**Supplementary Information File S4: Bayesian modeling**

**Pandora & IsoMemo modeling**

The illustrative case studies described in the main text employed R-based[1](https://www.zotero.org/google-docs/?cpB2Wg) modeling tools (TimeR, AverageR, OperatoR, KernelTimeR and LocateR) developed within the Pandora & IsoMemo initiatives and made available via Shiny[2](https://www.zotero.org/google-docs/?cNIHRn) graphical interfaces (https://isomemoapp.com/). Below a description of these models is given and the full model settings are given in Supplementary Information File S5. The R code for these apps can be downloaded from <https://isomemoapp.com> and apps run locally using RStudio[3](https://www.zotero.org/google-docs/?GTTKbm).

*TimeR*

‘TimeR’ is a model available within the IsoMemo app listed at <https://isomemoapp.com/> within the menu options “Modeling”.

‘TimeR’ is a Bayesian geostatistical model that estimates the expected value of a “dependent” variable across time and space. The underlying model formula is:

Y\_i = g(long\_i, lat\_i, time\_i) + gamma\_site\_i + epsilon\_i

gamma\_site\_i is a random effect with ~ N(0, tau^2)

where g()- is a three dimensional (spatial coordinates plus time) smooth function using a so-called thin plate regression spline (“tprs”[4](https://www.zotero.org/google-docs/?BluQz8)) and epsilon follows a normal distribution N(0, sigma^2). As the time variable is measured with uncertainty, a Metropolis-Hastings step is employed to account for it (further details given in Groß[5](https://www.zotero.org/google-docs/?Gz5s0J)). The model was employed to model spatiotemporal variations in human bone collagen isotopic values for early medieval Europe and for the site of Rome (Fig. 4-6). Human data was filtered to include only non-elite adult individuals with bone and tooth collagen C:N atomic ratios within the acceptance interval given by DeNiro[6](https://www.zotero.org/google-docs/?zhKYLr).

*AverageR*

‘AverageR’ is a model available within the IsoMemo app listed at <https://isomemoapp.com/> within the menu options “Modeling”.

‘AverageR’ is a Bayesian geostatistical model that estimates the expected value of the “dependent” variable across space. ‘AverageR’ is similar to ‘TimeR’ but does not include time dependence[5,7](https://www.zotero.org/google-docs/?cliWLv).The model was employed to map the spatial distribution of δ13C and δ15N mean and prediction error values (double the square root of the following sum: the square of the predicted standard error of the mean plus the square of the predicted population standard deviation) for bone collagen from medieval domesticated animals (Fig. 3) and to establish reference baselines for mobility studies (see below, LocateR). For the animals, we modeled separately isotopic values for cattle and sheep/goat *versus* pig and chicken with acceptable C:N atomic ratios[6](https://www.zotero.org/google-docs/?hsE1EA).

*OperatoR*

‘OperatoR’ is available within the IsoMemo app listed at <https://isomemoapp.com/> within the menu options “Modeling”.

OperatoR was used to plot the differences among maps generated using AverageR. This difference was calculated by subtracting two-dimensional posterior estimates of the time sliced g()-smooth, i.e. the expected values for all considered locations for a fixed date. OperatoR was used to show the temporal differences in early medieval diets for two different time-slices (Fig. 4). ‘TimeR’ was used to generate spatial models in three different time-slices (200-500-800 CE) followed by the use of OperatoR to map differences.

*KernelTimeR*

‘KernelTimeR’ is available within the IsoMemo app listed at <https://isomemoapp.com/> within the menu options “Modeling”.

‘KernelTimeR’ is a 3-dimensional spatiotemporal kernel density estimator[8](https://www.zotero.org/google-docs/?AkRnxA). It was employed to show research gaps in early medieval isotopic studies and to assess temporal variability in human mobility patterns (Fig. 8). Mobile *versus* non-mobile individuals were identified by comparing individual values with a 87Sr/86Sr and δ18Ophosphate tooth enamel baseline for Britain[9,10](https://www.zotero.org/google-docs/?IaOt55) modeled using ‘AverageR’. Tooth enamel carbonate values reported relative to VPDB standard were converted into values relative to the VSMOW standard (δ18OVSMOW = δ18OVPDB \* 1.03092 + 30.92). These were then converted into phosphate values using the expression (δ18Ophosphate = δ18Ocarbonate \*1.0322 - 9.6849) reported by Chenery and colleagues[11](https://www.zotero.org/google-docs/?vtowhX). Individuals were classified as mobile if their 87Sr/86Sr or δ18O tooth values were outside baseline ranges. For 87Sr/86Sr we considered the modeled 2-sigma range while for δ18O we used a conservative uncertainty of 1‰ to account for previously reported variability arising from different factors (e.g. diagenesis, cooking, etc.)[12,13](https://www.zotero.org/google-docs/?b0RKkM).

*LocateR*

‘LocateR’ is available within the IsoMemo app listed at <https://isomemoapp.com/> within the menu options “Modeling”.

Given a 2-dimensional grid of locations and corresponding estimates of mean and residual error from the ‘TimeR’ or ‘AverageR’ models (here the baseline spatial variations in oxygen and strontium isotopes), for a new given value of the dependent variable (here the oxygen and strontium isotope values for an individual), ‘LocateR’ assigns a density value to each location[14](https://www.zotero.org/google-docs/?wNYkN6). The model was employed to show probable dwelling locations (and likely places of origin for early formed teeth) for four different medieval individuals buried in England. Human enamel stable oxygen values were converted into phosphate values relative to the VSMOW standard following the same procedure as described in the previous paragraph. Conversion of these into δ18O for ingested water (δ18Odw = δ18Ophosphate \* 1.55 – 33.49) followed Pollard *et al.*’s formula[15](https://www.zotero.org/google-docs/?rXPfcg) .We used ‘AverageR’ to establish a baseline for water δ18O using the Cluster-based Water Isotope Prediction Model (RCWIP), which relies on modern measurements from the Global Network of Isotopes in Precipitation (GNIP)[16](https://www.zotero.org/google-docs/?sjWckW) and a 87Sr/86Sr and δ18Ophosphate tooth enamel baseline for Britain[9,10](https://www.zotero.org/google-docs/?VUgwir).

**ReSources**

‘ReSources’ is an app listed at <https://isomemoapp.com/>.

‘ReSources’ is a software used to define Bayesian mixing models that can be employed for isotope-based diet reconstruction. This software is an upgraded version of the Bayesian software FRUITS[17](https://www.zotero.org/google-docs/?iD2vzk). We employed the model to quantify caloric and macronutrient contribution of each food source within human diets in the area of Rome across three time-slices: 200 CE, 500 CE, and 800 CE. The model employs a random effects structure on the categorical covariate "Time" with levels 200 CE, 500 CE, and 800 CE. In contrast to a model without covariates, the Dirichlet prior values of the source contribution parameters ("alpha") are not fixed but come from a distribution with common mean and standard deviation for each factor level (200 CE, 500 CE, 800 CE) and source group.

Although the model has been employed in recent years to reconstruct past human diets[18–20](https://www.zotero.org/google-docs/?B4aDei), the chosen food categories were often very broad (e.g. following chemical and/or habitat classifications such as C3/C4 plants, C3 animals, marine animals, etc.). In our case-study, we relied on archaeobotanical, zooarchaeological and historical evidence to define the following main food groups for Roman and medieval populations at the city of Rome: Wheat; Barley; C4 Cereals (i.e. millet or sorghum); Pulses; Other C3 Plants (i.e. Vegetables, fruit, nuts); Cattle; Sheep/Goat; Pig; Poultry; Marine Sources; Freshwater Sources. Missing from the above, given a lack of isotopic references, is olive oil whose dietary contributions will likely fall within modeling results among C3 plants.

Human mean isotopic values for Rome (Lat. 41.9; Long. 12.5) were modeled using TimeR from bone collagen measurements available in the CIMA and IsoArcH[21](https://www.zotero.org/google-docs/?BMcVJG) databases. We considered three separate time slices (200 CE, 500 CE, and 800 CE) with the following results: 200 CE: δ13C=-19.14±0.11‰, δ15N=10.08±0.11‰; 500 CE: δ13C=-19.24±0.2‰, δ15N=9.57±0.23‰; 800 CE: δ13C=-19.05±0.38‰, δ15N=8.6±0.23‰. As for the isotopic food baseline (tab. S4.1 below), wheat, barley and pulses isotopic values were obtained from the O’Connell *et al.* publication on Portus[22](https://www.zotero.org/google-docs/?SsjCXU). Given the lack of direct isotopic measurements on archaeological fruit and vegetables, isotopic values for the ‘other C3 plants’ were calculated by applying a trophic isotopic offset correction to herbivore mean bone collagen carbon and nitrogen stable isotope values (δ13C=-4‰; δ15N=-3.5‰,[23,24](https://www.zotero.org/google-docs/?muAu7l)) between these and C3 plants. Lacking coeval isotopic values on C4 cereals, we employed isotopic measurements from two sites in Bronze Age Greece[25](https://www.zotero.org/google-docs/?AwHzdM), as reported in the IsoArcH database. As for food products from cattle, sheep/goat and pig the isotopic references given below were modelled using ‘TimeR’ for Rome (Lat. 41.9; Long. 12.5). For poultry, given a limited amount of data, we calculated the mean and standard deviation for isotopic values available from CIMA[19,22,26–33](https://www.zotero.org/google-docs/?ZppiTE). A similar approach was employed for Mediterranean marine sources by combining CIMA and IsoArcH data[22,30,34–36](https://www.zotero.org/google-docs/?DDcuXO). For freshwater sources, we collected medieval measurements from Italy[32](https://www.zotero.org/google-docs/?LHSezH), Switzerland[37](https://www.zotero.org/google-docs/?YAm6Wd) and France[38](https://www.zotero.org/google-docs/?ZTiOxV). Food sources isotopic values were the following:

|  |  |  |  |
| --- | --- | --- | --- |
|  | 200 CE δ13C | 500 CE δ13C | 800 CE δ13C |
| Charred Wheat remains | -23.18±0.87‰ | -22.07±0.96‰ | -22.45±0.35‰ |
| Charred Barley remains | -24.4±0.7‰ | -22±0.4‰ | -23.46±0.15‰ |
| Charred C4 Cereals remains | -10.4±0.27‰ | -10.4±0.27‰ | -10.4±0.27‰ |
| Charred Pulses remains | -24±1.3‰ | -26.5±0.4‰ | -21.87±0.75‰ |
| Other C3 as trophic isotopic offset towards herbivore bone collagen | -24.3±0.4‰ | -24±0.3‰ | -24±0.3‰ |
| Cattle bone collagen | -20.2±0.34‰ | -19.76±0.15‰ | -19.75±0.29‰ |
| Sheep/Goat bone collagen | -20.35±0.19‰ | -20.31±0.23‰ | -20.25±0.17‰ |
| Pig bone collagen | -20.15±0.12‰ | -19.88±0.07‰ | -20.16±0.11‰ |
| Poultry bone collagen | -18.7±2‰ | -18.7±2‰ | -18.7±2‰ |
| Marine Sources bone collagen | -11.3±3‰ | -11.3±3‰ | -11.3±3‰ |
| Freshwater Sources bone collagen | -23.39±1.3‰ | -23.39±1.3‰ | -23.39±1.3‰ |

|  |  |  |  |
| --- | --- | --- | --- |
|  | 200 CE δ15N | 500 CE δ15N | 800 CE δ15N |
| Charred Wheat remains | 8.53±3.11‰ | 6.76±3.84‰ | 4.3±0.28‰ |
| Charred Barley remains | 6.1±1.3‰ | 6.9±0.4‰ | 5.63±0.97‰ |
| Charred C4 Cereals remains | 6.8±2.74‰ | 6.8±2.74‰ | 6.8±2.74‰ |
| Charred Pulses remains | 2.5±0.6‰ | 2.5±0.6‰ | 2.4±0.46‰ |
| Other C3 as trophic isotopic offset towards herbivore bone collagen | 2.1±0.6‰ | 2±0.8‰ | 2.3±0.6‰ |
| Cattle bone collagen | 5.96±0.41‰ | 5.99±0.77‰ | 6.27±0.43‰ |
| Sheep/Goat bone collagen | 5.29±0.41‰ | 4.94±0.25‰ | 5.32±0.39‰ |
| Pig bone collagen | 6.34±0.24‰ | 6.13±0.16‰ | 5.98±0.34‰ |
| Poultry bone collagen | 7.6±2.1‰ | 7.6±2.1‰ | 7.6±2.1‰ |
| Marine Sources bone collagen | 10.7±1.9‰ | 10.7±1.9‰ | 10.7±1.9‰ |
| Freshwater Sources bone collagen | 7.98±1.88‰ | 7.98±1.88‰ | 7.98±1.88‰ |

Tab. S4.1. Isotopic values for food remains and time-slice employed in Bayesian dietary modeling. These do not include yet corrections for offsets between edible tissues and food remains (e.g. muscle meat protein or lipids vs. bone collagen collagen). Corrected values are given in Table Tab. S4.2.

To obtain δ13C and δ15N values for food macronutrient components (carbs/lipids vs. protein) we applied offset corrections between the measured material (e.g. bone collagen) and the edible nutritional component of the respective food group (muscle meat protein) (Tab. S4.2, below). We applied the following offset corrections with uncertainties for macronutrient isotopic values rounded up to multiples of 0.5[18](https://www.zotero.org/google-docs/?H7CoDG)(updated in Soncin *et al.*[39](https://www.zotero.org/google-docs/?ID5Ia3)): Plants: Δ13Cprotein-bulk=-2‰, Δ13Ccarbohydrates-bulk=+0.5‰, Δ15Nprotein-bulk=0‰; terrestrial animals: Δ13Cprotein-collagen= -2‰, Δ13Clipids-collagen= -8‰, Δ15Nprotein-collagen=0‰; aquatic animals: Δ13Cprotein-collagen=-1‰, Δ13Clipids-collagen=-7‰, Δ15Nprotein-collagen=+1.5‰). Below a list of isotopic reference values employed in modeling:

|  |  |  |  |
| --- | --- | --- | --- |
|  | 200 CE δ13C Protein | 200 CE δ13C Lipids/Carbohydrates | 200 CE δ15N Protein |
| Wheat | -25.2±2‰ | -22.7±2‰ | 8.5±4.5‰ |
| Barley | -26.4±2‰ | -23.9±2‰ | 6.1±2.5‰ |
| C4 Cereals | -12.4±1.5‰ | -9.9±1.5‰ | 6.8±4.0‰ |
| Pulses | -26.0±2.5‰ | -23.5±2.5‰ | 2.5±2‰ |
| Other C3 Plants | -26.3±1.5‰ | -23.8±1.5‰ | 2.1±2‰ |
| Cattle | -22.2±1.5‰ | -28.2±1.5‰ | 6±1.5‰ |
| Sheep/Goat | -22.4±1.5‰ | -28.4±1.5‰ | 5.3±1.5‰ |
| Pig | -22.2±1.5‰ | -28.2±1.5‰ | 6.3±1.5‰ |
| Poultry | -20.7±3‰ | -26.7±3‰ | 7.6±3.5‰ |
| Marine Sources | -12.3±4‰ | -18.3±4‰ | 12.2±3‰ |
| Freshwater Sources | -24.4±2.5‰ | -30.4±2.5‰ | 9.5±3‰ |

|  |  |  |  |
| --- | --- | --- | --- |
|  | 500 CE δ13C Protein | 500 CE δ13C Lipids/Carbohydrates | 500 CE δ15N Protein |
| Wheat | -24.1±2‰ | -21.6±2‰ | 6.8±5‰ |
| Barley | -24.0±1‰ | -21.5±1‰ | 6.9±1‰ |
| C4 Cereals | -12.4±1.5‰ | -9.9±1.5‰ | 6.8±4.0‰ |
| Pulses | -28.5±1‰ | -26±1‰ | 2.5±2‰ |
| Other C3 Plants | -26.0±1.5‰ | -23.5±1.5‰ | 2±2‰ |
| Cattle | -21.8±1.5‰ | -27.8±1.5‰ | 6.0±2‰ |
| Sheep/Goat | -22.3±1.5‰ | -28.3±1.5‰ | 4.9±1.5‰ |
| Pig | -21.9±1.5‰ | -27.9±1.5‰ | 6.1±1.5‰ |
| Poultry | -20.7±3‰ | -26.7±3‰ | 7.6±3.5‰ |
| Marine Sources | -12.3±4‰ | -18.3±4‰ | 12.2±3‰ |
| Freshwater Sources | -24.4±2.5‰ | -30.4±2.5‰ | 9.5±3‰ |

|  |  |  |  |
| --- | --- | --- | --- |
|  | 800 CE δ13C Protein | 800 CE δ13C Lipids/Carbohydrates | 800 CE δ15N Protein |
| Wheat | -24.5±1.5‰ | -22.0±1.5‰ | 4.3±1.5‰ |
| Barley | -25.5±1.5‰ | -23.0±1.5‰ | 5.6±2‰ |
| C4 Cereals | -12.4±1.5‰ | -9.9±1.5‰ | 6.8±4.0‰ |
| Pulses | -23.9±2‰ | -21.4±2‰ | 2.4±1.5‰ |
| Other C3 Plants | -26±1.5‰ | -23.5.0±1.5‰ | 2.3±2‰ |
| Cattle | -21.8±1.5‰ | -27.8±1.5‰ | 6.3±1.5‰ |
| Sheep/Goat | -22.3±1.5‰ | -27.8±1.5‰ | 5.3±1.5‰ |
| Pig | -22.2±1.5‰ | -28.2±1.5‰ | 6±1.5‰ |
| Poultry | -20.7±3‰ | -26.7±3‰ | 7.6±3.5‰ |
| Marine Sources | -12.3±4‰ | -18.3±4‰ | 12.2±3‰ |
| Freshwater Sources | -24.4±2.5‰ | -30.4±2.5‰ | 9.5±3‰ |

Tab.S4.2. Corrected isotopic food macronutrients values as employed in dietary modeling.

Within the Bayesian mixing model we employed macronutrient caloric concentration values as reported in Fernandes *et al*.[17](https://www.zotero.org/google-docs/?d1XvCd) but with doubled uncertainty values. These were for plant foods: protein: 10±5%; carbs/lipids 90±5%%, terrestrial animals: protein: 30±5%; carbs/lipids 70±5%, and aquatic animals: protein: 65±10%; carbs/lipids 35±10%.

The Bayesian mixing model also accounted for isotopic offsets between diet and human tissues and dietary routing mechanisms. Bone collagen δ15N was assumed to fully derive from dietary protein with an isotopic offset of 5.5±0.5‰[18](https://www.zotero.org/google-docs/?zbohgD). For bone collagen δ13C we considered an offset of 4.8±0.5‰ towards food values and that the isotopic signal was routed: 74±4% from dietary protein and 26±4% from carbohydrates/lipids[40](https://www.zotero.org/google-docs/?yXPBqS).

To improve the precision of dietary estimates we employed prior dietary information from zooarchaeological, archaeobotanical and historical evidence relative to ancient Rome (Fig. 6). We considered that, in farming societies plants were the main caloric sources for lower status individuals. We set the following constraint in the Bayesian model: Wheat+barley+C4 cereals+pulses>57% of the caloric contribution. This value is the mean caloric contribution from starches consumed in Mediterranean countries between 1960–1965 (table 14.2 reported in Garnsey and Scheidel[41](https://www.zotero.org/google-docs/?9EZENu)).

We collected archaeobotanical evidence from central and southern Italy[27,42–46](https://www.zotero.org/google-docs/?7isWTr), and from this ordered plant starch dietary contributions as follows: Wheat>Pulses>Barley>Millet. This data plus that from written sources[47](https://www.zotero.org/google-docs/?5EQVdO) shows a temporal decrease in wheat consumption. The consumption of C4 cereals increased during the medieval period for rural Italian populations[47](https://www.zotero.org/google-docs/?RX7LN8). During the Late Roman and early medieval period the consumption of animal food sources decreased and populations relied increasingly on cereals, legumes, and other plants[47](https://www.zotero.org/google-docs/?7lO2jZ).

The zooarchaeological evidence[48–50](https://www.zotero.org/google-docs/?APA8r2) shows that pig remains were the most abundant for all periods although this decreased through time in favor of sheep/goat and to a lesser extent cattle.

Dietary modeling results are shown in Fig. 6 and summarized in Supplementary Information file S6. The latter also includes dietary estimates for modern Italians. For this we employed data from FAO food balance sheets (<http://www.fao.org/faostat/en/#data/FBS>) for Italy during 2018 and from 1994–96[51](https://www.zotero.org/google-docs/?gqftE1). These results are given in Supplementary Information File S6. These were compared with Bayesian dietary estimates for Roman and medieval populations at Rome but only for sources available in the past (normalized values).

The full model is available within the MATILDA repository (<https://pandoradata.earth/dataset/cima-compendium-isotoporum-medii-aevi/resource/6dd3aeab-01d6-4f0e-8e82-bbcef5ac507c>) as a R file (.RData). All model inputs are also given in Supplementary Information File 5.

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