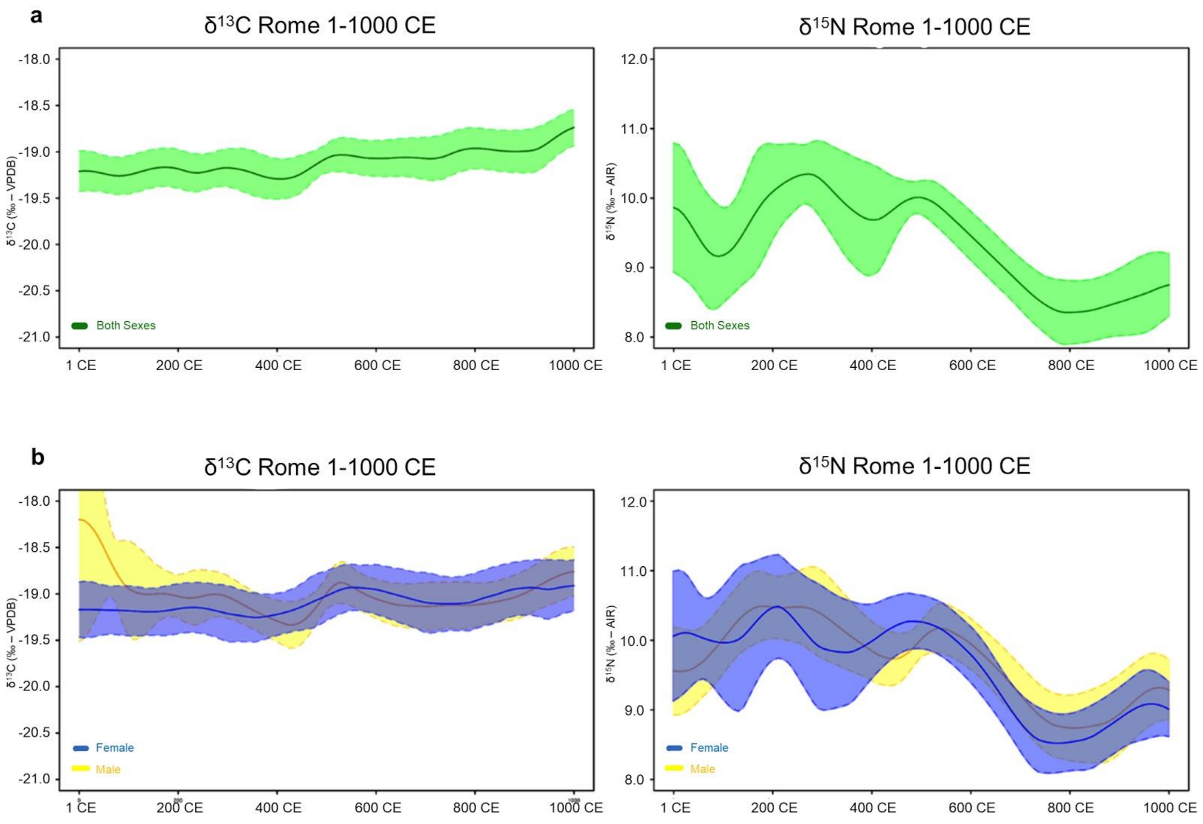

Fig. 5. Temporal Bayesian plots for adult bone collagen $\delta^{13}C$ and $\delta^{15}N$ values for Rome. a) both sexes $\delta^{13}C$ and $\delta^{15}N$; b) female versus male $\delta^{13}C$ and $\delta^{15}N$.

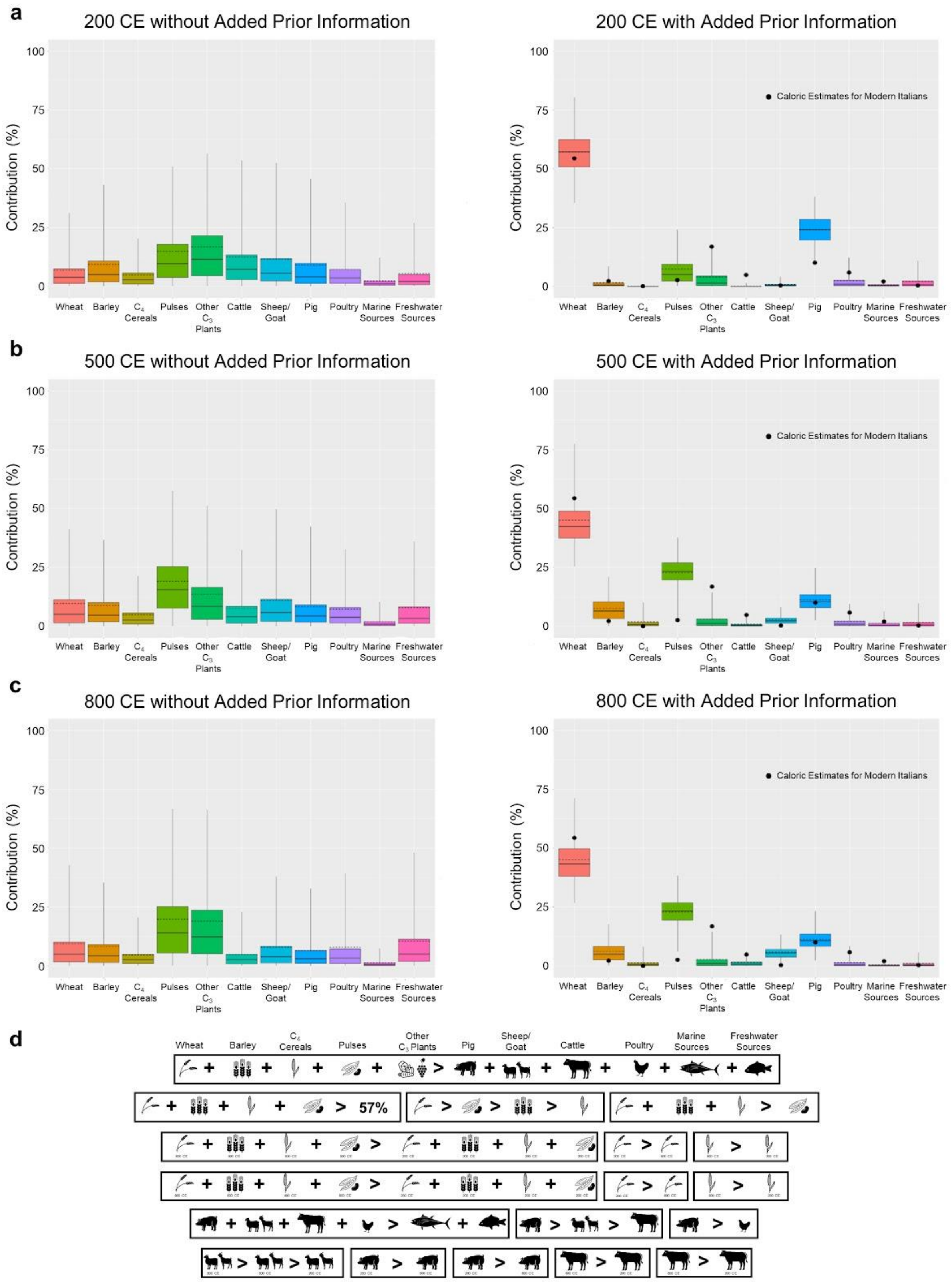

Fig. 6. 200 CE (a), 500 CE (b), and 800 CE (c) dietary estimated models of main food sources caloric contribution for the city of Rome without (left) and with (right) added prior dietary information (d). Black circles within plots correspond to modern dietary estimates. See also Supplementary Information files S4-S5-S6 for modeling details.

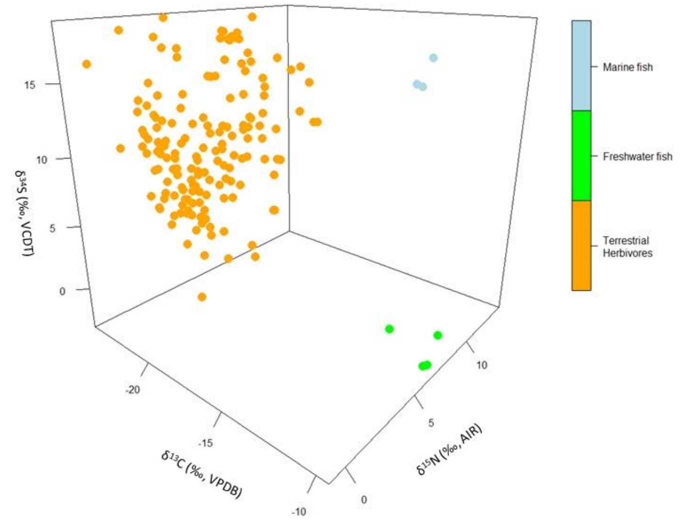

Fig. 7. Distribution of $\delta^{34}S$, $\delta^{15}N$, and $\delta^{13}C$ measurements on bone collagen included in CIMA from terrestrial herbivores, freshwater fish, and marine fish that passed elemental quality criteria (atomic ratios of C:N, C:S, and N:S).

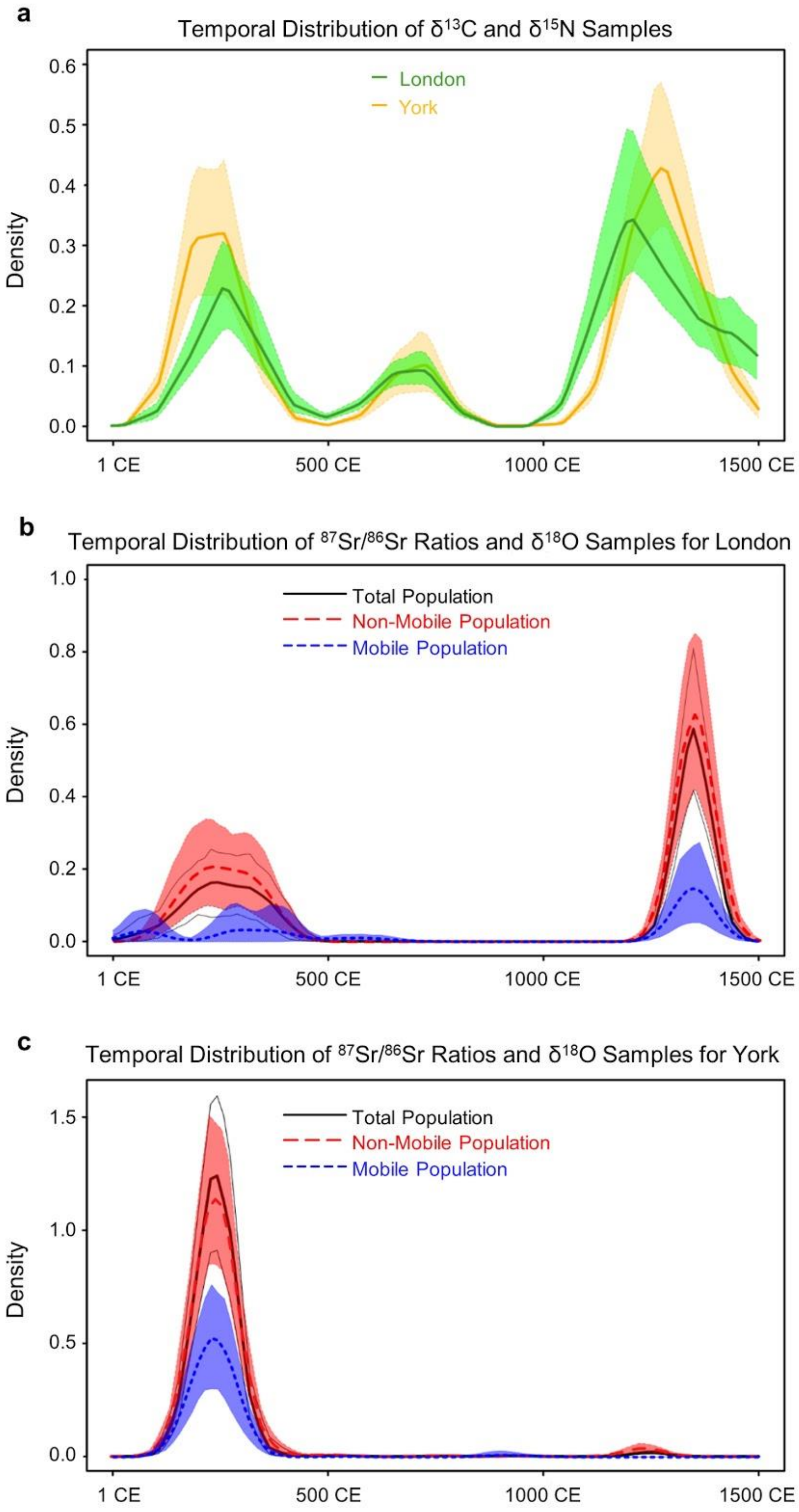

Fig. 8. Kernel density plots for human osteological samples from London and York. Heights reflect relative temporal abundance of samples with $\delta^{13}C$ and $\delta^{15}N$ measurements (a -yellow and green plots), of $^{87}Sr/^{86}Sr$ or $\delta^{18}O$ measurements (white plots), and of mobile (blue plots) and non-mobile (red plots) individuals.

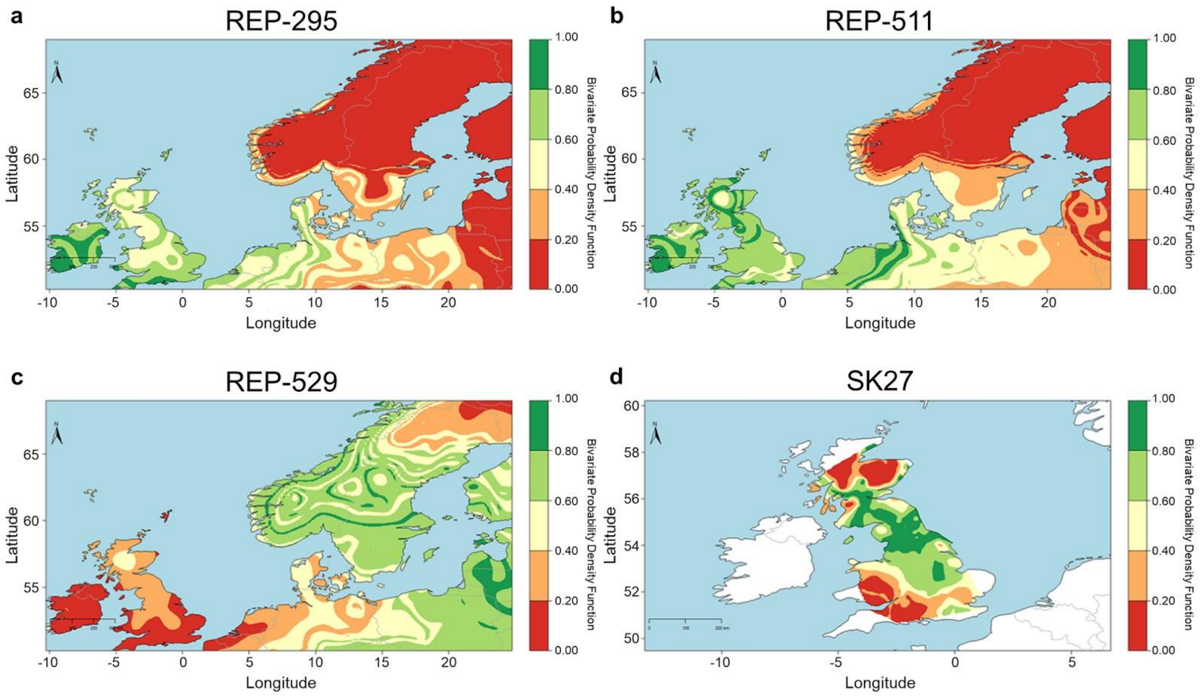

Fig. 9. Probability density maps for place of origin for individuals REP-295, REP-511, REP-529 and SK27.

THE BLACK DEATH KILLED FAR FEWER EUROPEANS THAN COMMONLY THOUGHT, BIG DATA PALEOECOLOGY REVEALS

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ABSTRACT

The Black Death (1347–1352 ce) is the most renowned pandemic in human history, believed by many to have killed half of Europe's population. However, despite advances in ancient DNA research that conclusively identified the pandemic's causative agent (bacterium Yersinia pestis), our knowledge of the Black Death remains limited, based primarily on qualitative remarks in medieval written sources available for some areas of Western Europe. Here, we remedy this situation by applying a pioneering new approach, 'big data palaeoecology', which, starting from palynological data, evaluates the scale of the Black Death's mortality on a regional scale across Europe. We collected pollen data on landscape change from 261 radiocarbon-dated coring sites (lakes and wetlands) located across 19 modern-day European countries. We used two independent methods of analysis to evaluate whether the changes we see in the landscape at the time of the Black Death agree with the hypothesis that a large portion of the population, upwards of half, died within a few years in the 21 historical regions we studied. While we can confirm that the Black Death had a devastating impact in some regions, we found that it had negligible or no impact in others. These inter-regional differences in the Black Death's mortality across Europe demonstrate the significance of cultural, ecological, economic, societal and climatic factors that mediated the dissemination and impact of the disease. The complex interplay of these factors, along with the historical ecology of plague, should be a focus of future research on historical pandemics.

Few doubt that the mid-fourteenth-century Afro-Eurasian plague pandemic, the Black Death, killed tens of millions of people. In western Asia and Europe, where its spread and mortality are best understood, upwards of 50% of the population is thought to have died within approximately 5 years[1–4]. Whole-genome sequencing confirms the pandemic as a novel introduction of the zoonotic bacterium Yersinia pestis[5,6]. Yet, despite advances in palaeogenetics and generations of written-source-based research on the cultural and economic transformations plague is credited with accelerating, from the Renaissance to the 'Great Divergence'[7,8], much about the Black Death's spread and demographic impact remains poorly understood. The regionality of the plague's mortality is particularly underexplored, owing to the availability of written sources and the limits of traditional historical methods. Here we pioneer a new approach, big data palaeoecology (BDP), that leverages the field of palynology to evaluate the demographic impact of the Black Death on a regional scale across Europe, independent of written sources and traditional archaeological material. Our analysis of 1,634 pollen samples from 261 sites, reflecting landscape change and agricultural activities, demonstrates Black Death mortality was far more spatially heterogeneous than previously recognized. Strikingly, BDP provides independent confirmation of the devastating toll of the Black Death reflected in written sources in some European regions, while establishing conclusively that the Black Death did not affect all regions equally. We attribute this mortality variation to cultural, ecological, economic, societal and climatic factors, which influenced Y. pesti s dissemination and prevalence, generating regionally unique outcomes.

Estimating Black Death mortality

Multidisciplinary studies are redefining the Black Death. In recent years, palaeogeneticists have confirmed the pandemic's Y. pesti s identity and established that the outbreak seeded novel plague reservoirs in Europe[5,6]. Archaeologists and historians meanwhile have begun to put sub-Saharan Africa on the Black Death map[9], to fill in lacunae in our understanding of the pandemic's Mediterranean and European spread[10,11], and to explore the pandemic's origins in central Asia and dissemination in east Asia, drawing on evolutionary biology and palaeogenetics[12]. But while multiple disciplines have reassessed the pandemic's spatiotemporality, its mortality estimates of which have drawn attention to the Black Death for centuries—remains underexplored and limited almost entirely to unidisciplinary, written-source-based approaches. Medieval mortality data are scarce and highly fragmentary. Nineteenth-century historians of the Black Death based their assertion that the pandemic claimed 25% or more of European lives on assessments of qualitative narrative sources[13]. Since the mid-twentieth century, historians have painstakingly built-up multiple instructive case studies of Black Death mortality for regions comparatively well-endowed with administrative sources allowing for statistical analysis (for example, regions of England, France, Italy and the Netherlands)[14–16]. Some of these case studies have argued for a death toll in the range of 50% or more. These numbers have been increasingly considered representative of the Black Death's broader mortality[1–4,9,12,14]. Although it has been suggested that regional variation characterized the demographic crisis the Black Death caused, little evidence—historical, archaeological or environmental—has been employed to substantiate such thinking[8,17,18]. As a result, case studies from better documented regions have been employed as proxies for Black Death mortality in European regions where direct evidence for the pandemic is nonexistent (for example Bohemia and Finland), slight (single sentences or vague passages; for example Moravia, Hungary and Scotland) or available but neither detailed nor quantitative (most regions, including areas of England, France, Italy and the Netherlands)[1]. By treating case studies of relatively well-documented regions as predictive of the pandemic's death toll in all regions the pandemic touched, histories of the Black Death implicitly rest on the untested assumption that plague mortality was uniform across regions regardless of local cultural, ecological, economic and societal contexts, and therefore that the prevalence of Y. pesti s, an ecologically and epidemiologically complex disease[19], was comparable across Europe. This methodology has lent itself to estimates of an aggregate European death toll upwards of around 50% (approximately 50 million deaths)[1,4], though studies accounting for regional source scarcities have estimated mortality to have fallen below that mark[8,17,20]. Problematically, many of the quantitative sources drawn upon to build cases studies of Black Death mortality relate to urban contexts, which owing to their crowding, generally poor sanitation and quite possibly heavier disease burdens, may have suffered higher plague mortality than rural areas[21,22], and in the mid-fourteenth century upwards of 75–95% of the population of every European region was rural[23]. Although every pandemic, plague or not, is distinct, a Black Death mortality across Europe of approximately 50% vastly exceeds the demographic losses sustained during the third plague pandemic in the late nineteenth century—the plague pandemic for which the most mortality data exists—including in China and India, which were then severely affected[24,25].

BDP and Black Death mortality

Here, we pioneer an alternative approach (discussed in detail in Methods). BDP allows us to evaluate the Black Death's mortality across Europe using quantitative palaeoenvironmental datasets, which can be employed for spatial statistical comparisons (Fig. 1). Our dataset consists of fossil pollen counts from 261 radiocarbon-dated sediment cores from 19 present-day European countries (Fig. 2; Supplementary Data 1). Pollen data can be used to assess past demographic dynamics as human pressure on the landscape in the pre-industrial period was directly dependent on the availability of rural labour. We focus on the period between 1250 and 1450 ce (comparing 100 years before and after the Black Death; 100 years representing roughly four generations, a time period during which pre-industrial populations could not recover from potentially high plague mortality[23]) for which 1,634 pollen-analysed sediment samples are available (Supplementary Data 2). In order to compare trends between different European bioclimatic zones, we assembled pollen types (taxa) representing different plants from species to family level into four standardized summary indicators, based on their subsistence value for human economy or their ecological needs as reflected in two major ecological indices, the Ellenberg light indicator and Niinemets and Valladares shade tolerance scale: (1) cereals; (2) herding (pasturelands); (3) fast forest secondary succession (pioneer shrubs and trees growing on former fields/pastures within 5–10 years of abandonment); (4) slow forest secondary succession (mature–late successional woodland on abandoned fields/pastures). We discuss the results of the Ellenberg-based indicators below, but the Niinemets-based indicators yielded the same results in 19 out of 21 regions and the differences do not bear on our discussion (Extended Data Figs. 1 and 2).

Results

Validity test using Sweden and Poland. We validated our BDP approach by examining two well-studied, but contrasting, regional case studies of the Black Death's mortality, in Sweden and Poland. An earlier multidisciplinary analysis discovered significant contraction in cereal cultivation, as well as a more general economic and demographic decline, in the uplands of southern Sweden following the Black Death[26]. By contrast, historians have long demonstrated that central Europe, particularly Poland, experienced economic growth over the fourteenth century, related to the centralization of royal power following a period of partition, few wars in the central provinces of the country, large-scale colonization of uncultivated lands and the development of cities[27]. Our BDP approach independently corroborates these trajectories. We validate the ability of our pollen datasets to reflect the extent of the Black Death's mortality by comparing them to historical data of national tax payments made to the pope (Peter's pence)[28–30] (Fig. 3). This validity test lends further support to our primary focus in this study on cereal cultivation, as argued in the Methods.

Four major scenarios of landscape and demographic change. Having validated our approach, we analysed the pollen dataset for all of Europe. We focused on contrasting the four summary pollen indicator values on a regional scale for subperiods of 100 years before and after the Black Death.

While we discuss the results of this analysis here (Fig. 4), our complimentary data presents 50-year (1301–1350 to 1351–1400) and 25-year (1325–1350 to 1351–1375) period analyses (Supplementary Figs. 1 and 2). For cereals, they returned the same results in terms of direction of change for 20 out of 21 regions for 50-year and 16 out of 19 regions for 25-year analyses, confirming the robustness of our conclusions (ExtendedData Fig. 3); the results for other indicators are also highly similar between different periods of analysis (Extended Data Figs. 4 and 5). BDP employs bootstrapping to evaluate statistical significance of the differences between the pre- and post-Black Death subperiods on a regional level. In this way, we identified four scenarios of post-Black Death agricultural change based on the cereal pollen indicator (Fig. 4): (1) substantial and statistically significant increase, reflecting arable expansion and limited Black Death mortality (top panel); (2) modest and statistically insignificant increase, suggesting stability or slow-paced agrarian growth (upper middle panel); (3) modest and statistically insignificant decrease, suggesting stagnation or some contraction of agrarian activities, possibly stemming from more limited demographic losses or economic disruption caused by the plague (lower middle panel); (4) substantial and statistically significant decrease, reflecting arable contraction and pronounced Black Death mortality (bottom panel). Scenarios 1 and 2 falsify the theory that Black Death mortality was significant everywhere. Scenario 3 and 4 demonstrate Black Death mortality was devastating in some regions. Changes in the herding indicator reveal trajectories similar to those of cereals in most cases or no change. We discovered only one region (southwest Germany) where there occurred a statistically significant decline in cultivation in parallel with a statistically significant increase in herding (some indication of this is also apparent in Greece), suggesting a shift to livestock production related to agrarian labour shortages and less demand for grain[31]. The fast forest succession indicator increases in a statistically significant way in central Italy and central France, confirming field abandonment. In central Italy, this is accompanied by discernible reforestation (statistically significant increase in the slow forest succession indicator), attesting to significant regional Black Death mortality and slow demographic and economic recovery. To confirm the robustness of our results, BDP combines statistical with independent spatial approaches (Fig. 5). The latter yielded results identical for all four BDP indicators to our statistical approach in our 100-year period analysis as well as in our 50-year (1301–1350 ce to 1351–1400 ce) and 25-year (1325–1350 ce to 1351–1375 ce) period analyses (Supplementary Figs. 4–7).

Discussion

The Black Death was a diverse and entangled phenomenon. Figure 6 visualizes the spatial distribution of the four trajectories of post-Black Death landscape change from Fig. 4, demonstrating that the Black Death's mortality varied significantly between European regions. The pandemic was immensely destructive in some areas, but in others it had a far lighter touch. Strikingly, BDP identifies a sharp agricultural decline in several regions of Europe, independently corroborating analyses of historical sources that suggest high mortality in regions of Scandinavia, France, western Germany, Greece and central Italy[1], and lending further validation to our approach. At the same time, there is much evidence for continuity and uninterrupted agricultural growth in central and eastern Europe, and several regions of western Europe, particularly in Ireland and Iberia. In this way, BDP invalidates histories of the Black Death that assume Y. pesti s was uniformly prevalent, or nearly so, across Europe and that the pandemic had a devastating demographic impact everywhere. While we have centred our study on estimating the impact of the Black Death on the landscape, plague recurred in several regions within the 100-, 50- and 25-year periods of our analyses. It is not implausible that some recurrences, notably the so-called pestis secunda of the late 1350s and early 1360s[32], could have been more devastating in a few regions we studied than the Black Death and that some of the arable contraction we detect may be attributable to both the Black Death and early second-pandemic recurrences. That the results of our 100-, 50- and 25-year period analyses were largely uniform, strongly suggests that if early plague recurrences contributed considerably to the landscape change, the earliest of those recurrences, occurring within the first 25 years, were the most significant. Of course, if the pestis secunda partially accounts for the arable contraction and forest succession shown here for parts of Europe, our results would further call into question the demographic toll of the Black Death, even where we have discerned significant arable contraction, as in parts of France, Italy and Scandinavia. At the same time, if we are to include the earliest recurrences, where we have discerned little change or arable expansion, the significance of both the Black Death and those earliest recurrences is limited. These remarks aside, our approach has shown conclusively that the Black Death did not significantly alter land use everywhere or affect all regions equally. The significant variability in mortality that our BDP approach identifies remains to be explained, but local cultural, demographic, economic, environmental and societal contexts would have influenced Y. pestis prevalence, morbidity and mortality. Ongoing transformations of rural economy in many European regions would have also modified the plague mortality, or—to an extent—the amplified impact it had on the landscape. Importantly, regional population densities cannot explain the complex landscape dynamics we discern (as visualized in Supplementary Fig. 8), nor the geographical location of the 261 coring sites (see Supplementary Fig. 9, showing the averaged elevation of our sites). The spread of the pandemic depended on numerous factors, which would have generated compound effects, feedback loops and regionally unique outcomes. Plague is an ecologically and epidemiologically complex zoonotic disease, maintained by sylvatic rodents and their fleas, and transmittable to and between people via multiple pathways, including commensal and sylvatic rodent flea bites, respiratory secretions, direct contact with infected animals, human ectoparasites (fleas and lice) and fomites[19]. The behaviour of Y. pestis hosts and vectors, and their capacity to efficiently transmit the pathogen, is partly constrained by complex interactions with seasonal climate variability and local ecological conditions, both in anthropogenic and rural environments (cities, villages and fields versus mountains, forests or wetlands[32]). Regional variation in population density and distribution, ectoparasite burdens, living conditions, and commensal rodent populations and their fleas, undoubtedly mattered. Local climatic contexts were also shown to have strongly determined third plague pandemic dynamics in Asia[33,34]. In Europe, where the Black Death spread over several years (1347–1352 for the regions considered here), different seasons and annually variable climatic conditions may have influenced Y. pestis prevalence and the pandemic's mortality. Furthermore, while hypothesized links between early-fourteenth-century famines and the Black Death remain to be substantiated, and while Y. pestis is often lethal in lieu of antibiotics[19], it has been shown that Black Death mortality was selective and the immunological and nutritional heterogeneity of the populations the pathogen interacted with would have ensured uneven toll[35,36]. That climatic, cultural, ecological and economic factors shaped regional Black Death outcomes is well illustrated by the initial phases of the pandemic in Europe. Cereal trade is thought to have been instrumental for the introduction of the pandemic to Mediterranean Europe, and along established conduits of commerce and communication, ecological factors, associated contingency effects and historical path dependency mattered from the outset. Before the pandemic arrived in the Crimea, the volume of cereal trade between Italy and the Black Sea was sizable, yet blocked by embargo[11,37,38]. High demand in southern Europe for Black Sea cereals from 1345 onwards was associated with a period of excessive precipitation and cooling[39,40] negatively affecting cereal supplies in Italy and beyond, 1345–47[8,37,41,42]. Cereal imports from Black Sea coasts resumed once the situation improved in 1347, and by early 1348 Venetian merchants had filled many Italian granaries with Black Sea produce[11,37,39,43] and introduced plague to Europe. Plague outbreaks disseminated from major cereal ports in southern and north-western Italy from January 1348[1,44]. To the contrary, plague hardly spread in north-western Italy, which was independent from overseas cereal imports[37,43,45]. Local circumstances shaped the outcome of the pandemic on regional scales from the outset. In summary, our BDP approach shows Black Death mortality was far more spatially heterogeneous than previously thought. This significant variation in Black Death mortality may be explained by the pathogen's entanglement with a dynamic nexus of cultural, ecological, economic, societal and climatic factors that determined its prevalence and the pandemic's mortality in any given region. That the pandemic was immensely destructive in some regions, but not all, falsifies the practice, not uncommon in Black Death studies, of predicting one region's experience on the basis of another's. Regional mortality outcomes must be reconstructed using local sources, including BDP as proxies of changes in cultural landscapes. As a few well-documented case studies of the Black Death's destructive mortality in Europe have informed estimates of the pandemic's mortality not only in other European regions, but also in several regions of Africa and Asia, our findings have significant implications both for the wider history of the Black Death and for how historical disease outbreaks are reconstructed.

Methods

Pollen-inferred landscape change and pre-industrial demography. Recently, data derived from tree rings or ice cores have been employed to approximate changes in human economic activity related to past epidemics, as well as to warfare and climatic variability[46,47]. However, none of these proxies is directly related to human demography or provides a basis to estimate variation in the Black Death's mortality on a regional scale across Europe (to date only a single archaeological study using pottery as a proxy for demographic change on the national level, focusing on just a single country—England—has appeared[48]). In recent years, pollen data have been proven to be closely related to demographic variability. Most importantly, detailed comparisons of historical documentary data on population trends and landscape changes as revealed by pollen data have been carried out on a local scale and a close link between changes in European pollen data and changes in European local demography over the past millennium has been demonstrated on multiple occasions, that is, during the period and region of our concern here[49,50]. A strong link between long-term demographic trends as visible in regional settlement numbers and macro-changes in land cover (deforestation/afforestation) have also been confirmed for ancient Greece[51]. Additionally, a recent publication successfully employed pollen data to test the extent of the mortality associated with the sixteenth-century Spanish and Portuguese empires' colonization of tropical regions in the Americas and Asia[52]. However, as of now there is no method to quantify past demographic trends in absolute numbers based on palaeoecological data. Consequently, we also focus in this paper on relative changes in historical societies' populations and test the now common idea that the Black Death caused enormous mortality across Europe (with many scholars now arguing for a mortality exceeding 30% and upwards of 50% of the population within a few years) (see also Fig. 1). Using our BDP approach, we conclude this hypothesis is not maintainable. Our evidence for demography-related landscape changes (or lack thereof) negates it. Our main indicator is cereal pollen. In pre-industrial economies, rural labour availability (hence rural population levels) and the spatial scale of cereal cultivation were directly related. An increase in the extent and intensity of cereal cultivation—as reflected in pollen data—would have required not only a predilection and demand for cereals, but also greater availability of labour and thus population growth or significant immigration. The maintenance of existing agricultural activity, in turn, would have required relatively stable population levels[53–55]. The uniform ~50% mortality postulated for the Black Death across Europe should have resulted in a large and significant decline of cereal cultivation and parallel forest regrowth across Europe, as previously demonstrated for mid-fourteenth-century Sweden[26] and singular sites in some regions of western Europe[56]. This result agrees with the fact that Black Death mortality could be high among people at productive age, as illustrated for England[57,58]. Moreover, even in the case of England, a comparatively commercialized and adaptive rural economy in mid-fourteenth-century Europe, the loss of 50% of the population led to a significant decline in the total area under cultivation (as documented by heterogeneous written sources)[59]. In Italy, another well-developed economy at that time, the expansion of large estates following the Black Death also did not compensate for the general loss of cereal productivity[60]. This effect, high mortality driving arable contraction, must have been yet more pronounced in more subsistence-oriented and less adaptive economies, with limited surplus production, such as in regions of the Iberian Peninsula, Germany, Sweden and particularly east-central Europe. Importantly, palaeoecological evidence for arable contraction may be indicative, to some extent, of not only rural population decline but also urban population decline in the region, as there is evidence in some areas, following the pandemic, of rural-to-urban migration, of country-dwellers repopulating urban centres[10]. Possibly less common was intraregional rural migration, as marginal lands were abandoned for better quality soils, which were more likely to remain under cultivation[26,61]. Therefore, cereal pollen remains our most potent pollen indicator related to demographic changes in pre-industrial European societies. Other pollen indicators, reflecting rewilding and reforestation (secondary ecological succession) of cereal fields abandoned as a result of significant mortality, or the transformation of cereal fields into pastures, which required less rural labour and thus also could have been a response to high plague mortality, play a secondary role in our analysis and provide further support for our conclusions.

BDP data collection. Existing online palynological databases (the European Pollen Database (EPD)[62] www.europeanpollendatabase.net, and the Czech Quaternary Palynological Database (PALYCZ)[63], https://botany.natur.cuni.cz/palycz/), as well as personal contacts of the study authors and a systematic publication search were employed to identify palynological sites in Europe reaching the required chronological and resolution quality for the study of the last millennium. In order to enable statistical analysis, we included only sites clustered in well-defined historical-geographical regions, excluding isolated sites even if the quality of a site's data was very good. Data of sufficient quality and amount from regions for which the Black Death is well-studied, notably central and northern England and the Low Countries, is not presently available; to the best of our knowledge, for each of these regions there currently is not more than a single isolated site[56], which does not allow for the application of statistical approaches. In total, 261 pollen records with the average temporal resolution of 58 years and ^{14}C-age control (or varve chronology), have been collected. The age–depth models of the sequences have been provided by authors in original publications, by the EPD or developed through the Clam package (version 2.3.4) of R software for the purpose of this study. The analytical protocol for pollen extraction and identification is reported in the original publications. The Pollen Sum includes all the terrestrial taxa with some exceptions based on the selection done in the original publications. The full list of sequences, exclusions from the Pollen Sum, age-depth models and full references are reported in Supplementary Data 1. The taxa list has been normalized by applying the EPD nomenclature. In this respect, the general name Cichorioideae includes Asteraceae subf. Cichorioideae of the EPD and PALYCZ nomenclatures, which primarily refers to the fenestrate pollen of the Cichorieae tribe[64]. Ericaceae groups Arbutus unedo, Calluna vulgaris, Vaccinium and different Erica pollen types, whereas deciduous Quercus comprehends both Q. robur and Q. cerris pollen types[65]. Rosaceae refers to both tree and herb species of the family. Finally, Rumex includes R. acetosa type, R. acetosella, R. crispus type, Rumex/Oxyria and Urtica groups U. dioica type and U. pilulifera.

BDP summary pollen indicators. In order to connect changes visible in the pollen data to human demographic trajectories, we assembled four summary pollen indicators that describe specific landscapes related to human activity. They reflect different degrees of demographic pressure on the landscape (cereal cultivation, pastoral activities, which are less-labour intensive than cereal cultivation, abandonment and rewilding) as well as different durations of land abandonment that might have occurred post-Black Death. Our indicators account for the fact that Europe is a continent rich in natural heritage, with a wide range of landscapes and habitats and a remarkable wealth of flora and fauna, shaped by climate, geomorphology and human activity. In order to ensure uniform interpretation of the indicators, we relied on criteria that can be applied to all European landscapes regardless of their local specificity. Cereals and herding are directly related to human activities and are barely influenced by spatial differences. More complex is the succession of natural plants with their ecological behaviour and inter-species competition. For this reason, we relied on existing quantitative indicators of plant ecology. The Ellenberg L – light availability indicator66 provides a measure of sunlight availability in woodlands and consequently of tree-canopy thickness, reflecting the scale of the natural regeneration of woodland vegetation after cultivation or pasture activities[61]. Nonetheless, ecological studies have suggested that geographic and climatic variability between different European regions can influence the Ellenberg indicator system[67–71]. The original indicators were primarily designed for Central Europe[58], but several studies developed Ellenberg indicators for other regions, reflecting the specific ecology of the selected taxa (British Isles;[72] Czech Republic;[73] Greece;[74] Italy;[75] Sweden[76]). Plants with L values between 5 and 8 are listed in the fast succession indicator, the ones with L values ranging from 1 to 4 are included in the slow succession indicator. The result is the following list: 1) Cereals: only cultivated cereals have been included: Avena/Triticum type, Cerealia type, Hordeum type, Secale. 2) Herding includes pastoral indicators linked to the redistribution of human pressure: Artemisia, Cichorioideae, Plantago lanceolata type, Plantago major/media type, Polygonum aviculare type, Rumex, Trifolium type, Urtica, Vicia type. 3) Fast Succession comprises indicators of relatively recent reforestation of cultivated land after abandonment: Alnus, Betula, Corylus, Ericaceae, Fraxinus ornus, Juniperus, Picea, Pinus, Populus, deciduous Quercus, Rosaceae. 4) Slow Succession includes indicators of secondary succession established after several decades of abandonment: Abies, Carpinus betulus, Fagus, Fraxinus, Ostrya/Carpinus orientalis, Quercus ilex type. In order to validate the indicators overcoming the regional limits of Ellenberg values, a different subdivision has been provided following the Niinemets and Valladares shade tolerance scale for woody species of the Northern Hemisphere[77]. The subdivision of taxa in the Fast and Slow succession indicators remains the same with only three changes: Fraxinus ornus and Picea move from Fast to Slow succession and Fraxinus from Slow to Fast succession. Extended Data Figs. 1 and 2 show that the two groupings yield the same results, which confirms the reliability of our indicators. There is only one clear exception (Russia), with one more region where smaller-scale diversion occurs for only one indicator, Slow Succession (Norway). The different indicator behaviour results from the different attribution of Picea in our two sets of succession indicators: at high latitude, Picea characterizes the final stage of the ecological succession and hence its different attribution results in different summary indicator values in Russia for the two stages of ecological succession, fast and slow. Please note our summary indicators are not designed to reflect the entirety of the landscape and reconstruct all of its different components. Rather, they are a means of approximating changes in the landscape related to the types of human activities, and their intensity, as much as they relate to demographic changes in human populations using and inhabiting these landscapes.

BDP analytical statistical and spatial methods. To control for local specificity, pollen percentages of every taxon from each pollen site were standardized. From the taxa percentage in a given year the arithmetic mean calculated for the observations from the period 1250–1450 was subtracted and the result divided by the standard deviation for the 1250–1450 period. Standardized taxa results were assembled for each site into four BDP summary indicators. Since each indicator has different numbers of taxa, the sum of standardized taxa values calculated for a given year and site was divided by the number of taxa in the indicator. For the purposes of replication, this standardized pollen dataset, comprising the four indicators for each sample from each site, is available as Supplementary Data 2. This dataset has been analysed in two ways, statistically and spatially. For the statistical approach, standardized regional indices of landscape transformation were created for each region by calculating the average value for all sites within the region, for each of the subperiods analysed in the study (12501350 and 1351–1450; 1301–1350 and 1351–1400; 1325–1350 and 1351–1375). Differences between means for each subperiod were measured by the use of the bootstrapping based on 10,000 resamples. The 90% and 95% confidence intervals were estimated with the bias-corrected and accelerated method (BCa)[78]. These results are visualized in Fig. 5 for the comparison of the subperiods of 1250–1350 versus 1351–1450, and in Supplementary Figs. 4 and 6 for the comparison of the subperiods of 1300–1350 versus 1351–1400 and 1325–1350 versus 1351–1375, respectively. For the spatial approach, we employed the Bayesian model AverageR developed within the Pandora and IsoMemo initiatives (https://pandoraapp.earth/) to map the distribution of pollen indices across Europe. AverageR is a generalized additive model that has been described previously[79]. It relies on a thin-plate regression spline[80] to predict new, unseen data using the following model:

$$Yi = g(\text{longitude}, \text{latitude})+\varepsilon i$$

Where Yi is the independent variable for site i; g(longitude, latitude) is the spline smoother; and $\varepsilon i \sim N(0, \sigma\varepsilon)$ is the error term. The spline smoother can be written as $X \times \beta$ where X is a fixed design matrix and β is the parameter vector. Surface smoothing is controlled by employing a Bayesian smoothing parameter estimated from the data and trades-off bias against variance to make the optimal prediction[75]. This parameter β is assumed to follow a normal distribution: $\beta \sim N(0, 1 /\delta \times \lambda \times P)$, where P is a so-called penalty matrix of the thin plate regression spline, which penalizes second derivatives[81]. The δ parameter is by default set to 1 but this can be adjusted to suit smoothing needs for each application. In our study δ was set at 0.9 to match the preferred spatial scale of analysis for our dataset (approx. 250 to 500 km). AverageR was employed to generate smoothed surfaces for three sets of temporal bins (1250–1350 versus 1351–1450, as well as 1300–1350 versus 1351–1400 and 1325–1350 versus 1351–1375) and for the four BDP indicators (Supplementary Figs. 3, 5 and 7). For the same indicator the difference between the two temporal bins was plotted (Fig. 5; Supplementary Figs. 4 and 6).

Reporting Summary: Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data Availability: All data generated or analysed during this study are included in this published article (as the Supplementary Data).

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Author contributions

AI, AM and PG designed the study. AI drafted the paper with contributions from MB, RF, AM, TN, PG, RP, FCL, and CV. AM, LM, JP and CV created the pollen database, with the support of JALS (Spain), PL (Sweden), and TR (Estonia). AI, RP, RF and CC carried out the analyses. All other authors provided palynological data and contributed to the text and the interpretation.

Competing interests

The authors declare no competing interests.

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Supplementary Information is available for this paper.

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Figures

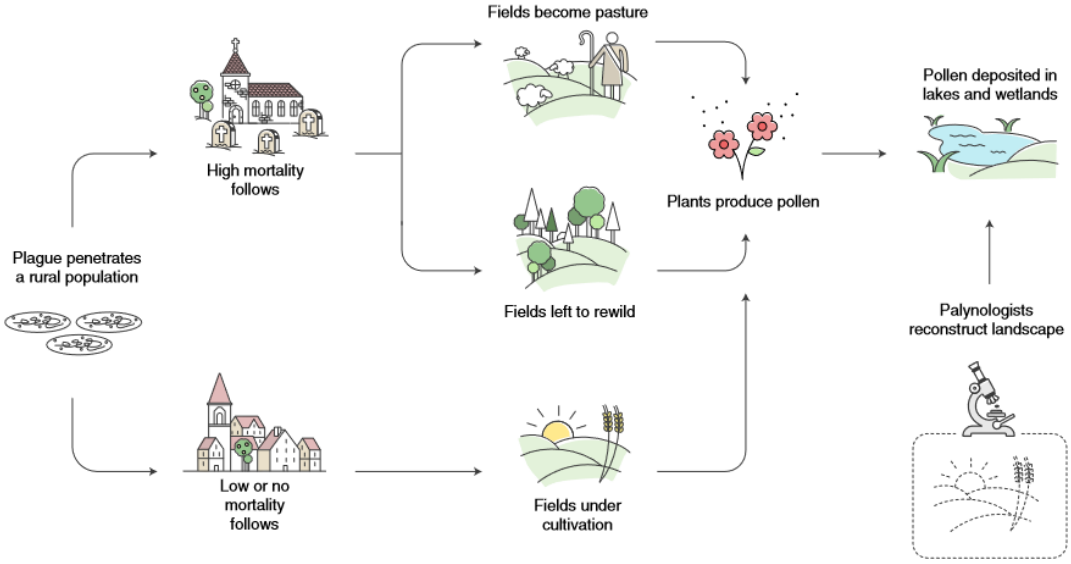

Fig. 1 | The BDP approach to verifying Black Death mortality levels. credit: A.I., T.N., Hans Sell and Michelle O’reilly.

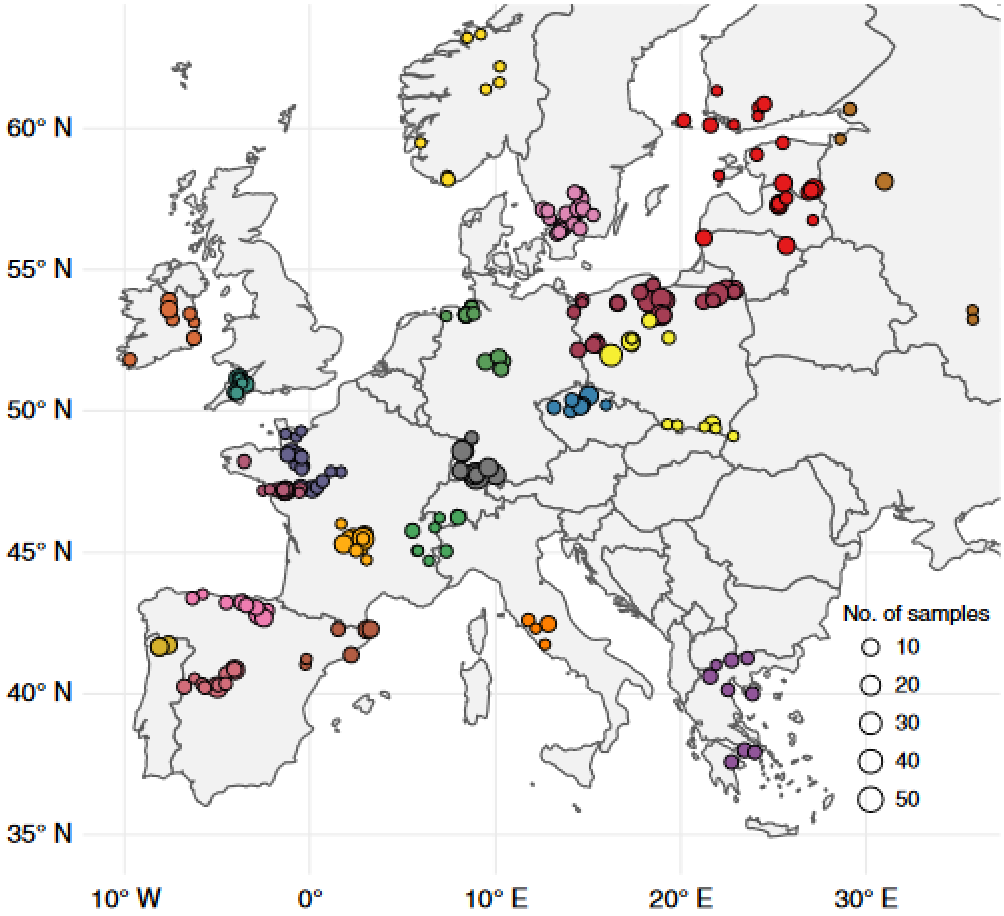

Fig. 2 | Location of pollen-analysed sediment cores used in this study. circle size reflects the number of samples per site for the period of 1250-1450 CE, different colours reflect division of sites into regional clusters for the purpose of the analysis presented in Fig. 3.

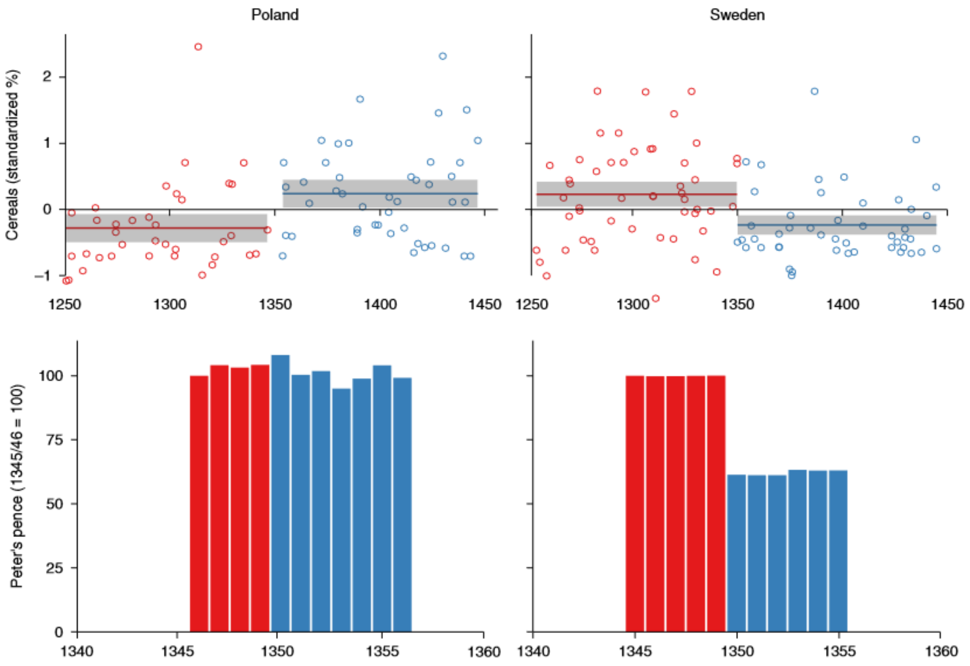

Fig. 3 | Comparison of historical and palaeoenvironmental indicators of the demographic impact of the Black Death in Poland and Sweden. Top panel, pollen data (cereal pollen, standardized percentage values from individual sites and 100-yr mean with standard deviation), see Supplementary Data 2. Bottom panel, Peter's pence tax[27–29].

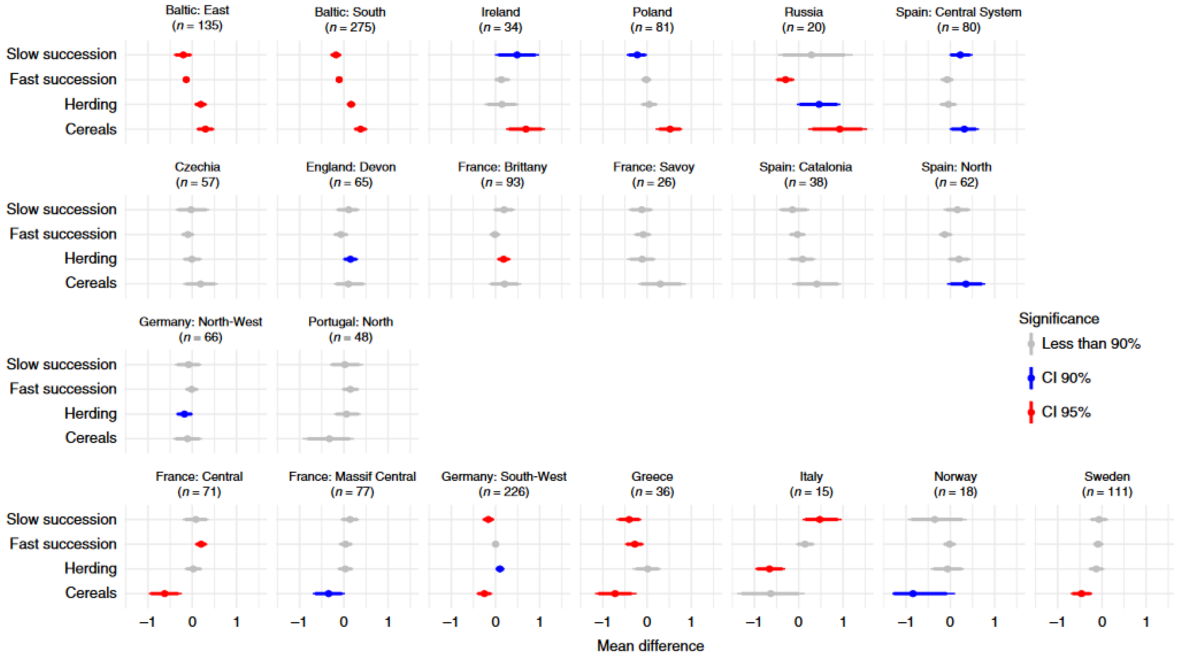

Fig. 4 | Regional-scale changes following Black Death in four BDP pollen indicators. Difference between the means of 100-yr periods of 1250–1350 and 1351–1450 ce, with the standard deviation. Statistical significance is based on bootstrap estimates. The indicators are presented in four rows from statistically significant increases in standardized mean percentages of cereal pollen (top) to statistically significant declines in standardized mean percentages of cereal pollen (bottom).

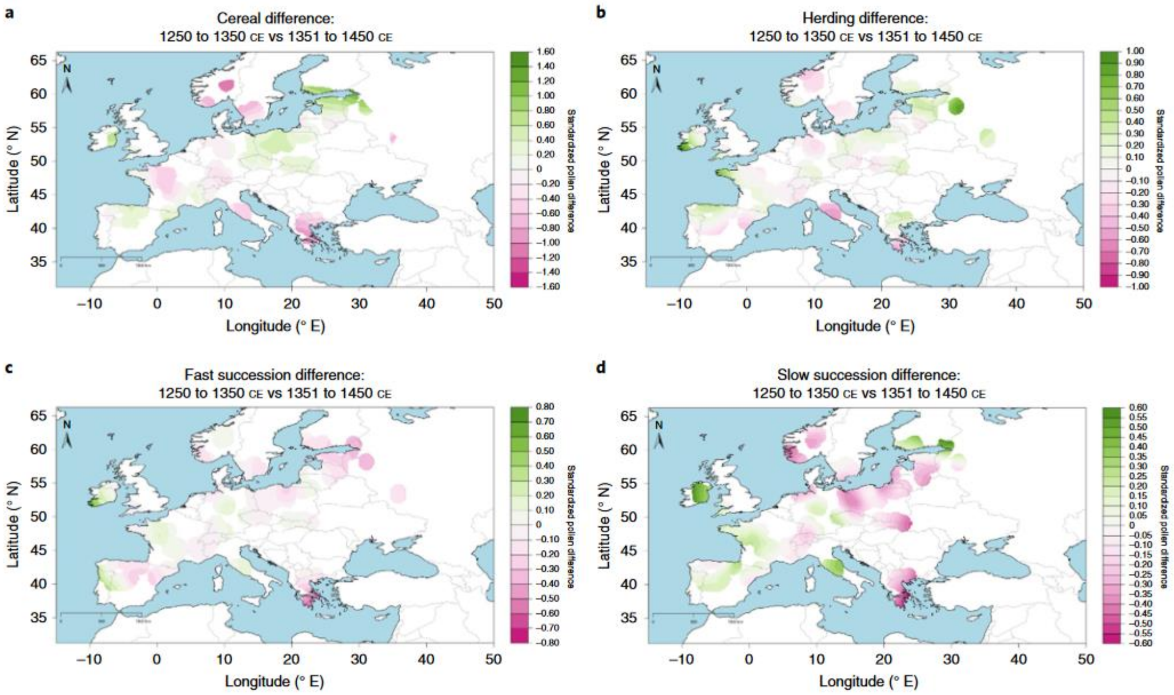

Fig. 5 | Spatial extrapolation showing 1250–1350 ce versus 1351–1450 ce temporal variation in the BDP pollen indicators. a–d, cereal (a), herding (b), fast succession (c) and slow succession (d). Based on results from Supplementary Fig. 3.

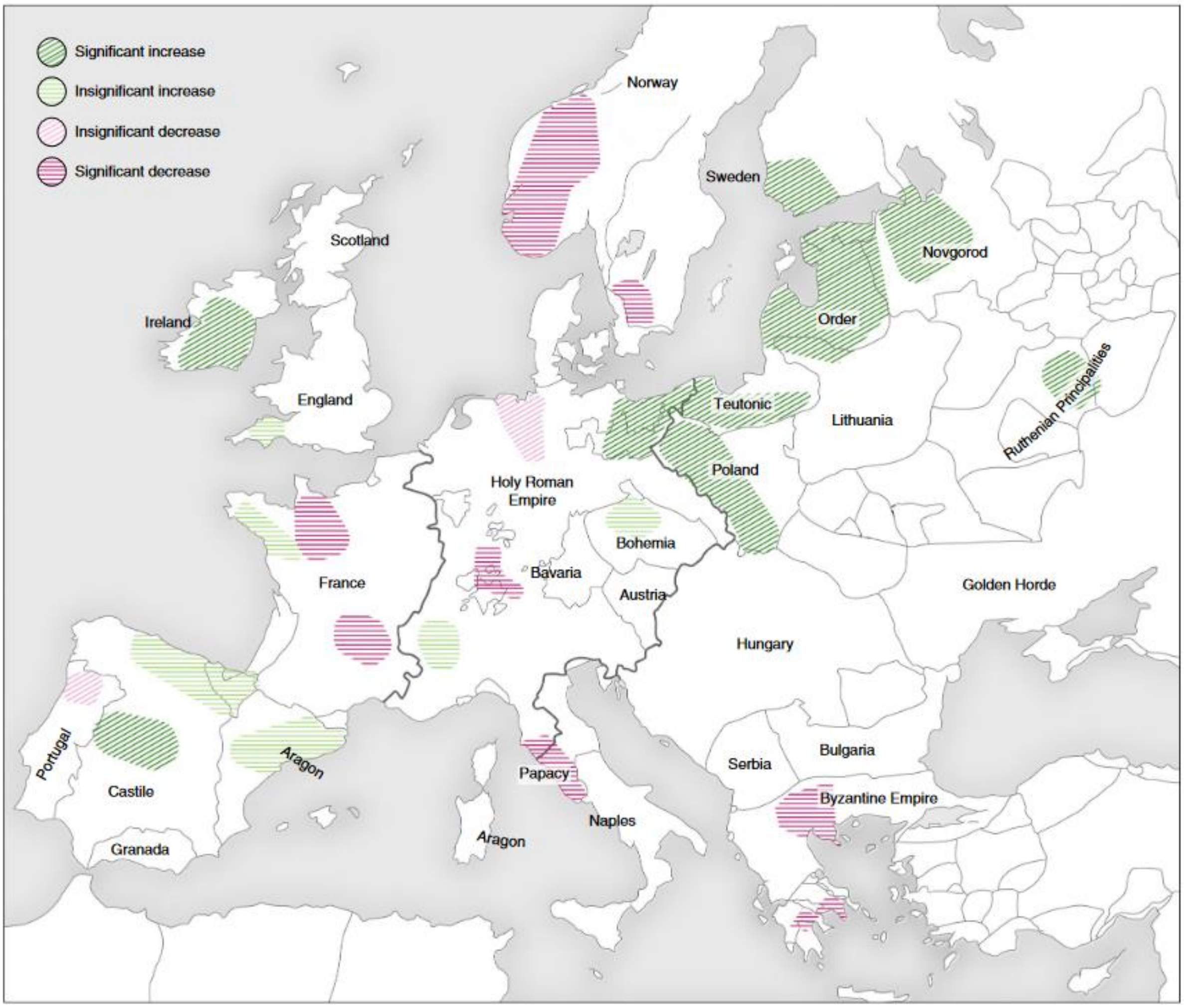

Fig. 6 | BDP-determined regional scenarios of Black Death demographic impact. colours reflect centennial-scale changes in the cereal pollen indicators from Fig. 2. Background map with political borders of fourteenth-century Europe. credit: Hans Sell, Michelle O'reilly and A.I.

INVESTIGATING INFANT FEEDING STRATEGIES AT ROMAN BAINESSE THROUGH BAYESIAN MODELLING OF INCREMENTAL DENTINE ISOTOPIC DATA

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Running Head: Infant Feeding Strategies at Roman Bainesse.

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ABSTRACT

We present the first study employing Bayesian modelling of isotopic measurements on dentine increments (five human upper first molars) to address Romano-British infant feeding practices at Bainesse (UK). The stable carbon and nitrogen isotope results modelled to six-month intervals with novel OsteoBioR software, revealed some common patterns, with weaning not starting before the age of six months and higher animal protein consumption after the age of seven. The latter possibly indicated a 'survival' threshold, evidenced by historical sources and osteological data, hence marking a rise in social status of children. The important role of Bainesse as commercial hub in relation to the fort of Cataractonium does not exclude a priori the possibility that medical treatises and Roman culture were known at the site. However, our results also showed significant intra-individual differences with weaning cessation taking place between two and five years, suggesting that these were followed only partially and other aspects influenced family decisions on infant feeding practices in Bainesse.

INTRODUCTION

Infant feeding practices are the human cultural reflection of a natural physiological need. Newborns consume breast milk as an easily digestible food source of high nutritional quality essential for the support of their immunological system. WHO and UNICEF currently recommend that infants are exclusively breastfed during the first six months following birth, and indicate breast milk can provide up to a third of an infant's nutritional needs into their second year of life alongside solid foods (World Health Organization 2013). Exclusive breastfeeding is defined as "an infant's consumption of human milk with no supplementation of any type" (Gartner et al. 2005), whereas weaning is "the process by which a baby slowly gets used to eating family or adult foods and relies less and less on breast milk." (World Health Organization & United Nations Children's Fund 1988). In practice, cultural and socio-economic factors have much control over the timing and speed at which weaning takes place, which can vary widely across past and present day human populations (Wells 2006).

Within the Roman Empire, infant feeding practices have been investigated using a variety of methods. The study of material culture, such as fictile baby-bottles, provides evidence of the techniques employed by Roman carers to feed their infants, albeit these may be biased by the funerary context in which they are found (Carroll 2018: 82–85). The critical study of written evidence such as medical works of ancient physicians and of other ancient sources (e.g. work contracts for wet-nurses) provides invaluable information on otherwise invisible socio-cultural habits (Centlivres-Challet 2017). However, we still have to consider that medical works must be contextualised to the audience they were written for, mostly higher strata of Roman society, and that socio-cultural practices suggested by both archaeological and historical evidence may have varied within the Empire (Centlivres-Challet 2017).

Stable isotope analysis of skeletal remains has been widely applied in Roman contexts to investigate adult and infant diets (Müldner 2013). Nitrogen and carbon stable isotope analyses of bones and teeth have been employed to estimate breastfeeding and weaning age onsets (Dupras et al. 2001; Fuller et al. 2006a; Dupras & Tocheri 2007; Prowse et al. 2008; Redfern et al. 2018). Group comparisons of isotopic measurements on collagen extracted from bone remains of adult females and non-adults apparently suggest fairly consistent weaning times across the Roman Empire, i.e. between two and four years of age (Prowse et al. 2008; 2010; Redfern et al. 2018). However, these group comparisons constitute an example of the 'osteological paradox' since these rely on the study of infants that died prematurely (Wood et al. 1992; Beaumont et al. 2015). The presence of a potential association between early mortality and weaning practices could thus bias the interpretation of the results (Beaumont et al. 2018). Group comparisons also lack temporal resolution as they are conducted on bones that typically integrate dietary isotopic signals from multiple years of an adult individual due to turnover (Hedges et al. 2007). These group comparisons also do not allow for a direct matching of the diets of individual mothers/carers and their infant(s) (Reynard & Tuross 2015).

Higher temporal precision in the study of past weaning practices can be achieved by isotopic measurements carried out on dentine extracted from multiple teeth in a single individual, with each tooth having specific formation periods (Dupras & Tocheri 2007). A subsequent methodological improvement was the ability to perform isotopic measurements on tooth dentine increments offering a chronological resolution equal or better than one year (Beaumont et al. 2013; 2014). Nitrogen stable isotopes provide information on protein sources according to their position in a food chain and their measurements on tooth sections usually provide a clear temporal signal for weaning, since the isotopic values of the carers' milk are higher than those of their own diet (Fogel et al. 1989; Schurr 1998). As infants consume less breastmilk in favour of solid foods during the weaning process, their stable isotope nitrogen ratios values decrease. Measurements of carbon stable isotopes on tooth sections are also employed to study weaning although they offer a less clear signal for the onset and completion of weaning (Fuller et al. 2006b; Beaumont et al. 2018). Stable isotope measurements of tooth sections have been widely employed to investigate weaning practices in past populations (e.g. King et al. 2018). However, until now, this method has not been employed to investigate Roman infant feeding practices.

In this paper, we present the first study to investigate Romano-British weaning practices through nitrogen and carbon stable isotope measurements in incrementally-sampled dentine. Permanent first molars were sampled from five individuals from Bainesse (UK), aged between 15 and 45 years (Holst et al. 2019). We employed Bayesian modelling to allow for the comparison of isotopic patterns in different individuals using a common temporal scale.

MATERIALS AND METHODS

The settlement at Bainesse (Fig. 1), founded during the Flavian period (69–96 CE), was likely a civilian settlement that had potential links with the nearby Cataractonium fort (Wilson 2002; Teasdale et al. 2019). The settlement was initially built in timber, but during the second century CE a new phase of stone buildings may represent a period of economic prosperity; both agricultural and crafting activities are inferred, although Wilson (2002) also proposes the important commercial role Bainesse may have fulfilled for travellers. The location itself of the settlement on both the Swale river and along Dere Street, the main Roman road in Northern Britain, may have promoted Bainesse as an important commercial hub in the area. The settlement was permanently inhabited, unlike the nearby Cataractonium fort, and continued to be occupied even after the departure of Roman troops from Britain in 409–410 CE, as implied by the presence of later Anglian burials. However, a period of decline during the third and fourth centuries is still suggested by Wilson (2002).

A cemetery (54.370449 N; -1.635731 W) containing more than 200 burials has been intensively excavated and the archaeological evidence suggests that it was used from the late first to the late fifth centuries CE (Teasdale et al. 2019). Osteological and palaeopathological analyses, (Holst et al. 2019), radiocarbon dating (Moore et al. 2019) and stable carbon and nitrogen isotope analyses (Chenery et al. 2011; Moore et al. 2019) have previously been carried out on the burial assemblage at Bainesse. Isotopic results of faunal remains as reported by Chenery et al. (2011) suggested a primarily C_3 plant based human diet with some contribution from ^{15}N-enriched foods such as freshwater fish or pork.

We performed stable carbon and nitrogen isotope analysis on first upper molar sections from five individuals buried at the Bainesse cemetery, radiocarbon dated somewhere between the third and fifth centuries CE (Moore et al. 2019). The sampled individuals consist of one 36–45 year old female (BN213, Cal 230–400 yrs CE), one 26–35 year old likely female (BN144, Cal 265–410 yrs CE), one 18–25 year old male (BN15, Cal 255–395 yrs CE), one male older than 36 years (BN197a, Cal 260–420 yrs CE), and one 15–16 year old individual whose sex is undetermined (BN124, Cal 315–420 yrs CE) (Holst et al. 2019; Tab. 1). Within the cemetery there were differences in burial practices including burial location. However, it is unclear if these were related to socio-economic aspects or if they were influenced by kinship relationships (Teasdale et al. 2019). In our sampled population there is an absence of grave goods, little variation in burial practice but burials were chosen from across different cemetery locations (Teasdale et al. 2019: Grave Catalogue). This dataset is not representative of the whole Bainesse population, although sample selection followed criteria of equal representation in terms of age and sex.

Teeth, once fully formed, do not undergo further remodelling and in the case of first molars the sequential deposition of dentine allows for the reconstruction of dietary histories from birth until approximately the age of 10 (AlQahtani et al. 2010). Different methodologies have been proposed to investigate infant feeding practices by sampling tooth sections (e.g. Eerkens et al. 2011; Beaumont et al. 2013). The Beaumont et al. (2013) sampling methodology, with temporal estimates described in Beaumont & Montgomery (2015), has become a standard for investigating infant feeding practices given the high temporal resolution (ca. six months) that it offers. In our study we employed method 2 as described in Beaumont et al. (2013).

Collagen was extracted using a modified Longin (1971) method for carbon and stable isotope measurements. The lab work was carried out at the BioArCh laboratories (University of York). Further details on employed lab protocols can be found in Supporting Information Method S1.

We employed the novel Bayesian model OsteoBioR developed within the Pandora and IsoMemo initiatives (https://isomemoapp.com) to model stable isotope measurements on tooth increments. This allowed us to take into account the varying thickness of sampled tooth increments and to estimate the temporal progress of $\delta^{15}N$ and $\delta^{13}C$ at equal time intervals (six months) for all individuals. Further details on model description and its implementation can be found in Supporting Information Method S2.

RESULTS AND DISCUSSION

Measurement results of stable isotope analysis on dentine increments are reported in Supporting Information Table S1. To avoid bias related to different intra- and inter-individual temporal scales arising from combined increments (due to low collagen yield) and small variations in the thickness of sampled sections we employed the Bayesian model OsteoBioR to represent for each individual the variations in isotopic ranges at a common scale (Supporting Information Method S2). Traditional $\delta^{13}C$-$\delta^{15}N$-Age plots are available in Supporting Information Figure S1. The model uncertainty for isotopic ranges is larger than raw measurements since variations in sample thickness and measurement on combined segments are taken into account.

The first increment of the M1 tooth corresponds approximately to the first six months of the life of an individual, a period during which the infant is expected to rely only on breastmilk (Beaumont & Montgomery 2015). The highest $\delta^{15}N$ values are expected for the first increment assuming that only the mother breastfed the infant and that she did not change her diet prior to weaning completion. This maximum is typically followed by a temporal decrease which is indicative of a reduction in breastfeeding and an increase in the consumption of solid foods. Physiological stress may also impact isotopic values and thus can complicate dietary interpretation (Beaumont & Montgomery 2016). In our dataset, only BN144 lacks palaeopathological evidence for undetermined physiological stress during childhood, although this might also be a preservation bias (Holst et al. 2019; Tab. 1). There are some instances where a rise in $\delta^{15}N$ section values is accompanied by a decrease in $\delta^{13}C$ (BN124, BN144, BN213) for which one cannot exclude a possible malnutrition event. However, a clear distinction between nutritional stress and dietary change is problematic. Research on modern individuals has primarily relied on hair keratin allowing for a high temporal resolution. Neuberger et al. (2013) and D'Ortenzio et al. (2015) reported isotopic shifts of 1-2‰ for $\delta^{15}N$ and ~1‰, for $\delta^{13}C$ in extreme cases of starvation and cachexia over short time spans and were related with different physiological stress conditions (e.g. terminal cancer). However, these shifts might also reflect a contribution from a change in diet as exemplified in the case of a pregnant woman by D'Ortenzio et al. (2015). Assuming that isotopic shifts of similar magnitude are expected for tooth dentine we can probably assign larger isotopic shifts primarily to dietary changes. As for the interpretation of smaller isotopic changes we are constrained by instrumental uncertainty and uncertainties introduced during sampling although the latter are reflected in the Bayesian modelling results. Furthermore, it is possible that dietary shifts may result in isotopic patterns that could also be associated with malnutrition. An increase in the consumption of freshwater fish results in an increase in human collagen $\delta^{15}N$ values and a decrease in $\delta^{13}C$ values, an isotopic pattern that could otherwise be associated with metabolic stress (Fuller et al. 2006b).

At Bainesse exclusive breastfeeding appears to cease at six months or soon after. Bayesian estimates show that weaning for the Bainesse individuals was completed between [2–2.5] and [4.5–

5] years (Fig. 2–6). Previous research relying on the comparison of bone and tooth isotopic measurements of infants and mothers from across the Roman Empire placed the completion of weaning between the ages of two and four (e.g. Dupras et al. 2001; Prowse et al. 2008), a range consistent with that proposed for Roman Britain (e.g. Fuller et al. 2006a; Redfern et al. 2018). Nonetheless, this result might be biased by methodological issues related to group comparisons of bone measurements (Reynard & Tuross 2015). Our results would indicate that this range may be extended even further, perhaps up to the age of five. Given a lack of incremental studies from other Roman sites, we compared our data with published examples from early medieval individuals from Britain (fifth and tenth centuries) (Beaumont et al. 2014; 2018), Greece (fifth–sixth centuries) (Kwok et al. 2018) and continental Europe (fourth–seventh centuries) (Czermak et al. 2018; Crowder et al. 2019). To make our results directly comparable with previous literature results we also modelled these at six-months intervals using the Bayesian model OsteoBioR (see Methods section). For early Anglo-Saxon Britain, a single individual from fifth-century West Heslerton, Yorkshire, completed weaning at [1.5–2] years (after Beaumont et al. 2014). Another six British individuals from late Anglo-Saxon Raunds (tenth century) completed weaning between [2.5–3] and [4–4.5] years (after Beaumont et al. 2018). A study at early Byzantine Nemea (no.=25) showed that the majority of infants were fully weaned at approximately between [1.5–2] and [2.5–3] years apart from two outliers fully weaned at [1–1.5] and [4–4.5] years (after Kwok et al. 2018). As for populations that settled within the Roman Empire during the Migration Period, we compared our results with those from a Gepid cemetery in Archiud, Romania and an unspecified Germanic population settled in Niedernai, France. At Archiud, four individuals completed their weaning between [2.5–3] and [4–4.5] years (after Crowder et al. 2019). At Niedernai, four individuals completed weaning between [2–2.5] and [3.5–4] years (after Czermak et al. 2018). Thus, most sampled early medieval individuals completed weaning between the ages of two and four, although there were a few with earlier or later dates of weaning completion. In contrast, our Romano-British dataset, shows that three out of five individuals were fully weaned after the age of four, i.e. BN124 at [4.5–5], BN144 at [4–4.5] and BN213 at [4–4.5]. BN15 and BN197a were fully weaned at [2.5–3] and [2–2.5], respectively.

The isotopic results for post-weaning stages vary among the different individuals (Fig. 2). Individual BN197a, in particular, shows temporal oscillations in δ^{15}N values and for the last age interval [9–9.5] also a significant drop in both δ^{13}C and δ^{15}N values. Lower δ^{15}N values are likely to result from a lower intake of animal protein whereas lower δ^{13}C values could arise from a higher consumption of an unknown fat source with comparatively more negative δ^{13}C values than protein or carbohydrates (Fernandes 2016). However, it is also possible that this isotopic shift is associated with malnutrition or physiological stress (D'Ortenzio et al. 2015). The remainder of the individuals show an overall increase in δ^{15}N values with age, as expected during anabolic growth stage, although this occurs at different rates and at different time gaps following the completion of weaning. The increase of δ^{15}N values becomes steeper around the ages of seven or eight for individuals BN15, BN144, and BN213. BN124 also shows an increase in δ^{15}N following weaning but the sample was not preserved beyond the interval [6–6.5] years. The δ^{13}C values for the different individuals are approximately within the range -22 to -20‰, which likely indicates dietary intakes from predominantly terrestrial C_3-type protein sources, but some consumption of freshwater fish cannot be excluded, as also hypothesised by previous isotopic analysis undertaken on adults from the site (Chenery et al. 2011; Moore et al. 2019).

The most notable ancient Roman authors on topics related to infant feeding practices were Soranus of Ephesus (second century CE), Galen (129–ca. 200 CE), and Oribasius (ca. 320–403 CE), who spent most of their professional lives in Rome and wrote primarily for Roman aristocracy and Roman provincial elites (see Prowse et al. 2008). The start of weaning practices observed in our study are generally consistent with the advice given by Soranus (Gyn., 2.17–48; Temkin 1956) to Roman parents, who recommended the introduction of semi-solid foods six months after infants' birth. The Greek physician Damastes (second century CE) (reported in Soranus, Gyn., 2.48; Temkin 1956) recommended prolonging exclusive breastfeeding up to the age of one but only for female infants. The δ^{15}N values for the female individual BN213 show an increase after six months which could have resulted from a change in the mother's diet, or malnutrition (Neuberger et al. 2013; Reitsema 2013) or continued breastfeeding by the employment of a wet-nurse (Centlivres-Challet 2017). For this individual the peak in δ^{15}N values was reached at the age of one year and few months approximately in accordance with the Damastes' recommendations. A similar pattern is observed in BN144, a probable female individual. As for the completion of the weaning process, Soranus suggested that this should be completed at the age of two. The same recommendation was given by Antyllus (second century CE) (lost work cited in Orybasius, Incert.; Grant 1997) and Oribasius (Incert.; Grant 1997). However, Galen (Hygiene; Johnston 2018), recommended that weaning should be completed at the later age of three. To what extent the population at Bainesse would have access to the recommendations made by Roman physicians is unclear. It is possible that they were knowledgeable of the medical treatises, perhaps through the medium of travellers and soldiers headed to Cataractonium, but if so, our results suggest that this was followed only partially.

It is possible that local and family traditions influenced the adoption of certain weaning practices, but the variability that we observed may also be indicative of socio-economic aspects. Written evidence (e.g. Diocletian's Edictum de pretiis rerum venalium; Graser 1940) points to the greater economic value that animal foods had in comparison to plant foods and thus it is expected that they were less accessible to individuals belonging to lower socio-economic classes, which possibly included infants. Concerning the latter, many ancient Graeco-Roman physicians and philosophers identified the age of seven as the end of early childhood (infantia) (Laes 2011: 77–100). Gaius' (c. 110–170 CE) Institutes, collected in Justinian's Institutes (sixth century CE), regulated that a child under the age of seven was "non multum a furioso distant, quia huius aetatis pupilli nullum intellectum habent" ('not very different from a mentally disabled person, since during this age, children do not possess any intellectual faculty') (Inst. 3.19.10; Moyle 1911), remarking how an infans (or pupillus) could not be considered an autonomous person. This age transition seems to have been part of a cultural concept commonly recognised by Graeco-Roman authors, likely to be grounded on changing biological features (such as the transitional replacement of deciduous teeth and physical growth) and philosophical beliefs (Eyben 1972; Laes 2011: 77–100).

The idea of a common cultural knowledge in the Roman world has been heavily criticised, especially when it comes to Britain (e.g. Barrett 1997; Freeman 1997). However, what is here inferred is not the vision of a deterministic homogeneous Roman culture, where one could imply the existence of common patterns in Rome as well as in Northern Britain for the only reason of being 'Roman'

('Romanisation', see Pinto 2017), but rather an observation on the mechanisms that may have led to this similarity suggested by our results. Beyond the possibility that culture was spread with goods in the commercial hub of Bainesse due to its relationship with Cataractonium, a concurring socio-demographic explanation may also be possible. Graeco-Roman authors imbued symbolism to an individual's every seventh year of life, which was considered an annus climactericus ('critical year') of transition on both biological and social levels (Eyben 1972). Although we are aware of the risks of the 'osteological paradox' and bias related to funerary commemoration, a high degree of mortality during early childhood is attested in the Roman world (Rawson 2003; Carroll 2011). In Bainesse, Holst et al. (2019) observed that 69% of non-adult buried individuals were aged between one and six years, with a peak between three and five years. Hence, it is possible that to the eyes of Roman society, even in Bainesse, the age of seven may have marked a perceived 'survival' threshold and thus a step on the social scale.

Isotopic studies have also shown that Roman male individuals reaching the status of PaterFamilias during adulthood increased their intake of animal protein (Martyn et al. 2018). Also Prowse et al. (2008; 2010) found that children in Roman Italy likely had a lower social status that was reflected by a lower quality of their diet. Thus, a hypothesis that emerges from our study is that an improvement in children's diet, perhaps with the addition of higher trophic level protein such as freshwater fish, was only made once these passed the socio-cultural step at seven years. This 'survival' threshold in Bainesse might also help to find an explanation for the prolonged weaning process we observed in surviving individuals from our dataset. Families possibly may have spent more time and care in the process of weaning as a logical solution attempting to protect the child from morbidity and malnutrition. In conclusion, our results would concur with the cultural idea that a certain age may have led to an elevation of Roman children's status and, perhaps, also the access to foods of a higher economic value.

CONCLUSIONS

This study presented the first use of isotopic measurements on tooth increments to reconstruct Roman infant feeding practices for five individuals from the Romano-British settlement at Bainesse. Bayesian modelling was employed to make diachronic results directly comparable among the different individuals and to generate temporal isotopic estimates with an uncertainty reflecting the tooth section sampling process. This revealed significant differences in weaning and post-weaning practices. Nonetheless, all individuals were fed exclusively on breastmilk at least until six months of age. Following the introduction of semi-solid food into infants' diet, each individual completed weaning at different ages, between two and five years. The variability in our data suggests that local socio-economic aspects may have had an impact on weaning practices at Bainesse, although some degree of observed consistency with ancient medical recommendations leads us not to a priori exclude that these were known. Post-weaning isotopic values show an increase in the consumption of animal protein following weaning completion. This becomes particularly accentuated around the age of seven for most individuals, when Roman children potentially rose from their 'infantia' status.

Future tooth incremental studies on other Roman populations are necessary to characterize in more detail the variability in infant feeding practices across regions and time periods. It would be of particular interest to investigate how infant feeding practices at the heart of the Roman Empire contrasted with those in Roman provinces. At Bainesse, we suggest that future bioarchaeological analysis could focus on the relationship between the site and the nearby fort of Cataractonium.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

FIGURES

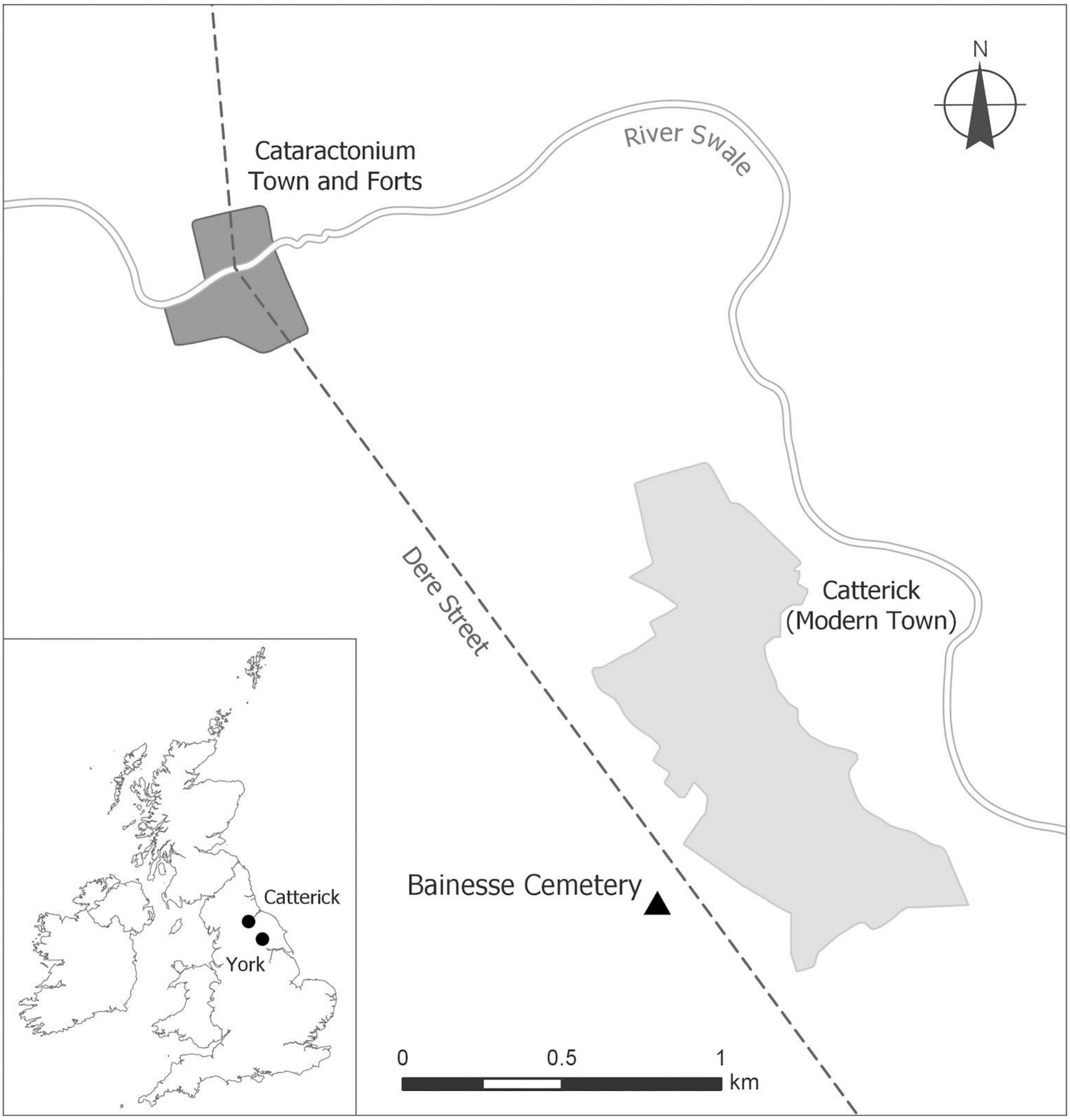

Fig. 1. Location of Bainesse cemetery. Map by Helen Goodchild, after Chenery et al. (2011); Contains OS data © Crown Copyright [and database right] (2020).

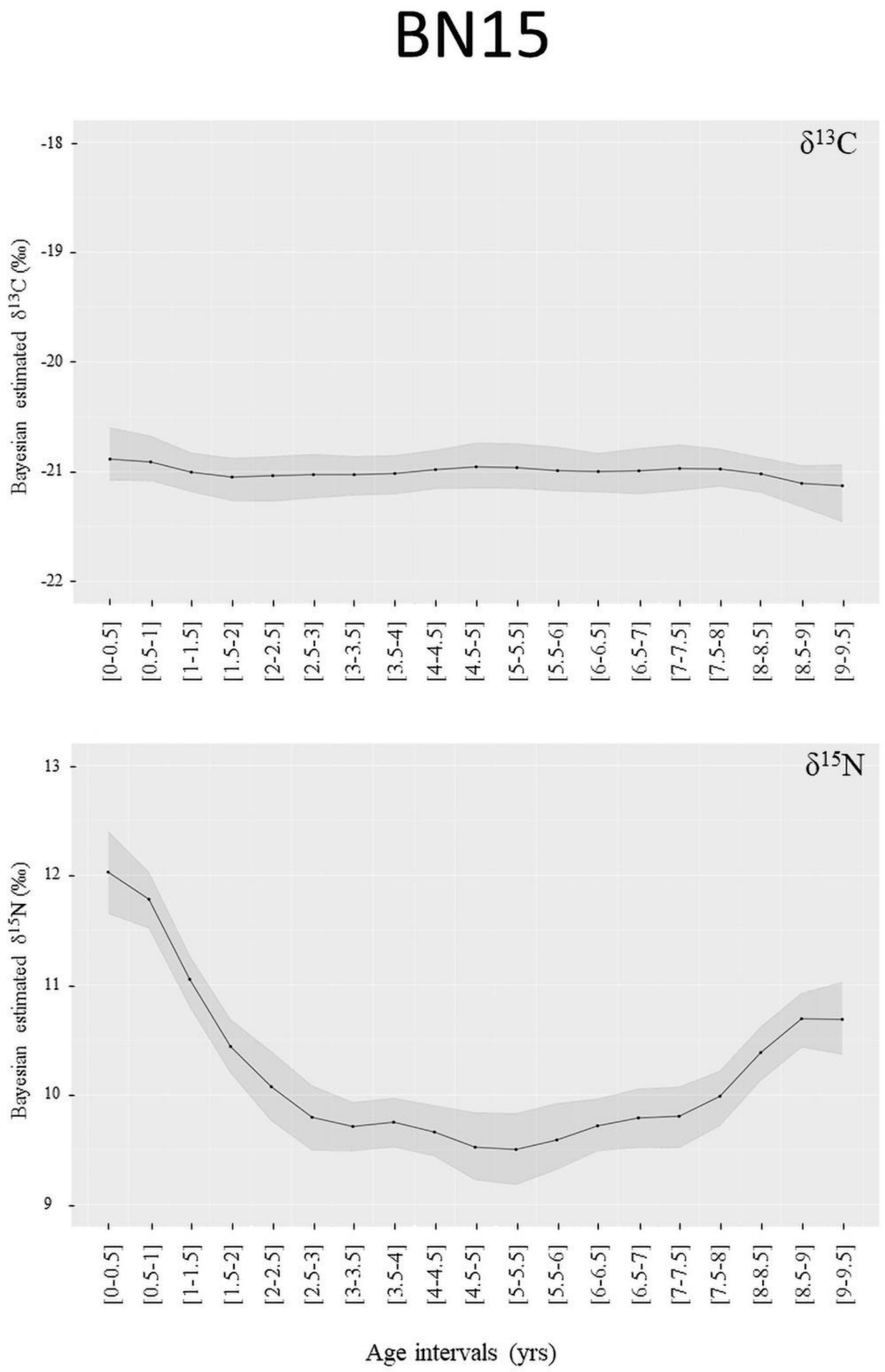

Fig. 2. Bayesian temporal modelling of M1 incremental dentine $\delta^{13}C$ and $\delta^{15}N$ for BN15.

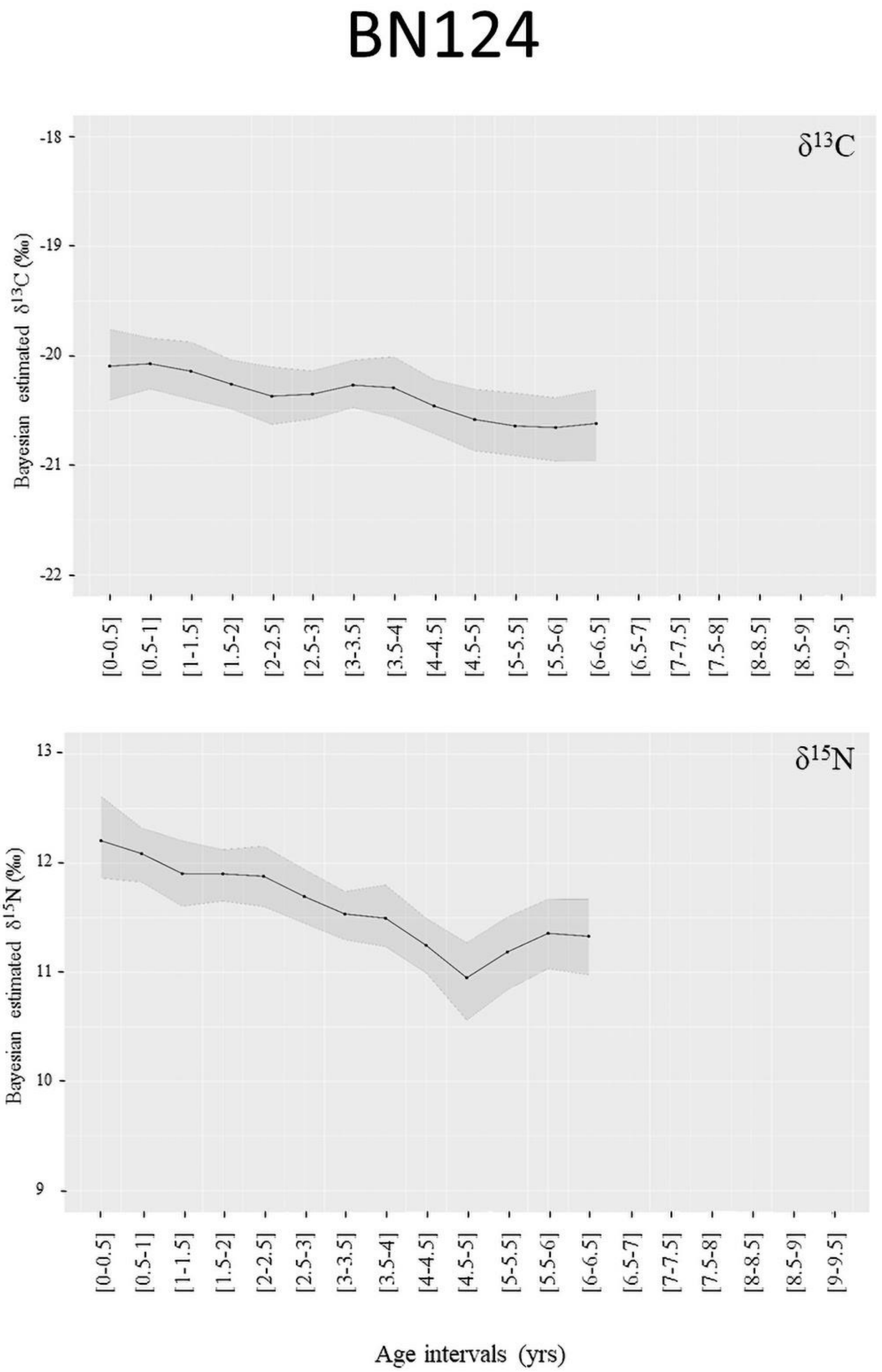

Fig. 3. Bayesian temporal modelling of M1 incremental dentine $\delta^{13}C$ and $\delta^{15}N$ for BN124.

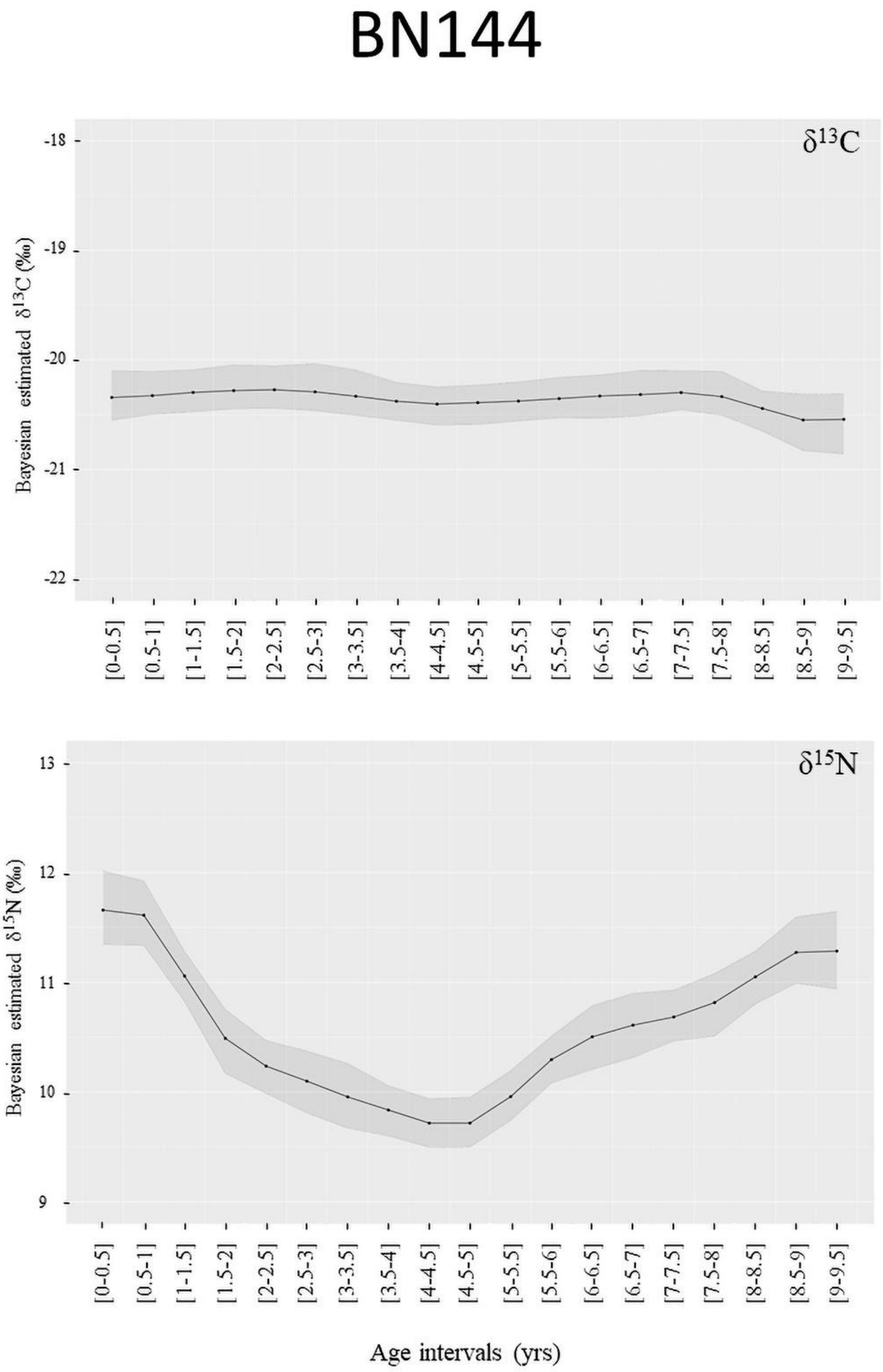

Fig. 4. Bayesian temporal modelling of M1 incremental dentine $\delta^{13}C$ and $\delta^{15}N$ for BN144.

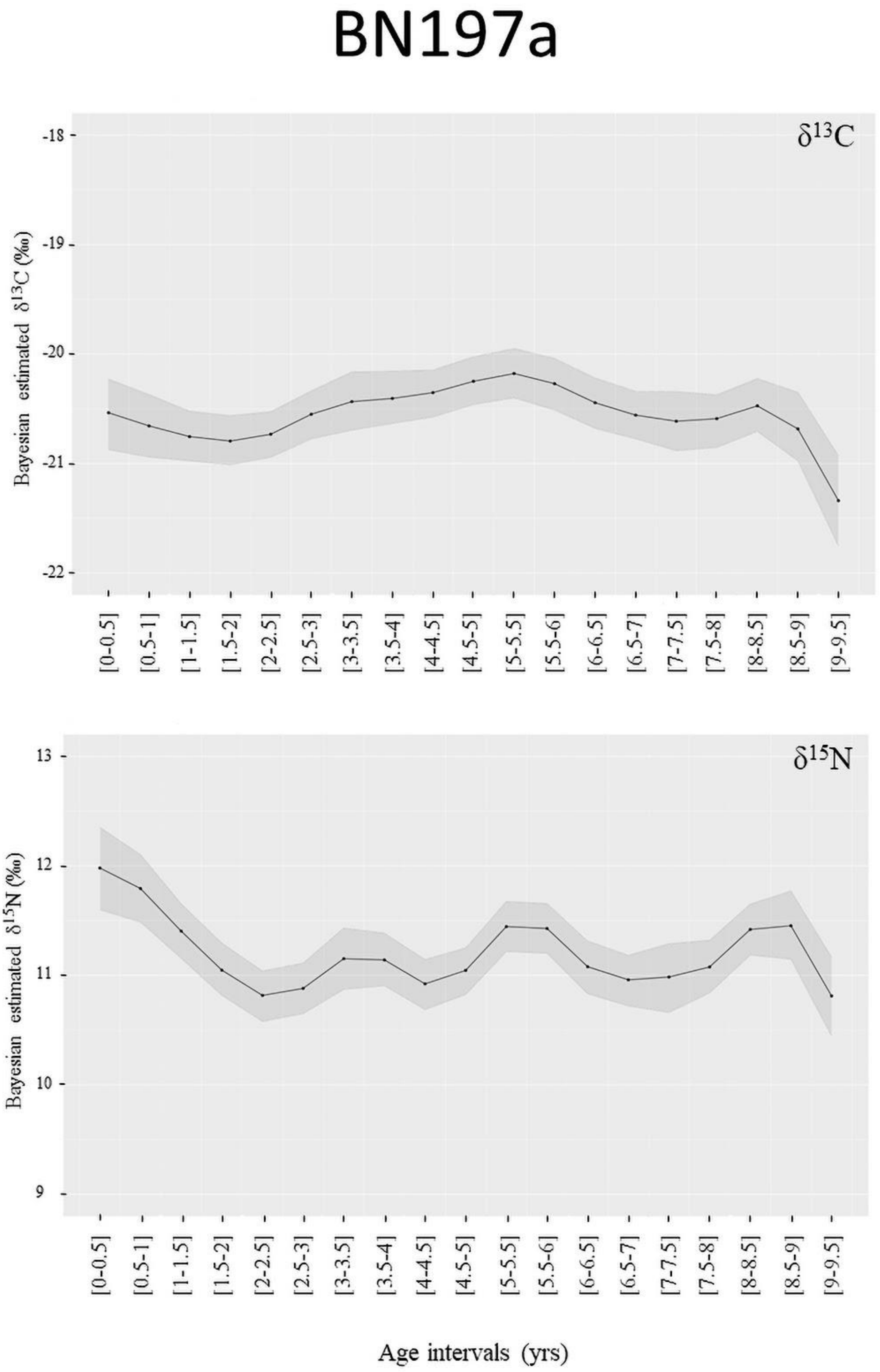

Fig. 5. Bayesian temporal modelling of M1 incremental dentine $\delta^{13}C$ and $\delta^{15}N$ for BN197a.

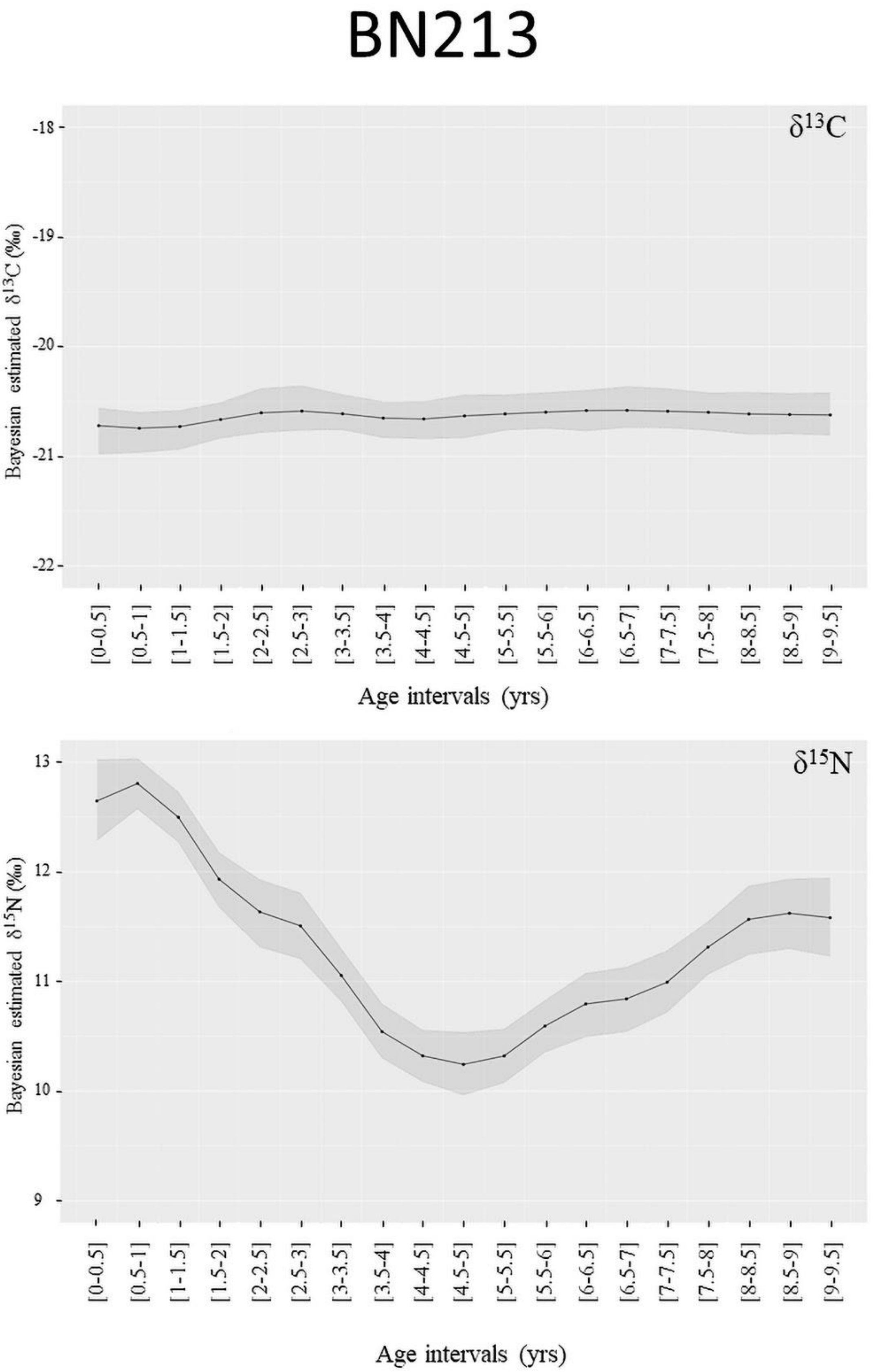

Fig. 6. Bayesian temporal modelling of M1 incremental dentine $\delta^{13}C$ and $\delta^{15}N$ for BN213.

TABLE

Individual	Radiocarbon Lab Code	Sex	Age at Death	Uncal 14C (yrs BP)	Cal 14C (yrs BP, 2σ)	Palaeopathological Stress Markers
BN15	SUERC-67722	M	18-25	1734 ±32	Cal 255-395 CE	Dental Enamel Hypoplasia; Cribra Orbitalia
BN124	SUERC-67693	UN	15-16	1705 ±32	Cal 315-420 CE	Dental Enamel Hypoplasia
BN144	SUERC-67704	?F	26-35	1724 ±32	Cal 265-410 CE	Absent
BN197a	SUERC-67716	M	36+	1678 ±32	Cal 260–420 CE	Dental Enamel Hypoplasia; Cribra Orbitalia
BN213	SUERC-67732	F	36-45	1758 ±32	Cal 230-400 CE	Dental Enamel Hypoplasia

Tab. 1. Description of individuals analysed in this study. Radiocarbon measurements were reported previously in Moore et al. 2019. Palaeopathological markers of potential stress were reported in Holst et al. 2019.

A BAYESIAN MULTI-PROXY CONTRIBUTION TO THE SOCIOECONOMIC, POLITICAL, AND CULTURAL HISTORY OF LATE MEDIEVAL CAPITANATA (SOUTHERN ITALY)

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Keywords: Stable Carbon, Nitrogen and Oxygen Isotope Analysis; Late Medieval Italy; Bayesian Modelling; Human Diet; Spatial Mobility; Agriculture

ABSTRACT

Medieval southern Italy is typically viewed as a region where political, religious, and cultural systems coexisted and clashed. Written sources often focus on elites and give an image of a hierarchical feudal society supported by a farming economy. We undertook an interdisciplinary study combining historical and archaeological evidence with Bayesian modelling of multi-isotope data from human (n=134) and faunal (n=21) skeletal remains to inform on the socioeconomic organisation, cultural practices, and demographics of medieval communities in Capitanata (southern Italy). Isotopic results show significant dietary differences within local populations supportive of marked socioeconomic hierarchies. Bayesian dietary modelling suggested that cereal production, followed by animal management practices, was the economic basis of the region. However, minor consumption of marine fish, potentially associated with Christian practices, revealed intra-regional trade. At the site of Tertiveri, isotope-based clustering and Bayesian spatial modelling identified migrant individuals likely from the Alpine region plus one Muslim individual from the Mediterranean coastline. Our results align with the prevailing image of Medieval southern Italy but they also showcase how Bayesian methods and multi-isotope data can be used to directly inform on the history of local communities and of the legacy that these left.

INTRODUCTION

The Middle Ages in Italy has been argued to have been marked by political and cultural fragmentation from the collapse of the western Roman empire (476 CE) until the end of the twelfth century, although other scholars note a persistence and reconfiguration of economic and urban networks[1–4]. Southern Italy represents a particularly interesting case of how populations in this part of the world responded to the collapse of the western Roman empire and transitioned into the new economic, social and cultural world of the medieval period[2,4,5]. Showing the strikingly high level of political fragmentation of the region, unlanded aristocrats from Normandy (France) famously sought their fortune in southern Italy during the eleventh century, intervening in local disputes among Lombard princes, Byzantine rulers, the Pope and Muslim pirates[4,6,7]. Through this, Normans accumulated wealth, land and titles culminating in the establishment of the Kingdom of Sicily in 1130 by the Hauteville family. The Normans imposed a feudal system based on their French experience, although it also included political traits from previous local Byzantine and Muslim forms of government. The Hauteville family was succeeded by the Swabian Hohenstaufen dynasty in 1194, which lasted until 1266, when Charles count of Anjou conquered the kingdom with papal support. While much is known historically about these political upheavals, far less is known in relation to the lived experiences of the multicultural populations navigating this changing social and economic landscape that was to reshape power dynamics in the Mediterranean world. Sites from southern Italy hence provide ideal case studies for exploring how changing political regimes and contact with areas of the eastern Roman empire, Mediterranean islands, and northern Africa altered economic systems and the demographics of local populations[2–4,8–10]. Furthermore, they were sites of increasing social differentiation during the medieval period that increasingly revolved around connection to the Christian faith and land ownership[7,10,11].

Medieval Capitanata - a region in northern Apulia - has a centuries-long history as a buffer zone between Lombard states and Byzantine Apulia. However, the Norman conquest of the region in the mid-eleventh century led to its pacification and to wide economic transformations[12–14]. This pushed towards a demographic increase and to new food production systems adapted to local geographic features (e.g. fishing in coastal sites, pig husbandry in the plain and sheep/goat husbandry in the Apennines)[12]. Socio-economic shifts have been inferred through the analysis of the archaeological record, zooarchaeological studies, and limited archaeobotanical evidence on the region[12,13,15,16]. However, there is little anthropological[17] and no biomolecular evidence for late medieval Capitanata. Previous archaeological isotopic studies in the region investigated only the Neolithic period[18–20]. The closest isotopic studies dating to the medieval period are those from Montella (Campania), Apigliano, and Quattro Macine (southern Apulia)[21,22].

Overall, the Norman productive system was maintained for the entirety of the late medieval period, with a successive increase of agricultural production and the introduction of '*masserie*'[12,15]. These were large land estates often under direct administration of the crown. However, in the 13th century this region also observed the arrival of a melting-pot of cultures from both Mediterranean and continental regions. This is, for example, the case of Lucera (Fig. 1), a city that hosted the Islamic population that was deported from Sicily by order of the Hohenstaufen king Frederik II[4,23–25]. Tertiveri, one of the sites analysed in this study (Fig. 1), was also donated by the Angevin king Charles II to 'Abd al-'Azīz, a powerful Muslim knight from Lucera[23,24]. Two individuals found in this site (here sampled and analysed) were buried according to an Islamic rite. Frederik II was also Holy Roman Emperor, but he kept his court in southern Italy and spent most of his time in Apulia[25]. Hence, diplomats, noblemen, and ecclesiastic personalities were often supposed to travel from northern Italy, Austria, and Germany to Capitanata. Additional evidence of the high-level of cultural admixture involves movements from Provence (France) during the late 13th century. Written records attest that the new Angevin king Charles I relocated soldiers to the turbulent Capitanata region to ensure its pacification[26]. This was followed by donations of lands and the settling of many Provençal individuals with their families[20]. Thus, late medieval Capitanata presents a high research potential to investigate the impact of migrations and economic systems on past societies.

Much of our historical knowledge of medieval southern Italy relies on written sources which often are not representative of a large proportion of past communities, particularly for population segments with a lower socioeconomic status[27]. Stable isotope analysis, by contrast, has been widely employed in archaeology to reconstruct past human subsistence or spatial mobility, and crop and animal management practices[21,22,28–31]. Isotopic ratios can be measured in osteological remains and, depending on the type of tissue analysed (e.g. collagen extracted from bones), information can be obtained for different periods of an individual's lifetime[32–34]. The most common isotopic proxies employed in archaeological dietary studies are carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopes measured in collagen extracted from bone or dentine. These are primarily informative on dietary protein consumption[35,36], whereas $\delta^{13}C$ measurements on carbonate from bone or tooth bioapatite inform on the dietary mix of protein, carbohydrates, and lipids. Measurement of the latter will more easily reveal the consumption of C_4 plants when the primary source of protein is C_3 (or vice-versa). Local environmental and climatic conditions determine the isotopic values of plant and animal food sources[37,38]. These can also be influenced by agricultural management practices such as irrigation, manuring, penning, etc.[36,39,40]. Thus, human isotopic values reflect the isotopic values of the food sources and their relative consumption. Human and animal spatial mobility can be investigated using $\delta^{18}O$ measurements on carbonate from tooth enamel or bone bioapatite, taking into account potential complications caused by cooking activities, diagenesis and mathematical conversions of human $\delta^{18}O$ values into $\delta^{18}O$ of ingested water[41–44].

We combined historical and archaeological evidence with novel Bayesian modelling of multi-isotope data ($\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$) from human (n=134) and animal (n=21) skeletal remains to inform on the socioeconomic organisation, cultural practices, and demographics of the medieval communities of Tertiveri, Montecorvino, and San Lorenzo in Carminiano (Capitanata, southern Italy). We were specifically interested in evaluating the implementation of a feudal system at the study sites. Individual isotopic variability was employed as a proxy for socioeconomic hierarchy and/or Christian religious practices. While overall population diets informed on the economic importance of farming and trade activities. The significance of external influences was investigated isotopically through the identification of migrants and the tracking of their places of origin.

RESULTS

Isotopic results, together with other supporting measurement, archaeological, and historical information are given in Supplementary Information file S1 and also deposited in the MATILDA online repository (https://www.doi.org/10.48493/w01v-fe90). The data was also aggregated to the CIMA database that compiles isotopic measurements for medieval archaeological samples[45,46].

Bone and tooth samples (human=134; fauna=21) areoverall well-preserved in accordance with established parameters for bone collagen preservation[47]. However, fifteen human samples from Tertiveri show poor preservation with atomic C/N ratios outside the acceptable range. In addition, sample TC100 did not produce sufficient collagen for measurement. These represent 11.9% of the human dataset. Bone carbonate results for samples with bad collagen preservation were also excluded from our analysis[48].

Faunal isotopic results

Faunal bulk bone and tooth collagen $\delta^{13}C$ and $\delta^{15}N$ measurements range from -24.1‰ to -19.8‰ and from 4.7‰ to 10.1‰, respectively (Fig. 2a). For $\delta^{13}C$, there is a significant difference between the Montecorvino and Tertiveri animals (mean $\delta^{13}C$: -21.9±0.9‰; -20.7±1.0‰). The sample size is small making the interpretation of the results difficult, but the difference is likely associated with differences in local environmental conditions and/or animal management practices, including a possible 'canopy effect' associated with dense forests surrounding Montecorvino[40,49]. These are mentioned in Angevin documents[50] and also attested by palaeo-environmental analysis[51]. For $\delta^{15}N$ values there are no significant differences between the two sites (mean: 6.7±1.9‰ for Montecorvino; 6.8±1.1‰ for Tertiveri). However, the standard deviations for Montecorvino pigs and sheep/goats are relatively large (7.0±1.5‰; 5.8±2.3‰, respectively) when compared to $\delta^{15}N$ values measured in the same taxa from two other late medieval sites in southern Apulia, i.e. Apigliano (pigs: 5.3±0.4‰; sheep/goat: 6.1±0.4‰) and Quattro Macine (pigs: 5.8±0.7‰; sheep/goat: 5.4±0.8‰)[23] (Fig. 2b). Overall, domestic herbivores from Capitanata display larger $\delta^{15}N$ ranges (4.0‰ to 8.9‰; mean: 6.2±1.7‰) in comparison to those from southern Apulia (4.1‰ to 6.9‰; mean: 5.5±0.9‰). These likely reflect a variety of animal husbandry strategies including intensive husbandry, penning, feeding with plants grown in fields subject to manuring, and transhumance[39,40,52].

The deer remains from San Lorenzo (SLDE1) have a high $\delta^{15}N$ collagen value (bone: 7.4‰; tooth: 7.3‰. Fig. 2a) when compared to values observed for modern specimens[53]. Given historical evidence for a royal hunting ground around San Lorenzo in Carminiano[54], it is possible that deers had their diet managed by humans, which may have included access to ^{15}N-enriched plants. The bone remains of two tortoises from Tertiveri ($\delta^{13}C$: -22.4‰; $\delta^{15}N$: 6.0‰) and Montecorvino ($\delta^{13}C$: -24.1‰; $\delta^{15}N$: 4.9‰) have low $\delta^{13}C$ values suggesting that they fed on freshwater sources[55]. Tortoises were commonly consumed in medieval Italy and zooarchaeological remains are often found in sites associated with the clergy, since they were considered to be 'fish' and not included in the list of proscribed foods by medieval religious fasting rules[9,56].

Results of stable carbon isotopes for bone bioapatite in animals range between -14.1‰ and -8.3‰ (mean: -12.1±1.5‰) (Fig. 2c). The highest values for animals are observed for a chicken from Montecorvino (MOCH2 $\delta^{13}C_{carbonate}$: -9.1‰; $\delta^{13}C_{collagen}$: -21.7‰; $\delta^{15}N$: 10.2‰) and a cattle specimen from Tertiveri (TCCA2 $\delta^{13}C_{carbonate}$: -8.3‰; $\delta^{13}C_{collagen}$: -20.2‰; $\delta^{15}N$: 8.3‰), which were likely fed with a higher contribution of C_4 cereals compared to other animals. However, $\delta^{13}C_{collagen}$ values from these animals clearly reflect C_3 dominated diets. In the case of the chicken (MOCH2), the isotopic difference between $\delta^{13}C_{bioapatite}$ and $\delta^{13}C_{collagen}$ signals could derive from the combination of a predominant C_3 protein source and an overall caloric contribution that included significant C_4 components. Such an explanation is more difficult to extend to the cattle specimen (TCCA2), since this animal would only consume plants. A mixed diet of legumes and C_3/C_4 plants seems unlikely given that the animal has relatively high nitrogen values. Even assuming that this cattle specimen consumed plants from manured fields, which elevates plant $\delta^{15}N$ values, a predominant protein source from legumes (typically near 0‰ $\delta^{15}N$ values) would be inconsistent with our measurements. Another possibility is that the bioapatite and collagen $\delta^{13}C$ signals reflect different lifetime dietary stages. This would imply that bone collagen and bioapatite have different renewal rates as reported previously for other species[57]. However, these are unknown.

Values for bioapatite and enamel $\delta^{18}O$ in fauna from Tertiveri and Montecorvino show a wide range (measured $\delta^{18}O_{carbonate}$ range: -6.9‰ to -1.6‰; mean: -4.4±1.3‰; calculated $\delta^{18}O_{water}$ range: -10.4‰ to -1.7‰; mean: -6.3±2.1‰) (Fig. 3a). The age and time of death of the animals or the renewal rates of skeletal material are not known. Thus, some variation may be explained by seasonal shifts in water $\delta^{18}O$ values. For instance, pigs were commonly slaughtered at the end of the year, whereas sheep/goats were butchered around Easter in accordance with religious practices[9,56]. Spatial variations in water $\delta^{18}O$ values may have also had an impact, since vertical transhumance of ovicaprids and cattle has been recorded for late medieval Capitanata[58,59]. Although there is a large overlap between the $\delta^{18}O$ values for domesticated herbivores and omnivores (Fig. 3b).

One sheep/goat bone from Montecorvino (MOSG1) shows an unusually high $\delta^{18}O_{water}$ (-1.7‰) value. In addition to spatial and temporal variations in water $\delta^{18}O$ values it is possible that this sheep was consuming leaf water with $\delta^{18}O$ values higher than meteoritic water[60]. Ovicaprids are semi-obligate drinkers and obtain most of the water through the plants they consume[61]. Other sheep/goats from Montecorvino have $\delta^{18}O_{water}$ values between -6.1‰ and -4.0‰. However, one sheep/goat from Tertiveri (TCSG1) has the lowest $\delta^{18}O_{water}$ value (-7.6‰) among ovicaprids. Multiple factors could explain such variability. Differences in feeding behaviours, including the aforementioned consumption of leaf water, the practice of transhumance at various spatial and temporal scales, plus differences in killing season could explain the wide observed range in $\delta^{18}O_{water}$ values. To resolve this, it is necessary to study animal movements and diets at higher temporal resolutions by undertaking future isotopic measurements on tooth sections[61,62].

Human isotopic results and Bayesian modelling

Results for stable carbon and nitrogen isotopic values measured in human bone collagen from the region of Capitanata range from -20.7‰ to -17.4‰ and from 7.5‰ to 13.8‰, respectively (Fig. 4a). Mean values are -19.0±0.7‰ for δ^{13}C and 10.0±1.0‰ for δ^{15}N. Human δ^{13}C results measured in bone carbonate range from -14.6‰ to -5.2‰ (mean: -12.3±1.2‰) (Fig. 4b). Isotopic results for non-adults are presented separately from those of adolescents and adults. Non-adult individuals may include a dietary isotopic signal from the consumption from human milk and/or from food employed during infancy in post-weaning strategies[63,64]. Figure 4c demonstrates the distribution of δ^{13}C and δ^{15}N values for non-adults in Tertiveri (mean $\delta^{13}C_{collagen}$: -18.5±0.8‰; mean δ^{15}N: 10.5±1.5‰; $\delta^{13}C_{carbonate}$: -11.9±1.4‰) and Montecorvino (mean $\delta^{13}C_{collagen}$: -20.1±0.4‰; mean δ^{15}N: 10.2±1.2‰; $\delta^{13}C_{carbonate}$: -12.2±1.0‰). There is no significant difference among age groups for non-adults (Fig. 4c), although neonates present higher δ^{15}N values, which is likely a result of breastfeeding.From San Lorenzo only four adult individuals were analysed (mean $\delta^{13}C_{collagen}$: -19.8±0.3‰; mean δ^{15}N: 9.0±0.5‰; $\delta^{13}C_{carbonate}$: -12.4±0.4‰), while from Tertiveri 78 adults present an acceptable level of bone preservation (mean $\delta^{13}C_{collagen}$: -18.8±0.5‰; mean δ^{15}N: 9.9±0.9‰; $\delta^{13}C_{carbonate}$: -12.4±1.3‰) and from Montecorvino ten adults were analysed (mean $\delta^{13}C_{collagen}$: -20.0±0.4‰; mean δ^{15}N: 10.2±0.5‰; $\delta^{13}C_{carbonate}$: -12.7±0.7‰).

The $\delta^{13}C_{collagen}$ values for Tertiveri are significantly higher than Montecorvino (Mann–Whitney U test: U=26, n1=78, n2=10, $P<0.05$, two-tailed) and this may be related to differences in the isotopic baseline (e.g. environmental factors such as the ‘canopy effect’ or specific animal management practices such as C_3/C_4 feeding selection) or to differences in human diets. No significant stable carbon and nitrogen isotopic differences between adult male (mean δ^{13}C: -18.7±0.4‰; mean δ^{15}N: 10.0±0.9‰) and female (mean δ^{13}C: -18.8±0.7‰; mean δ^{15}N: 10.0±1.2‰) individuals were detected at Tertiveri (δ^{13}C: Mann–Whitney U test: U=800.5, n1=36, n2=17, $P>0.05$, two-tailed; δ^{15}N: Mann–Whitney U test: U=807.5, n1=36, n2=17, $P>0.05$, two-tailed), whereas at Montecorvino and San Lorenzo the small sample size does not allow for comparisons. When compared with previously published studies for medieval southern Italy, adult individuals from Capitanata show overall higher δ^{15}N values than Montella (mean δ^{13}C: -19.7±0.7‰; mean δ^{15}N: 7.1±1.1‰), Apigliano (mean δ^{13}C: -18.8±0.3‰; mean δ^{15}N: 7.9±0.7‰), and Quattro Macine (mean δ^{13}C: -18.9±0.2‰; mean δ^{15}N: 7.6±0.4‰) (Fig. 4d)[21,22]. The δ^{15}N values measured in faunal specimens from Capitanata were also higher (Fig. 2b), implying that the isotopic baseline, rather than diet, is the primary factor that accounts for the isotopic difference in adult populations from different sites.

The results for $\delta^{13}C_{carbonate}$ *versus* $\delta^{13}C_{collagen}$ are plotted in figure 4b and compared to C_3 protein and C_4/marine protein reference lines after Kellner & Schoeninger (2007)[65]. This shows that C_3 foods were the main protein source although there were minor contributions from C_4/marine protein foods for several individuals. The contribution from C_4 carbohydrates is also noticeable for several individuals having relatively high $\delta^{13}C_{carbonate}$ values. One individual (TC65) has particularly high $\delta^{13}C_{carbonate}$ values ($\delta^{13}C_{carbonate}$: -5.2‰; $\delta^{13}C_{collagen}$: -18.4‰; $\delta^{15}N$: 10.8‰) suggesting a large consumption of C_4 cereals. The source of protein for this individual was predominantly C_3 although there could have been a minor contribution from marine resources.

Cluster analysis of adult human $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values from Tertiveri revealed two main data clusters (details in methods section) (Fig. 5a). Cluster 1 shows a negative correlation between $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values suggesting a mixing line from C_3 to C_4 protein consumption. In contrast, Cluster 2 shows a roughly positive correlation between $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values suggesting a mixing line from C_3 protein (lower isotopic values) to marine protein (higher isotopic values) consumption. The former would include C_3 animal protein with $\delta^{15}N$ values higher than C_4 plants (e.g. millet).

A different classification of human $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values is also offered by archaeological descriptions. This is shown in Fig. 5b (burial locations are outlined in figure 6 and more details are given in Supplementary Info File S2). A privileged status is inferred for adult individuals buried in shafts discovered outside the Cathedral and parallel to the lateral walls (n=41; mean $\delta^{13}C_{collagen}$: -18.9±0.4‰; mean $\delta^{15}N$: 10.1±0.8‰; $\delta^{13}C_{carbonate}$: -12.5±1.4‰). A group of individuals were also recovered outside the remains of a second church reflecting a wider social stratification (n=30; mean $\delta^{13}C_{collagen}$: -18.6±0.4‰; mean $\delta^{15}N$: 9.7±1.0‰; $\delta^{13}C_{carbonate}$: -12.5±0.9‰). Finally, individuals were also discovered in the so-called 'ordinary' cemetery around the Cathedral, but only the collagen extracted from seven individuals were sufficiently well preserved for analysis (mean $\delta^{13}C_{collagen}$: -19.4±0.8‰; mean $\delta^{15}N$: 9.4±0.5‰; $\delta^{13}C_{carbonate}$: -10.9±0.7‰). When the two classifications (i.e. isotopic and archaeological) are compared, we notice that: for Cluster 1 (n=15) 20% of its individuals are from privileged shafts; 53% from outside a second church; and 27% from the 'ordinary' cemetery located outside the Cathedral. whereas these percentages for Cluster 2 (n=63) are 60%, 35%, and 5%, respectively. Overall, results suggest a higher consumption of marine resources by higher status individuals whereas lower status individuals would consume a higher proportion of C_4 plants, likely millet.

For dietary quantitative estimation, we employed the Bayesian mixing model ReSources (an updated version of FRUITS[66], details on model settings can be found in Supplementary Information File S3).

Seven main food groups were considered for dietary reconstruction (C_3 plants, C_4 cereals, cattle, ovicaprid, pigs, poultry, and marine resources). Additional Bayesian priors were included as constraints to improve dietary resolution. These were grounded on evidence obtained from archaeofaunal, archaeobotanical, and ethnographic studies plus from written records (Supplementary Information File S3). However, a relatively minor contribution from other resources (e.g. freshwater fish) cannot be excluded.

Bayesian dietary caloric estimates are shown in figure Fig. 7. The magnitude of the uncertainties for these do not allow us to identify clear dietary differences among the sites. Nonetheless, the modelling shows that C_3 plants (e.g. wheat, or barley, fruit, vegetables, legumes, and nuts) were the main source of calories for late medieval Capitanata. This is followed by pig products and by ovicaprid products (e.g. mutton, milk, cheese). Consumption of C_4 cereals is possible for all sites although the wide credible ranges allow for a near zero dietary contribution. A small contribution from marine fish intake is possible which would indicate trade with coastal settlements. Cattle and poultry products are also estimated to be consumed in very small amounts.

Human $\delta^{18}O_{carbonate}$ values range from -13‰ to -3.2‰ (mean: -5.8±1.6‰) (calculated $\delta^{18}O_{water}$ range: -16.5 to -5.3; mean: -8.4±2.2‰, Fig. 3a). Given the potential for a nursing signal in infants, in the following discussion we only consider adult individuals from Tertiveri and Montecorvino which given their proximity would likely have similar $\delta^{18}O_{water}$ values. For San Lorenzo only four individuals were available for analyses and the site is located at a greater distance from Tertiveri and Montecorvino.

Cluster classification with outlier detection (threshold 5%) was employed to classify the $\delta^{18}O$ values for Tertiveri and Montecorvino adult individuals (see methods section) (Fig. 8). Two clusters and four outliers were identified. A total of 57 individuals were assigned to Cluster A ($\delta^{18}O_{water}$ range: -9.8‰ to -6‰; mean: -7.7±0.8‰), whereas five individuals were assigned to Cluster B ($\delta^{18}O_{water}$ range: -14.2‰ to -11.8‰; mean: -12.9±0.9‰). The distribution of calculated human $\delta^{18}O_{water}$ values was compared to local water estimates based on the point values from the Regionalized Cluster-based Water Isotope Prediction model (RCWIP)[67]. Using these, a Bayesian reference baseline for $\delta^{18}O_{Water}$ values across western Europe was generated and the local average for Tertiveri and Montecorvino was estimated (Fig. 9a). This value (-7.1‰ for a standard error of the mean of 0.3‰) is close to the $\delta^{18}O_{water}$ average for Cluster A which is assumed to represent individuals residing in Tertiveri or Montecorvino. In contrast Cluster B represents incoming individuals. The overall variability for each cluster can be explained by post-mortem alterations to *in vivo* bone $\delta^{18}O$ values due to diagenesis or to changes to local water $\delta^{18}O$ values due to cooking/brewing practices[41,42,44].

In addition to the above mentioned factors influencing ingested water and post-mortem bone $\delta^{18}O$ values it is necessary to note that the bone bioapatite is undergoing renewal during the lifetime of an individual. Thus, the estimated human $\delta^{18}O_{Water}$ values are potentially the result of mixed contributions from water sources having different $\delta^{18}O_{Water}$ values. The outlier TC20 is placed between clusters A and B and could represent an individual originating from a location outside Tertiveri that moved and resided there for a considerable period of time. It is also possible that clusters A and B themselves include individuals with mixed $\delta^{18}O$ values. In the case of cluster A this is another variable to consider on why the average for this cluster is slightly lower than the estimated local RCWIP value.

The model LocateR[68] was employed to assign a spatial probability distribution for the place of residence associated with individuals from clusters A and B plus the four outliers. The model compares estimated human $\delta^{18}O_{Water}$ values with the spatial distribution of RCWIP values (Fig. 9a). As expected for Cluster A there is a high residence probability assigned to the Tertiveri/Montecorvino region (Fig. 9b) whereas for Cluster B highest probabilities are observed for the alpine region (Fig. 9c).

The four outliers correspond to individuals buried at Tertiveri. Individual TC77 (-16.4‰) and TC82 (-16.5‰) have the lowest $\delta^{18}O_{Water}$ values within the dataset and high residence probabilities assigned to the Alpine region (Fig. 9d-e). These individuals likely died within a short time of their arrival at Tertiveri. Individual TC20 was also assigned a high probability of residence in the Alpine region although high probabilities are also observed for eastern European regions (Fig. 9f). However, as mentioned above this individual is likely to have a strong mixed signal making the interpretation of LocateR results difficult. Individuals TC77, TC82, and TC20 were all found within the same shaft burial assumed to belong to privileged individuals. The fourth outlier, TC8 (-5.3‰), corresponds to an adult male individual buried in accordance with an Islamic burial rite. His death likely took place in 1296-1300 CE, when Tertiveri was controlled by a Muslim knight[23,69,70]. For this individual LocateR shows high residence probabilities for the Mediterranean coastline, including the southern tips of the Italian peninsula and Sicily (Fig. 9g).

DISCUSSION

The main source of calories for humans across the three sites was C_3 plants, a food group consisting of plants such as wheat, barley, rye, oat, fruit, nuts, vegetables, and legumes. Historical evidence suggests that these foods were the staple diet for southern Italian populations during the Middle Ages[9]. In Capitanata, the presence of multiple grain storage buildings (e.g. silos) marks the importance of cereal production as a main economic activity during the late Middle Ages[71]. However, these sources do not mention C_4 cereals as a significant crop. In contrast, our isotope-based estimates revealed the potential intake of a moderate amount of C_4 plants across the different sites. This is clearer for Tertiveri where individuals from Cluster 1 are in a mixing line between C_3 and C_4 protein (Fig 5). The earliest consumption of C_4 cereals in southern Italy (likely millet) was isotopically detected for the Bronze Age[72], although C_3 plants still dominated diets. A useful characteristic of C_4 cereals is that these overall ripen faster than C_3 cereals and are more durable[73]. Millet and sorghum are grown during the spring/early summer periods in southern Italy. This is when transhumance practices from Apulia to the Abruzzo Apennines took place[58,59] and so it is possible that the cultivation of C_4 crops in Capitanata may have been part of a transhumance economy, whereby shepherds consumed these cereals during their summer journeys across the Apennines.

Bayesian caloric estimates show that pigs were likely the main dietary source of animal products. This is unsurprising, given the accessible prices for pig products during the late Middle Ages in comparison to other animal meats[9,74]. A pig-based farming economy is often observed in association with demographic growth (e.g. imperial Rome[75]). Pig husbandry, paired with cereal production and transhumance, became the basis for the farming economy of late medieval Capitanata[76]. This matches the demographic growth following the onset of Norman rule which would require more intensive agricultural production[13].

During the late medieval period there was an increase in transhumance in the region[59]. Tertiveri and Montecorvino were located in the vicinity of transhumance routes and as a likely result of more intense animal traffic the local consumption of sheep/goat products increased. Bayesian estimates confirm a significant dietary consumption of sheep/goat products, either as meat (mutton) or dairy products, whereas estimates for cattle consumption were small. However, it is known from historical sources that cattle transhumance was also practiced[58]. During the late medieval period, cattle were usually used for ploughing, whereas their meat had a high market value and was therefore mostly consumed from old animals which could no longer be employed in the fields[9,15,74]. Our modelling results also indicate that poultry meat and eggs consumption was overall probably small.

The caloric contribution from marine foods was small across the different sites. However, given the distance for investigated sites and the coast, this suggests the presence of intra-regional trade networks connecting Adriatic sites with the Apennines. In Tertiveri, individuals from Cluster 2 (fig. 5a) had bone collagen isotopic values along a rough mixing line between C_3 and marine protein. These contrast with individuals from Cluster 1 where the consumption of C_4 cereals was higher although Bayesian estimates do not offer very precise estimates. What is clear is that there is a predominance of high socioeconomic individuals in Cluster 2, in contrast to Cluster 1. Millet was considered a low status food during antiquity while the fish imports were likely to be expensive and more easily accessible to individuals with a higher socioeconomic status[8,9].

Included in Cluster 2 is the so-called Tertiveri bishop (TC74)[70] showing moderately elevated isotopic values. The consumption of marine foods during the medieval period is often associated with the clergy, given that these represented one of the wealthier strata of society and were more likely to adhere to Catholic fasting rules[56]. Such rules varied with time, region and monastic order, but in the extreme could imply that terrestrial meat could not be consumed for up to nearly half of the year[56]. Whilst the so-called bishop does not have the highest isotopic values within the cluster, it is possible that the age of the individual (c. 70-80 years old) may have influenced dietary practices. Moreover, old people were often dispensed from religious fasting[56].

Two Muslim individuals (TC8 and TC21) were also found in Tertiveri and show bone collagen isotopic values that do not suggest the consumption of marine foods. Islamic fasting rules forbid the consumption of pork, which within our dataset has distinct isotopic values relatively to the other terrestrial food sources. Individual TC21 is an infant (0-3 years) and their isotopic values likely include a nursing effect[63]. Individual TC8 is an adult with a diet mainly consisting of cereals (mostly C_3 but with a moderate contribution from C_4), legumes and ovicaprid products. It should be noticed, however, that from the observed bone collagen isotopic values for TC8 it is not possible to fully exclude pork consumption.

Previous isotopic results for late medieval southern Italy are only available for three sites, i.e. Apigliano and Quattro Macine in southern Apulia[22] and the Franciscan monastery of Montella in the Campanian apennines[21]. The $\delta^{15}N$ bone collagen values for the adult population from these sites are considerably lower than those presented in our study. This could be the result of dietary differences and/or differences in food values as a result of varying environmental conditions and farming practices[36–40]. Manuring can elevate the $\delta^{15}N$ value of crops[39]. As mentioned above, the Capitanata region had an economy based on cereal cultivation plus the zooarchaeological record shows the presence of ovicaprids, cattle, and pigs making the practice of manuring possible. There are no direct isotopic measurements on plants for the studied region or from previous publications. However, herbivores from Capitanata show elevated $\delta^{15}N$ values when compared to those from Apigliano and Quattro Macine (the site of Montella had no faunal remains). The same applies to pigs. Similar regional disparities in agricultural practices and environmental conditions were observed in the rest of Italy, Iberia, and England[45]. This is associated with a high degree of economic and/or political fragmentation in Europe during the Middle Ages.

The distribution of human stable oxygen isotope values confirms the rich historical and cultural heritage of the sites of Tertiveri and Montecorvino. Our study identified buried individuals potentially originating from the Alpine region and from other Mediterranean locations. However, spatial mobility may have also taken place at smaller geographical scales. In this respect, transhumance activities, mentioned above, would require seasonal movements that are not detectable from bulk isotopic measurements due to a lack of temporal resolution[61]. Late medieval written sources, mainly originating from legislative and administrative records, provide detailed information on regulations applied to transhumance activities, calendar dates for the practice, and rent land prices in Capitanata[58]. Documents indicate that during the cold season (September - May), herds from the Abruzzo Apennines were grazed in the Tavoliere plain in Capitanata.

Migratory movements from the Alps to Capitanata during the late thirteenth century are described in written records[26]. These consisted of military expeditions and the settlement of veterans in the region following the Angevin conquest of the Kingdom of Sicily (1266)[4]. Documents attest that Angevin soldiers were enrolled from Bourgogne and Savoy (south-east France) and detached to the castle of Crepacore in 1269[26]. Once the region was pacified, these soldiers obtained lands nearby Crepacore and likely settled there with their families. A Franco-Provençal dialect similar to those from the French-Swiss border is spoken still today in two communities located less than 15km from Tertiveri[26]. Most individuals from Cluster B (C92, TC98, TC99, and TC101) were buried in the so-called 'ordinary' cemetery outside Tertiveri Cathedral. There are no clear indications that these were high-status individuals (two were assigned to dietary Cluster 1 and two to Cluster 2 and they could be Angevin soldiers or their family members).

There is no precise chronology for the individuals mentioned above but it is known that this differs from other individuals showing oxygen isotopic values associated with the Alpine region (outliers TC20, TC77, TC82, and individual TC83 from Cluster B). These date to the first half of the thirteenth century and were buried in a privileged burial shaft. During the proposed chronology, the Capitanata region was part of the Kingdom of Sicily and Holy Roman Empire, both ruled by Frederik II Hohenstaufen (1194-1250 CE). It is possible that these individuals had their origins in southern Germany and their presence on the site may be related to military expeditions (e.g. the sixth crusade) or diplomatic and political activities.

Individual TC8 was buried according to an Islamic rite and dated to the last decade of the thirteenth century. In 1296 CE, the bishopric was donated by the King Charles II of Naples to ‘Abd al-‘Azīz, a Muslim knight from the city of Lucera[23]. Lucera was a fortified town in Capitanata where Muslims from Sicily were resettled in the 1220s by Frederik II following religious unrests on the island[4,23,24]. The Islamic population of Lucera could live according to Muslim laws and cultural habits. They were also heavily involved in trading activities and the wars of the Kingdom. Within this, ‘Abd al-‘Azīz was one the most influential people and likely was given rule over Tertiveri by King Charles II following his participation in the War of the Vespers (1282-1302) in Sicily[23]. Tertiveri remained under ‘Abd al-‘Azīz’s control only until 1300 CE, when it was then donated to a Christian knight. Given the privileged burial and the short chronology, individual TC8 is likely a member of ‘Abd al-‘Azīz’s clan. His oxygen isotopic values indicate that he likely travelled from coastal regions in the western Mediterranean, including Sicily, or from north African coasts. A possibility involves the participation of this individual within the War of the Vespers in Sicily, alongside ‘Abd al-‘Azīz’.

Future research avenues could be pursued to further the knowledge presented in this paper. In particular, employing techniques such as radiocarbon dating and Bayesian chronological modelling could allow for a more precise chronology, which in turn could offer a more detailed insight into diachronic trends in the socio-economic strategies and links to changing political regimes in Capitanata. The small skeletal collections available for analysis from Montecorvino and San Lorenzo may be augmented by a recently recovered large skeletal assemblage from Montecorvino, which could offer a more comprehensive view of local lifeways in relation to biological sex and age. Additionally, further refinement of food isotopic values through direct analysis of archaeological materials could potentially lead to more precise Bayesian dietary estimates.

CONCLUSIONS

The farming economy of Late medieval Capitanata was based on cereal production and complemented by animal management practices. The rearing of animals, for the most part pigs and ovicaprids, allowed for intensive crop manuring. This practice is apparently absent in other Late medieval sites in southern Italy and may have contributed to a local demographic growth following the establishment of the Norman rule. Predominant cereal production consisted of wheat and barley although millet and/or sorghum were also grown in smaller amounts. The latter may have been linked to transhumance practices. Minor consumption of marine fish, potentially associated to Christian fasting rules, shows the existence of trade routes connecting the sub-Apennine region to the Adriatic coast.

Significant differences in individual diets likely reflect a socioeconomic hierarchy which determined purchase power. Millet and/or sorghum, viewed as lower quality grains, were more affordable than wheat or barley. While animal protein, including marine fish, were costlier food items and more easily accessible to higher status individuals. Among these were likely German elites or Angevin soldiers that moved into the region from Alpine regions during the thirteenth century. One single individual, buried according to an Islamic rite, likely travelled from other western Mediterranean coastal regions (e.g. Sicily).

The traditional image of Late Medieval southern Italy is one where a farming economy sustains a hierarchical feudal system and where a succession of foreign influences conflicted and co-existed. Our multi-isotope Bayesian approach employed in the study of bioarchaeological remains largely corroborates such an image but it also offers a high resolution reconstruction of the socioeconomic, cultural, and demographic dynamics of Late medieval communities. These historical aspects had a formative role that remains visible in the linguistic, religious, culinary, and genetic heritage of southern Italy.

METHODS

We carried out bulk collagen and bioapatite stable carbon, nitrogen and oxygen isotope analyses on skeletal samples from the late medieval sites of Tertiveri, Montecorvino and San Lorenzo in Carminiano[54,69,70,76]. Osteological material was sampled with the permission and collaboration of the Soprintendenza Archeologia, Belle Arti e Paesaggio per le Province di Barletta-Andria-Trani e Foggia. Individuals from Tertiveri are currently stored at the Soprintendenza in Foggia, whereas those from Montecorvino and San Lorenzo are curated by the University of Foggia. A description of the archaeological sites and of a preliminary osteological analysis can be found in Supplementary Information File S2. In total, 134 human individuals and 21 faunal specimens were sampled for stable isotope analysis (Supplementary Information File S1; https://www.doi.org/10.48493/w01v-fe90).

The largest number of human samples was recovered from Tertiveri (113 individuals). This included a so-called 'bishop' (TC74) and two individuals buried following an Islamic rite (TC8, TC21). Anthropological analysis from Tertiveri revealed a biological sex ratio of approximately three males to each female. Seven females, ten probable females, fourteen males and twenty-five probable males were identified across the adolescent and adult population. However, it was not possible to determine the biological sex of thirty-seven adolescent and adult individuals due to their fragmented and/or commingled state. The same applied to twenty-one non-adult individuals who did not display clear sexual dimorphism. The site was characterized by a high mortality rate among young adults aged between twenty and forty years old. Also a few elderly individuals over sixty were identified. Non-adults of all age groups were underrepresented, which is a common trait of medieval populations in Italy[77]. Supplementary Information File S2 provides additional detail on biological sex and age at death distributions in Tertiveri.

The dataset from Montecorvino (n=17) included four adult females, six adult males, and seven non-adults. This represents the original anthropological core of the site, whereas more recently a larger assemblage was excavated. Therefore, demographic profiles are still under investigation and cannot be determined yet. From San Lorenzo (n=4), two males, one female, and one undetermined adult could be sampled. Further details on this preliminary osteological analysis from the two sites is presented in Supplementary Information File S2.

For comparability purposes we sought to sample rib bones from all individuals. However, many skeletons found in Tertiveri were disarticulated and some did not have preserved ribs. Turnover rates of skeletal bioapatite and collagen vary with osteological element[32]. In the case of ribs, the collagen reflects the c. 3-5 years prior to death of an individual. For many osteological elements their turnover rates are not precisely know nor how these vary with the age of an individual. Thus, our dietary and mobility isotopic comparisons may reflect different life stages of the analysed individuals. The skeletal samples from Tertiveri consisted of: fifty ribs, twenty-nine cranium fragments (mostly parietal and frontal parts), twelve fibulae, four metatarsal bones, four vertebrae, three tibiae, two femora, two humeri, two scapulae, one clavicula, one mandibular fragment, one metacarpal bone, and one radius. In some instances, it was possible to sample multiple tissues (e.g. tooth plus bone) from the same human (e.g. TC86) or animal individual (e.g. MOPI1). In Montecorvino (n=17) and San Lorenzo in Carminiano (n=4), human ribs were sampled for all individuals.

The faunal dataset is composed by five specimens from Tertiveri, seventeen from Montecorvino, and one from San Lorenzo. The Tertiveri animal dataset consists of bone samples from two cattle, one pig, one ovicaprid, and one tortoise. From Montecorvino, bone fragments from two cattle, two poultry, one horse, four ovicaprids and one tortoise were collected. In addition, five teeth and two bone fragments from five pigs were also included. From San Lorenzo, only one tooth and one bone from the same deer specimen were sampled. Despite potential turnover differences across bone samples and teeth, we assumed that the shorter lifespan for animals should not significantly impact the interpretation of isotopic results.

Samples from Tertiveri were pre-treated at the stable isotope lab of the Max Planck Institute of Geoanthropology (former “for the Science of Human History in Jena”) (MPI-GEA), Germany, whereas samples from Montecorvino and San Lorenzo in Carminiano were pre-treated at the ‘iCONa’ lab at the Università degli studi della Campania ‘Luigi Vanvitelli’ in Caserta, Italy. All stable isotope measurements were carried out at the MPI-GEA. Sample pretreatment and analytical measurements are described in detail in Supplementary Information File 4.

We employed the Bayesian dietary mixing model ReSources (previously FRUITS) to quantitatively reconstruct late medieval diets in Capitanata[45,55,66,78]. Modelling options are described in Supplementary Information File 3.

Human mobility was investigated using δ^{18}O bone measurements. These were compared with a reference baseline for δ^{18}O values of drinkable water across western Europe. This baseline relies on a dataset of mean $\delta^{18}O_{Water}$ annual values from the Regionalized Cluster-based Water Isotope Prediction model (RCWIP)[67] from which a smoothed spatial surface for δ^{18}O was created using the Bayesian model AverageR[45,79]. Probabilistic assignment of residence was generated using the model LocateR[45,68]. For a direct comparison of human bone and water δ^{18}O values, the values for the former, reported as carbonate measurements relative to the standard VPDB, were re-expressed relative to the

VSMOW standard ($\delta^{18}O_{VSMOW} = \delta^{18}O_{VPDB} * 1.03092 + 30.92$). Following Chenery *et al.* (2012)[80] carbonate values were converted into phosphate ($\delta^{18}O_{phosphate} = \delta^{18}O_{carbonate} * 1.0322 - 9.6849$) and finally into drinkable water following Pollard *et al.* (2011)[43] ($\delta^{18}O_{Water} = \delta^{18}O_{phosphate} * 1.55 - 33.49$). For modelling purposes and in accordance with previous studies, we employed a conservative 2‰ uncertainty for modelled human $\delta^{18}O_{Water}$ values which reflects uncertainty introduced by a variety of factors (e.g. cooking, bone diagenesis, etc.)[41,42].

For cluster classification of human $\delta^{13}C$ and $\delta^{15}N$ values we employed the mclust R package[81]. Mixture estimation relied on the expectation–maximisation algorithm and the optimal number of clusters was identified using the Bayesian Information Criterion (BIC). For cluster classification of human $\delta^{18}O$ values we employed the tclust R package[82]. This gave a cluster assignment similar to mclust but tclust employs a trimming approach[83], based on a threshold value, to identify outliers. For our application we employed a trimming threshold value of 5%.

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DATA AVAILABILITY

Data that support the findings of this study are available in Supplementary Information file S1 and at https://www.doi.org/10.48493/w01v-fe90.

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AUTHOR CONTRIBUTIONS

CC Co-designed the study, analysed the data, wrote the manuscript and performed the modelling; WRT Co-designed the study, provided for anthropological analysis and interpretation, and co-wrote the manuscript; IV Provided for anthropological analysis and interpretation, and co-wrote the manuscript; PF Provided for archaeological materials and interpretation, and co-wrote the manuscript; RG Provided for archaeological materials and interpretation, and co-wrote the manuscript; IMM: Provided for archaeological materials and interpretation; DO Provided for archaeological materials and interpretation; LC Provided for archaeological materials and interpretation, and co-wrote the manuscript; MG developed modelling apps and co-wrote the manuscript; PR Provided for lab capabilities and edited the manuscript; CL Provided for lab capabilities and edited the manuscript; RF Co-designed the study, supervised the modelling, and edited the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

ETHIC STATEMENT

Archaeological, anthropological, and isotopic analysis of individuals from the sites of Tertiveri, Montecorvino, and San Lorenzo in Carminiano were conducted with the permission and collaboration of the Soprintendenza Archeologia, Belle Arti e Paesaggio per le province di Barletta-Andria-Trani e Foggia.

FIGURES

Fig. 1. Spatial distribution of medieval sites from the historical region of Capitanata (border division in black) and southern Italy mentioned in this study: A) Tertiveri; B) Montecorvino; C) San Lorenzo in Carminiano; D) Apigliano; E) Quattro Macine; F) Franciscan Friary in Montella; G) Crepacore Castle; H) Lucera. With a black font, sites for which new isotopic data is presented.

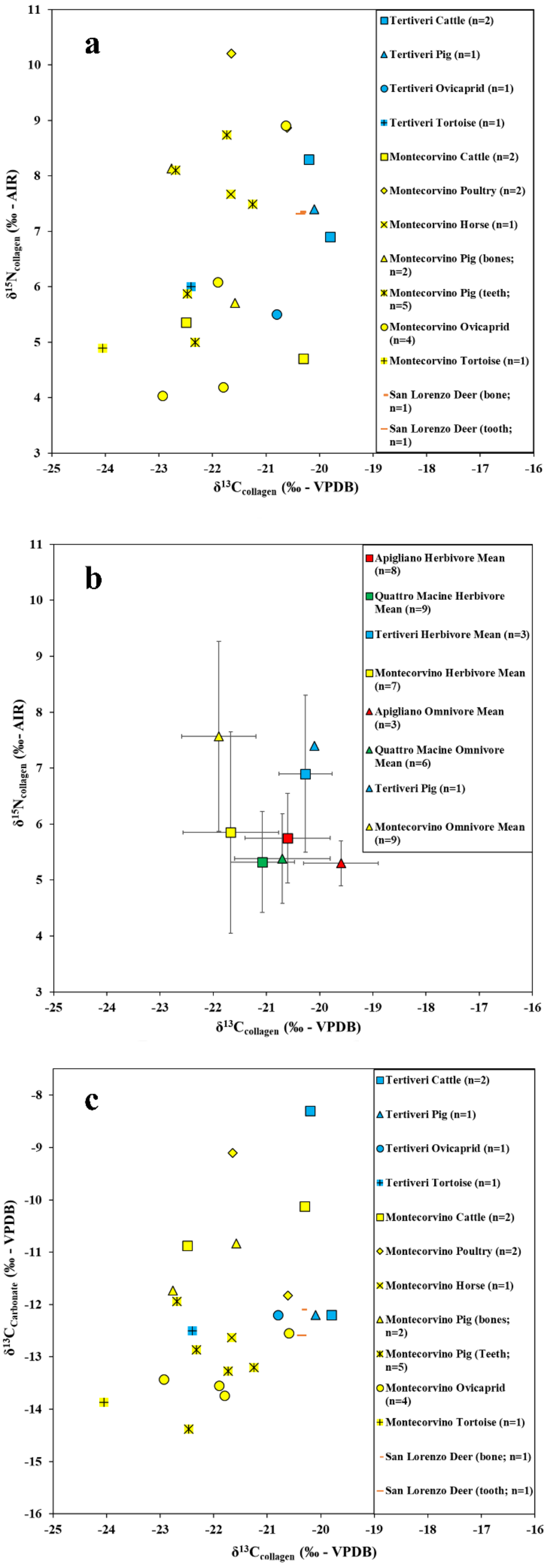

Fig. 2. Isotopic results for archaeological faunal samples. **a**) $\delta^{13}C$ *versus* $\delta^{15}N$ for fauna from this study; **b**) $\delta^{13}C$ *versus* $\delta^{15}N$ comparing mean isotopic values for herbivores and omnivores from this study *versus* those measured in the coeval Apulian sites of Apigliano and Quattro Macine[22]; **c**) $\delta^{13}C_{collagen}$ *versus* $\delta^{13}C_{carbonate}$ for fauna from this study.

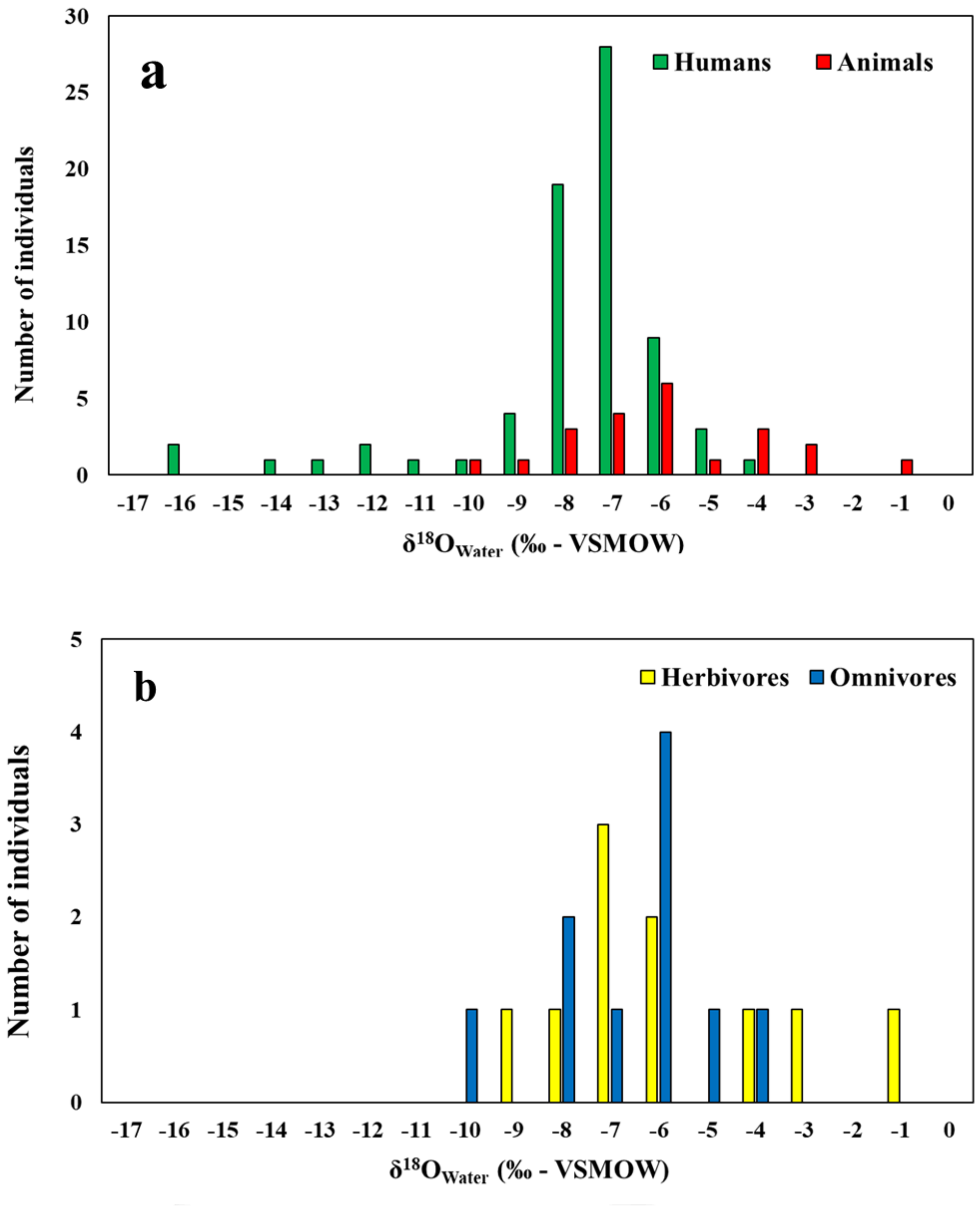

Fig. 3. Calculated values for ingested water $\delta^{18}O_{Water}$ for humans and fauna. **a**) histogram showing the distribution of human and faunal $\delta^{18}O_{Water}$ values; **b**) histogram showing the distribution of domesticated herbivore and omnivore $\delta^{18}O_{Water}$ values.

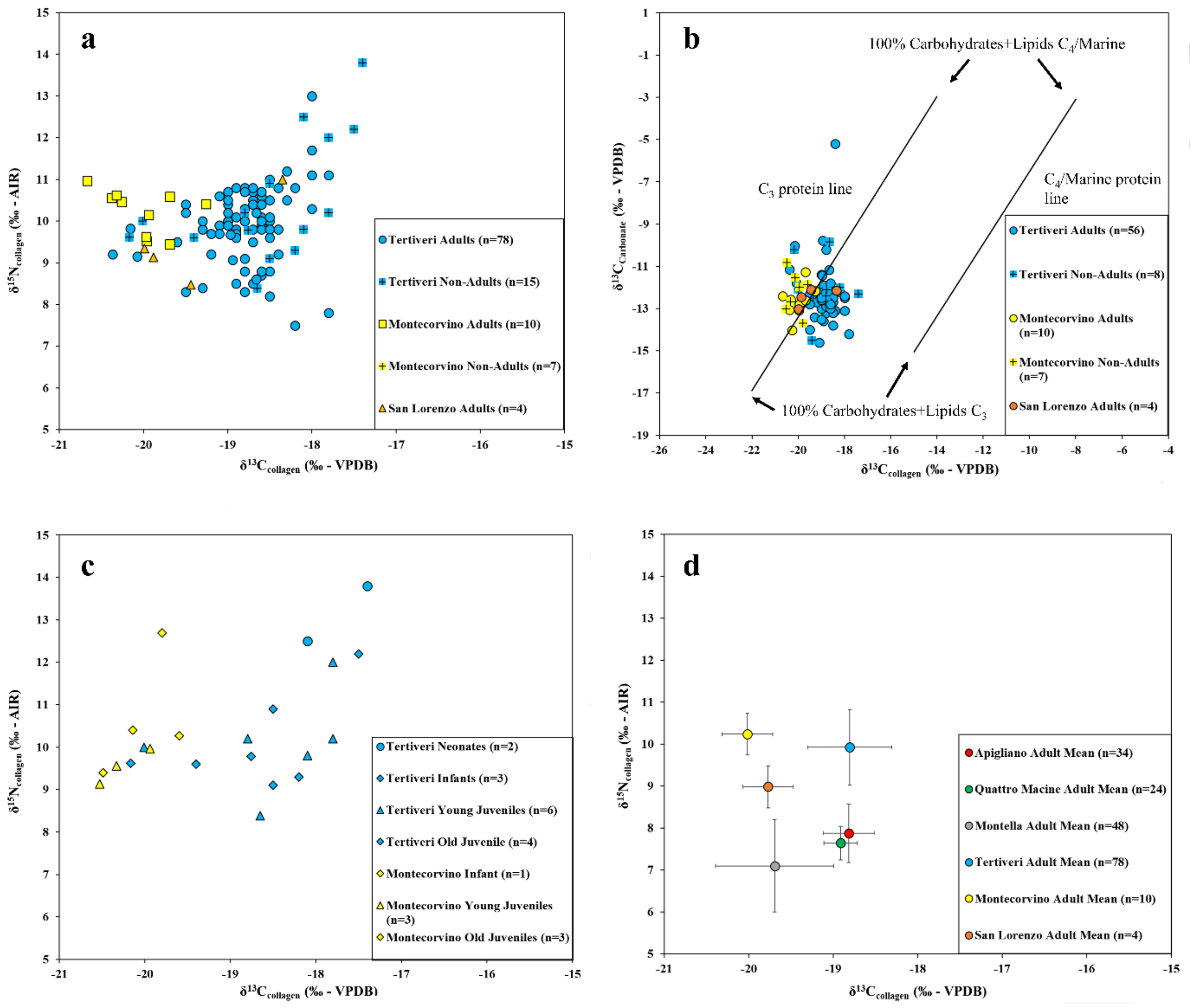

Fig. 4. Human isotopic results. **a**) $\delta^{13}C_{collagen}$ *versus* $\delta^{15}N_{collagen}$ values for human individuals from this study; **b**) $\delta^{13}C_{collagen}$ *versus* $\delta^{13}C_{carbonate}$ values for human individuals from this study (reference dietary lines after Kellner & Schoeninger 2007)[65]. **c**) $\delta^{13}C_{collagen}$ *versus* $\delta^{15}N_{collagen}$ values for human non-adult individuals from this study. Neonates: 0-1 y.; Infants: 1-3 y.; Young Juveniles: 3-7 y.; Old Juveniles: 7-13 y. **d**) $\delta^{13}C_{collagen}$ *versus* $\delta^{15}N_{collagen}$ biplot comparing mean isotopic values for adults from this study with those measured in the coeval southern Italian sites of Montella, Apigliano, and Quattro Macine (Torino *et al.* 2015; Rolandsen *et al.* 2019)[21,22].

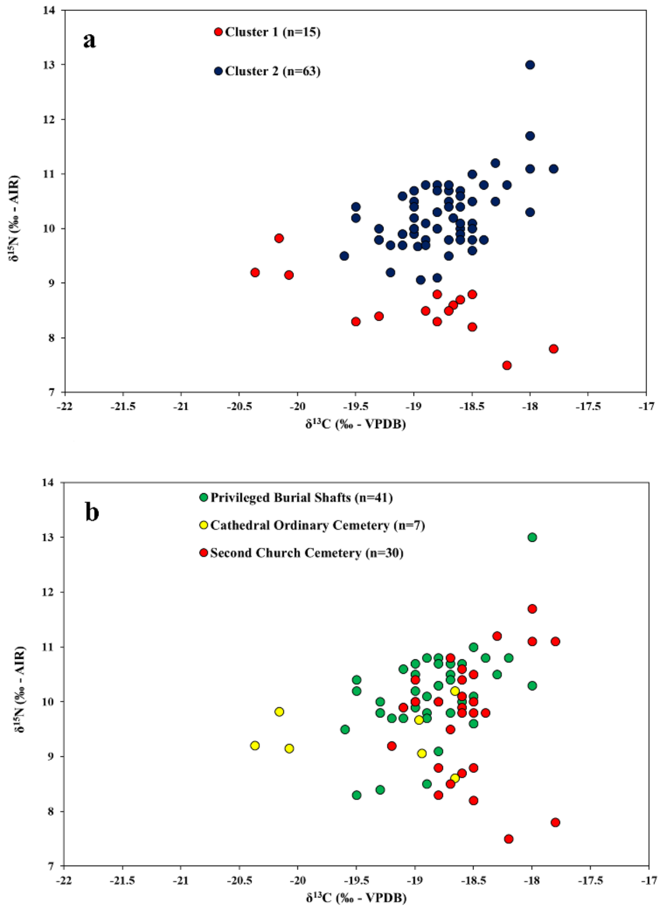

Fig. 5. Distribution of $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values for human adult individuals from Tertiveri. **a**) Cluster classification; **b**) Archaeological classification.

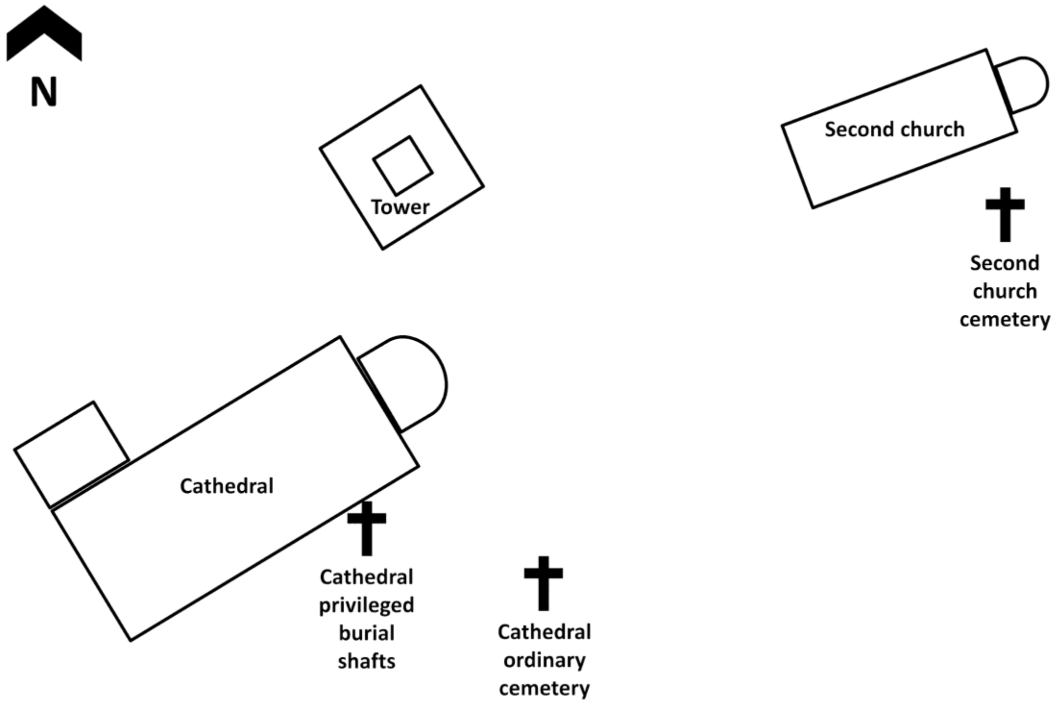

Fig. 6. Schematic representation of the relative positions of burial locations at Tertiveri. The figure is not to scale.

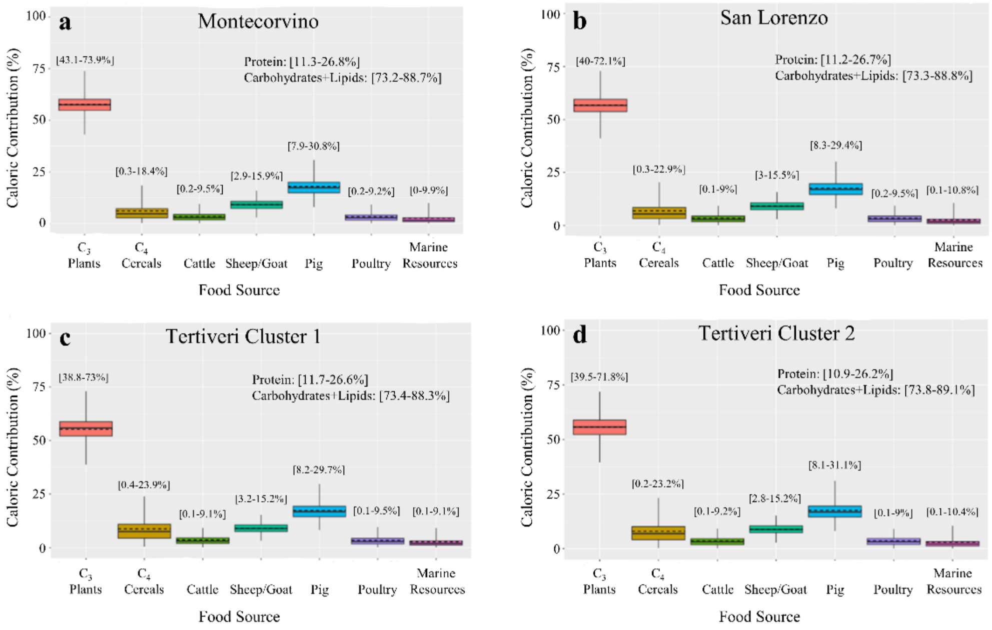

Fig. 7. Bayesian estimates of dietary caloric contributions (boxes and whiskers represent 68% and 95% credible ranges, respectively. Horizontal continuous lines represent the mean and dashed horizontal lines the median). Numbers in brackets represent 95% credible ranges. Also included within the graph are numeric estimates of the caloric contributions of protein *versus*. carbohydrates macronutrients. Estimate for: a) Montecorvino; **b**) San Lorenzo in Carminiano; **c**) Tertiveri Cluster 1; **d**) Tertiveri Cluster 2.

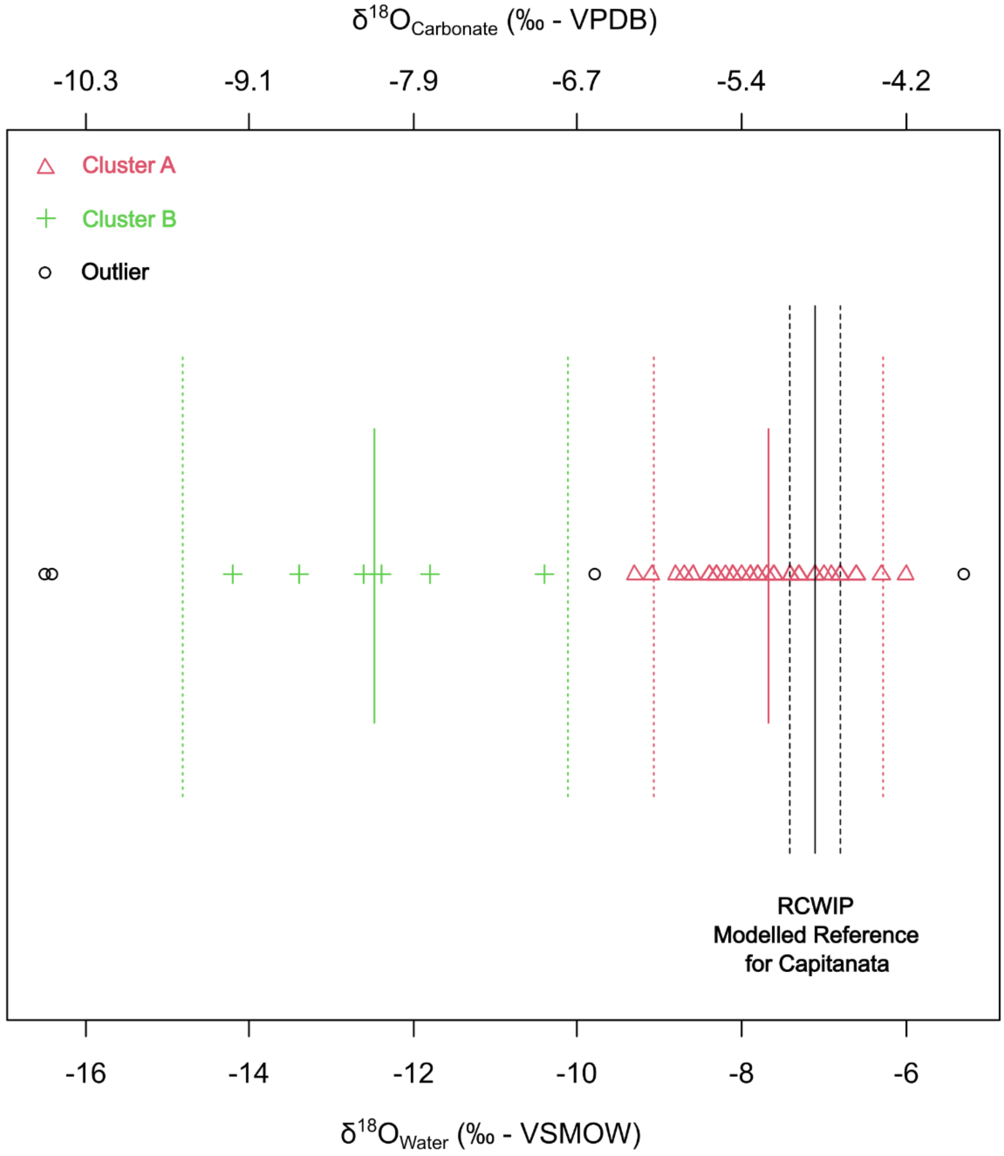

Fig. 8. Cluster classification and outlier detection for the distribution of $\delta^{18}O$ values for adult individuals from Tertiveri and Montecorvino. Solid green and red lines represent cluster mean values, whereas green and red pointed lines represent a 2-sigma interval. Continuous vertical black line represents the mean $\delta^{18}O_{Water}$ value for Tertiveri and Montercorvino (-7.1‰) determined using Bayesian modelling of RCWIP estimates while dashed vertical black lines represent the standard error of the mean for the estimates (0.3‰) (Terzer et al. 2013)[67].

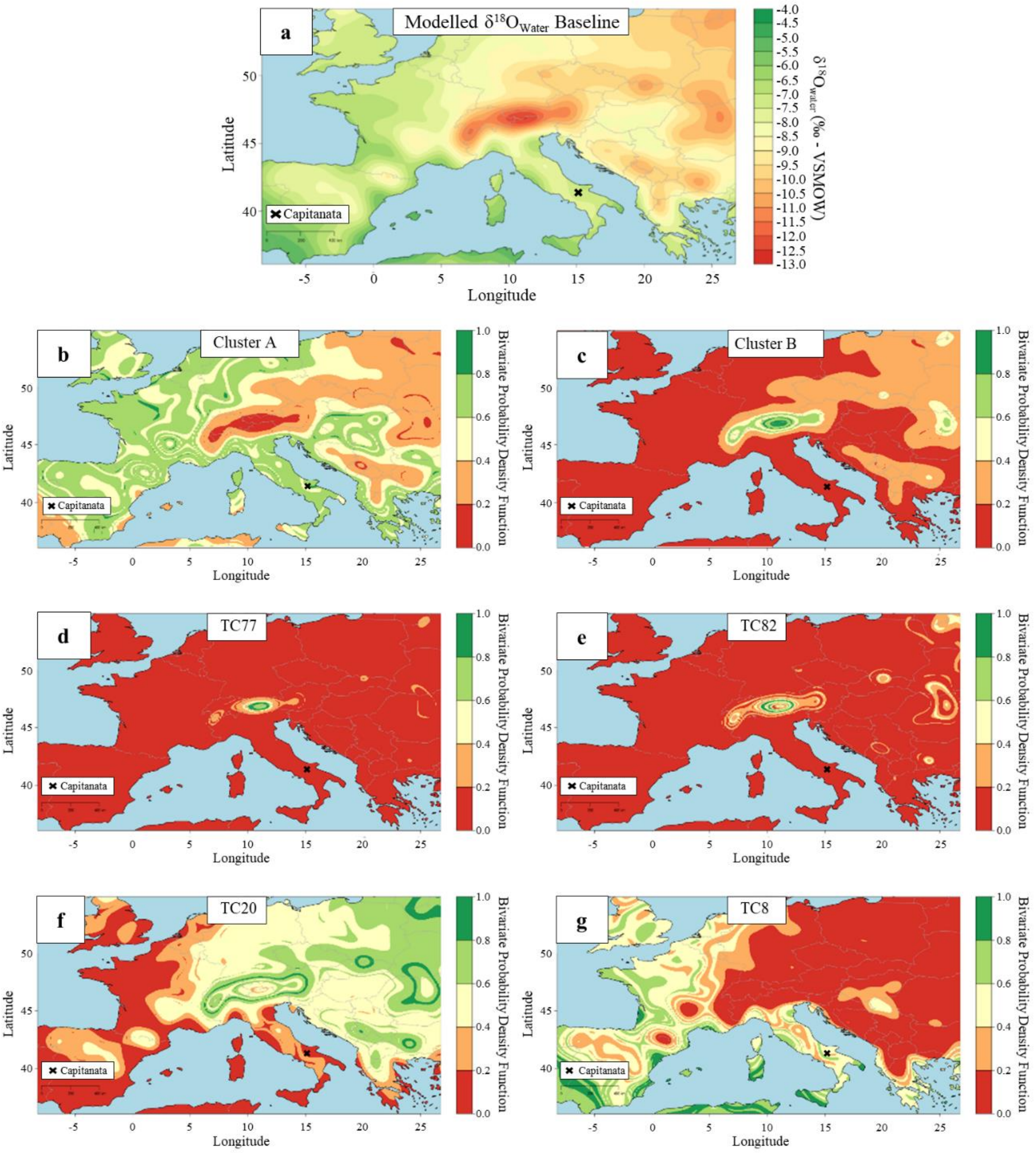

Fig. 9. Residence probability maps assigned using the model LocateR. **a**) Bayesian modelled $\delta^{18}O_{water}$ isotopic baseline based on RCWIP model. **b**) Cluster A (mean value); **c**) Cluster B (mean value); **d**) TC77; **e**) TC82; **f**) TC20; **g**) TC8.