Prehistoric Italian foodways: Meta-analysis of stable isotope data from the Neolithic to the Iron Age

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ABSTRACT

Italian Later Prehistory was characterised by profound changes that impacted everyday life in many aspects. Whether or not and how such changes were reflected in the subsistence practices of ancient populations is an ongoing question in the archaeological debate. This question has been investigated using stable carbon and nitrogen isotope analysis for several decades. Here, we present a 6000-year-long review of isotopic studies in the Italian Peninsula from the Neolithic to the Iron Age. We reconstruct chronological variations in food practices by observing δ^{13}C and δ^{15}N trends for 776 humans, 382 animals, and 432 C_3 plants from 111 archaeological sites. During the Neolithic, when farming is first introduced, a homogenous signal characterised by terrestrial protein consumption is visible. The Copper Age, instead, shows a more varied pattern, possibly representative of a more diversified use of the landscape, characteristic of those millennia. The new cultural paradigm that invested Europe during the Bronze Age is also reflected in food practices in Italy, with the introduction of millets - signalled by high δ^{13}C values in the Northern regions - possibly representing a pivotal shift. Not much data is available for the Iron Age, as only two sites from Northern Italy, showing a diffused consumption of C_4 plants, and one site from Southern Italy, with a diet centred around C_3 plants, are available for this period. The analysis of this extensive set of data suggests that the "Secondary Products Revolution" probably meant a shift in subsistence practices, with secondary sources substituting meat rather than integrating it.

1. Introduction

Over the last decades, a growing interest in understanding the relationship between socio-cultural changes and dietary trends has emerged (Eriksson et al., 2008; Boivin et al., 2012; Jones et al., 2011, 2016; Beaudry, 2013; Hastorf, 2016; López-Costas and Alexander, 2019; Twiss, 2019). Food has been tightly associated with cultural identity, social organisation and economic strategies (Boivin et al., 2012), as people need to organise its procurement, transportation, storage and preparation; it is also seen as a gift, and it reflects a connection to and a knowledge of the surrounding environment (Hastorf, 2016). Since Later Prehistory, subsistence strategies have changed, as have the social organisation of human communities and their related complexity. Throughout these changes, human reliance on farming has been established, becoming an underlying food practice still persistent over a large portion of the world today (1.06 billion people were employed in primary agricultural production as of 2019; Davis et al., 2023).

Italy presents one of the richest biodiversity records in Europe

(Agnesi et al., 2009) despite its limited extent. This makes it an excellent setting for understanding the driving forces in human responses to change.

1.1. The study area: Italy

Italy, with a total surface of 300,000 square kilometres, has a limited geographical extent. However, it stretches significantly latitudinally, resulting in a vast biodiversity. It is characterised by a diverse topography, with the Alps, the Apennines, several hilly areas, the Po and Tavoliere plains, numerous lakes and more than 8000 km of coastline. The high number of rivers provides all of Italy with accessible water supplies (Soldati and Marchetti, 2017). The topographical variety, together with a remarkable altitudinal gradient (from 3.4 m below sea level in the Po Valley to 4805 m above sea level at the Mont Blanc in the Alps), produces many different ecozones. The Appennines divide Italy into an eastern and a western part, although several passes allowed connections between the two coasts (Bietti Sestieri, 2013), with the Alps

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marking the division between Italy and continental Europe. The two main islands, Sicily and Sardinia, provide further ecological complexity, with endemic species and biological separation from the mainland (Muscarella and Baragona, 2017; Fois et al., 2022).

The latitudinal extent is also reflected in a diverse climate. Northern Italy and the Apennines experience frequent rainfall, while the south is more arid (Soldati and Marchetti, 2017). Lower temperatures characterise Northern Italy, defined by a continental climate, while the South experiences higher temperatures, with a subtropical temperate climate on the coasts of Sicily and Calabria (Soldati and Marchetti, 2017).

Given its position at the centre of the Mediterranean and the considerable extent of its coastline, Italy held a pivotal position in trade routes and seafarer explorations already during Prehistory (Bietti Sestieri, 2013). This created a variety of cultural practices, which, however, may have developed independently from environmental constraints.

Within this environmental complexity, it is hard to identify a possible driving factor that may have influenced human occupation in the Peninsula. Currently, material culture appears as the most suitable way to disentangle Italian Later Prehistory. Even considering its internal variability and complexity, archaeological evidence has traditionally been employed to subdivide Italy into three macroareas: North, Centre and South (e.g. Fugazzola Delpino et al., 2002; Cocchi Genick, 2009; Bietti Sestieri, 2013).

1.2. A diachronic analysis of Later Prehistory in Italy

Our study focuses on long-term dietary trends from the Neolithic to the Iron Age, observed from stable carbon and nitrogen isotope data extracted from human, animal and vegetal remains. With this work, we aim to collate published isotopic data available for Italy in Later Prehistory to obtain a comprehensive picture of food practices in the Peninsula. By exploring the isotopic record over the course of several millennia, we plan to better define the relationship between past populations and their surrounding environment while highlighting possible trends in the reliance on specific resources. As environmental constraints should not be considered the only driving force for change in food practices, we aim to understand the extent to which cultural phenomena have, in fact, influenced past foodways.

To do so, we divide the time range under analysis into macro-phases common to European Prehistory. Parkinson and colleagues provide in-depth analysis and chronological review of cultural phases in Italy during Later Prehistory (Parkinson et al., 2021), while Palmisano and colleagues' work (Palmisano et al., 2021) provides demographic and climatic information on the Peninsula from the Late Mesolithic to the Iron Age.

In brief, Italian Later Prehistory can be broadly divided into four phases.

- **Neolithic**: it started in the 6th millennium BCE with the introduction of agriculture in Southeast Italy, where the earliest evidence of Impressed Ware can be found (Binder et al., 2017; Cassano and Manfredini, 1987). It gradually spread throughout the Peninsula, with different speeds on the Adriatic and Tyrrhenian coasts, arriving in Northern Italy and Sardinia by the 5th millennium BCE. The difference in the diffusion rate created distinct, regionally codified cultures visible in the archaeological record (Palmisano et al., 2021; Parkinson et al., 2021; Starnini et al., 2018). The Neolithic occurred during a period of favourable climatic conditions that, together with the spread of farming, were probably responsible for an increase in human population size and settlement density (Palmisano et al., 2021; Fiorentino et al., 2013), with 774 sites identified in the Tavoliere region of Apulia alone (Hamilton and Whitehouse, 2020; Seager Thomas, 2020). The current state of archaeological research supports a mixed economy of farming and hunting (Robb, 2007). Despite the high number of settlements recorded during the Neolithic, arboreal pollen records suggest a limited anthropogenic

impact on the natural landscape (Magri et al., 2015; Palmisano et al., 2021).

- **Copper Age** (also known as "Chalcolithic" or "Eneolithic"; Pearce, 2019): dated between the fourth and third millennium BCE, the Copper Age period in Italy lacks a comprehensive settlement record. However, the number of cemeteries found in the Peninsula suggests an increase in population size during this period (Negroni Catacchio, 2006; Negroni Catacchio et al., 2016). Regarding cemeteries, these millennia are characterised by the introduction of places exclusively devoted to the burial of individuals, which were re-used over an extended period of time (Cocchi Genick, 2009). Grave goods deposited in natural or artificial caves, such as rock-cut tombs, were often not associated with single individuals but rather represented a symbol of the social organisation of the communities (Dolfini, 2015). During the Copper Age, several technological innovations were introduced: the plough, the wheel and the wagon, as well as the improvement of metalworking technologies and the production and circulation of lithic products (Cocchi Genick, 2009, 2011; Conati Barbaro et al., 2010; Jones, 2008). Evidence of occupation of upland areas during this period can be connected to both increasing pastoralism and a general tendency to monitor exchange routes, with differences among the settlements indicating differences in community organisation. In fact, inequality in access to materials, such as metal objects, could have implied an imbalance in the distribution of resources (Cocchi Genick, 2009). Anthropogenic impact on the environment still looks low, but it is more prominent than in the Neolithic due to the diffused pastoral and quarrying activities carried out throughout the Peninsula (Magri et al., 2015; Palmisano et al., 2021).

- **Bronze Age**: it spanned from the second half of the third millennium BCE to the beginning of the first millennium BCE. The Italian Bronze Age is characterised by several different cultural expressions (Bietti Sestieri, 2010). Lake settlements punctuated the northern regions during the Polada and Terramara cultures, showing similarities with central Europe (Barfield, 1994). Terramara sites, in particular, show monumental structures connected to defence and economic purposes. Central Italy shows signs of social and political complexity and cultural homogeneity, underlined by a general growth in population and settlement size during the Bronze Age (Bietti Sestieri, 2010). Southern Italy, on the other hand, shows marked heterogeneity in material culture, with small communities centred around agriculture and pastoralism. However, monumental sites are present in these regions as well, in coastal areas and along communication routes (Bietti Sestieri, 2010; Cazzella and Recchia, 2013, 2017; Scarano, 2011). During the Bronze Age, people exploited a wide range of resources and landscapes through intensive animal farming, with evidence of a strong reliance on secondary products such as wool and milk (which began already during the Copper Age; Dolfini, 2020). Central and Southern Italy show a strong reliance on caprines and less on cattle, while several differences are visible in the northern area. The cereal species introduced with the "Neolithic package" were still the most exploited crops - mostly barley and wheat. However, the Bronze Age also saw the introduction of new crops, especially millets (*Panicum miliaceum* and *Setaria italica*), characterised by a C$_4$ pathway, in Northern Italy (Tafuri et al., 2009, 2018; Carra, 2012; Varalli et al., 2022). This farming system impacted the natural environment to an unprecedented extent (Cremaschi et al., 2016; Mercuri and Sadori, 2012), probably inducing strong demographic growth (Palmisano et al., 2021).

- **Iron Age**: after the cultural homogeneity of the Final Bronze Age, the centuries from 1000 to 600 BCE show a complex patchwork of traditions. Together with the many indigenous peoples, a strong presence of external cultures is visible during these centuries: Phoenicians and Greeks in the south and Etruria (Bietti Sestieri, 2010; Sestieri, 1997) and Gauls in the north (Briggs, 2003). More broadly, evidence of long-distance trade is widespread throughout

the Peninsula, with a general economic and technological development and a strong reliance on metal objects. The need to control metal procurement, production and diffusion probably triggered a more structured political system, together with isolated and nucleated settlements located in naturally defended areas from which trade routes were controlled (Sestieri, 1997). A more substantial anthropogenic influence is visible in this period, with many forests replaced by pasture lands (especially in Northern Italy) and a spike in olive (*Olea*) cultivation in Central and Southern Italy (Magri et al., 2015; Mercuri et al., 2013).

1.3. Isotopic analysis in prehistoric Italy

The study of human remains is among the most direct ways to investigate past people's lifestyles and food practices, as the skeleton preserves signs of what happened in life. Since 1977 (Vogel and Van Der Merwe, 1977), dietary practices have been routinely investigated by applying stable isotope analysis, carbon (δ^{13}C) and nitrogen (δ^{15}N) especially, to skeletal remains (Roberts et al., 2018). Bone collagen, in fact, reflects dietary protein intake in the last decade of life (although discussion around turnover rates is still ongoing; Hedges, 2002), while collagen extracted from teeth reflects protein intake in the first years of life (AlQahtani et al., 2010) and can, therefore, reflect higher nitrogen ratios due to breastfeeding (Beaumont et al., 2018). By comparing isotopic values from human material with those from environmental proxies (animals and plants), we can infer what constituted the protein portion of the diet of ancient populations and which economic strategies were put in place. In fact, carbon and nitrogen isotopes fractionate during their cycles and such fractionations can be reconducted to specific dietary niches (Van Klinken et al., 2002; White, 2020). For instance, photosynthetic fractionation of carbon results in discrimination between C$_3$ ($-37‰ \leq \delta^{13}$C $\leq -20‰$, noting that modern data may influence this data as atmospheric δ^{13}CO$_2$ values varied over the past centuries; Kohn, 2010) and C$_4$ ($-12‰ \leq \delta^{13}$C $\leq -16‰$) plants (O'Leary, 1988). While terrestrial plants use CO$_2$ alone for their photosynthetic processes, aquatic plants instead use both CO$_2$ and HCO$_3^-$ and, therefore, show lower fractionation levels (White, 2020). No standard ranges are available for nitrogen values in plants. Archaeologically, as visible from the plant dataset published in the Mediterranean Archive of Isotopic dAta (Farese et al., 2023a), we observe a $-32.20 \leq \delta^{13}$C ≤ -18.50 range ($-23.18 \pm 2.98‰$) and a $-4.73 \leq \delta^{15}$N ≤ 16.30 range ($3.24 \pm 2.99‰$) for C$_3$ plants in the Mediterranean basin.

Along the food chain, more fractionation processes are prompted by animal and human metabolism. This results in higher isotopic signatures for carbon and nitrogen, also referred to as "trophic level effect" (Schwarcz and Schoeninger, 2012). Thanks to these fractionations, we can retrace ancient food choices. In particular, the enrichment between diet and consumer for stable carbon isotopes has been calculated to be 0.5–7.5‰ (Ambrose and Norr, 1993; Hare et al., 1991; Tieszen and Fagre, 1993; Warinner and Tuross, 2009). Stable nitrogen isotopes, instead, present a 3–5‰ enrichment (Hedges and Reynard, 2007), although experiments on modern humans suggest that it can reach a diet to consumer tissue offset of 6‰ (O'Connell et al., 2012).

As human and animal remains undergo several modifications after their deposition, also influenced by the climatic conditions of the surrounding environment (Hedges et al., 2004; White and Hannus, 1983; Kohn et al., 1999; DeNiro, 1985; Ambrose and DeNiro, 1986; Grupe and Piepenbrink, 1987; Nielsen-Marsh and Hedges, 2000; Nielsen-Marsh et al., 2007), quality criteria are in place to ensure that the isotopic signal observed in archaeological bones and teeth is endogenous and not a result of diagenesis (Ambrose, 1990; DeNiro and Epstein, 1978). Among the most commonly used, we report those adopted in this study: $2.9 \leq$ C:N ≤ 3.6, $13\% \leq \%$C $\leq 47\%$, $4.8 \leq \%$N ≤ 17.3 and collagen yield $>0.9 \%$ (Ambrose, 1990).

Stable isotope analysis has been extensively applied to the Italian Later Prehistory, as it can be used to investigate several cultural and economic questions. Dietary studies can help shed light, for instance, on how communities reacted to the introduction of agriculture (Lelli et al., 2012; Scorrano et al., 2019) and new crops (Laffranchi et al., 2016; Tafuri et al., 2009), the extent to which climatic conditions influenced subsistence practices (Mannino et al., 2015) and the possible impact of social complexity on food practices (Varalli et al., 2016; Bernardini et al., 2021). Several studies on Later Prehistory in Italy are available, most of which were collated in MAIA, the "Mediterranean Archive of Isotopic dAta" (Farese et al., 2023a, 2023b). Fig. 1 shows the geographical distribution of archaeological sites whose stable carbon and nitrogen isotopes have been included in this study. A total of 111 sites were investigated: 41 with only human data, 8 with only animal data, 3 with only plant data, 58 with animal and human data and 1 with human, animal and plant data. References for each site are included in Supplementary Data 1. Each study only focused on a restricted period or area, while our study aims to reconstruct the larger picture of prehistoric Italy.

2. Materials and methods

A total of 38 publications, collated in the Mediterranean Archive of Isotopic dAta (Farese et al., 2023a, 2023b), have been included in this study. Carbon and nitrogen isotopic data from 776 humans, 373 terrestrial animals, 9 aquatic animals and 432 C$_3$ plants have been included. No C$_4$ plant isotopic data are available for prehistoric Italy. A comprehensive list is available as a supplementary file (Supplementary Data 2). The MAIA dataset has been filtered to keep all samples from Italy, dated between 6000 BCE and 0, that present both δ^{13}C and δ^{15}N values. Dates are based on both calibrated and relative dates, as ^{14}C dates are available for 139 out of 1590 entries only.

Regarding humans, we only kept data from adult (>18 years old) individuals. Data obtained from subadult material, as well as teeth, have been excluded as they can present a ^{15}N enrichment due to breastfeeding (Beaumont et al., 2018). Regarding animals, we excluded samples for which no trophic or species information was available (in the "Domesticated" and "Trophic_Category" columns of the MAIA dataset). No incremental dentine data was included as this would provide several data for one individual and, therefore, alter the results.

Both animal and human data have been filtered to remove samples outside the quality criteria described by Ambrose (1990) and previously mentioned.

Statistical tests (descriptive statistics, variance, Wilcoxon rank-sum tests and T-tests) have been conducted using R (v. 2023.03.1; R Core Team, 2023) and the pairwiseAdonis (Martinez Arbizu, 2017), tidyverse (Wickham et al., 2019) and vegan (Oksanen et al., 2022) packages. Every mean reported has a 1 standard deviation (SD) associated. Maps and plots have been created using the ggplot2 (Wickham, 2016), rnaturalearth (Massicotte and South, 2023) and rnaturalearthdata (South, 2017) packages in R. To visualise isotopic data on a continuous time-scale, we created LOESS plots in R, setting the smoothing span to 0.85.

Bayesian maps to explore geographical variability have been created using the AverageR (Cubas et al., 2020) modelling tool available on the open-access online application IsoMemo (v. 23.12.0.2, https://isomemo app.com/app/iso-memo-app). Default parameters have been used, except for: "smooth type" set to "planar", "number of basis functions" set to 250 and "extrapolation behaviour" set to "constant". A Bayesian model has been chosen, with the "Number of MCMC iterations" set to 5000 and the "Number of burn-in iterations" set to 1000. The mask radius has been set to 100 km. As AverageR requires at least four unique pairs of geographical coordinates, we have not been able to produce a Bayesian map for the Iron Age period, for which data from only three archaeological sites is available.

To estimate the caloric contribution of terrestrial animals to the diet of the humans under study and to observe how it varied through time and space, we used an open-access concentration-dependent Bayesian mixing model, ReSources (v. 23.12.1, https://isomemoapp.com/app/
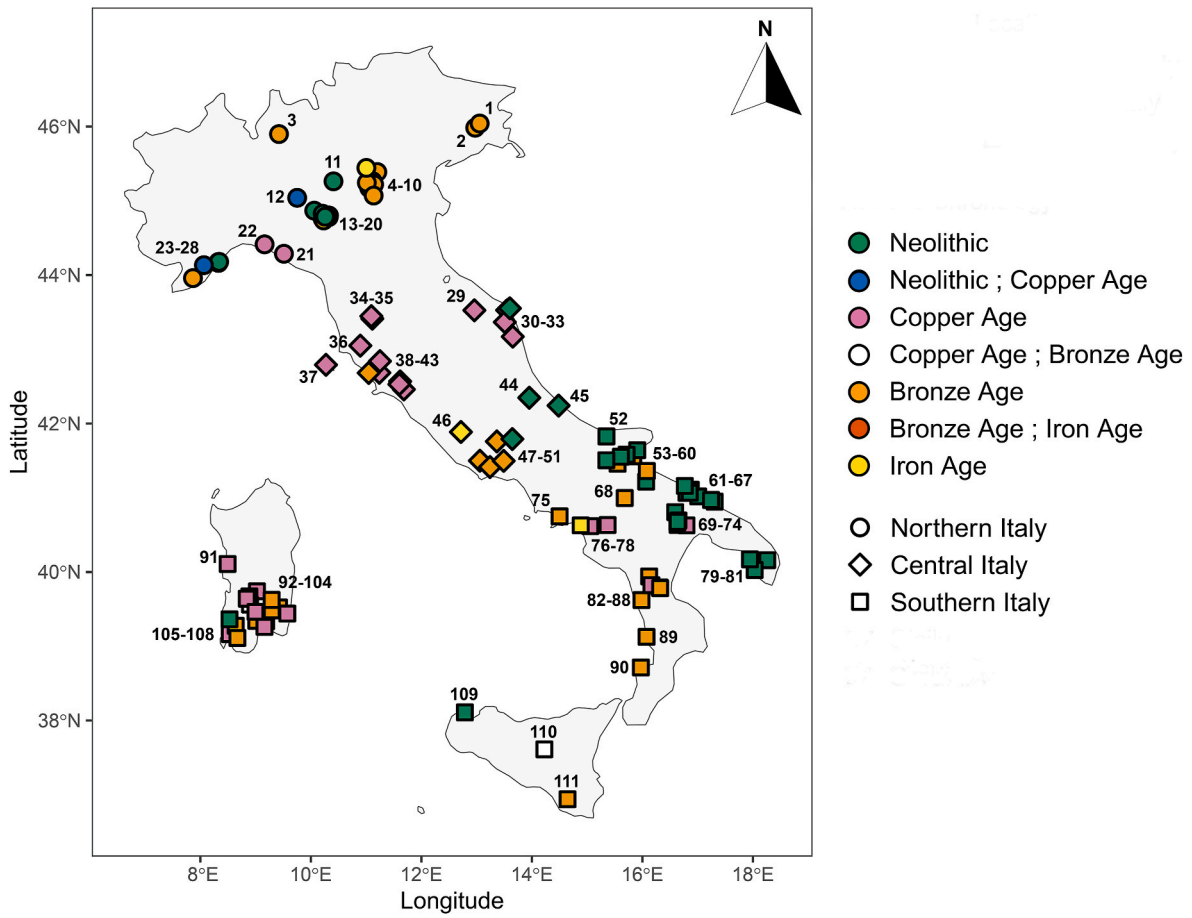
Fig. 1. Map showing the locations of Italian sites with available $\delta^{13}C$ and $\delta^{15}N$ data used in this study. Different colours represent different relative chronologies, from the Neolithic to the Iron Age, and different shapes represent different geographical locations. The numbers correspond to the archaeological sites in Supplementary Data 1 and 2.

resources (Sołtysiak and Fernandes, 2021). We included isotopic data for C_3 cereals and terrestrial animals. We used terrestrial animal data coeval with the human datasets for the Neolithic, Copper Age, Bronze Age and Iron Age. To account for the lack of botanical data in the Neolithic period, we included coeval $\delta^{13}C$ and $\delta^{15}N$ values from Greece (Bogaard et al., 2013; Isaakidou et al., 2022; Vaiglova et al., 2014, 2018, 2020, 2023) (Supplementary Data 3). The uncertainties associated with the source values correspond to 1SD. To account for the diet to consumer enrichment, the $\Delta^{13}C_{collagen-diet}$ offset was set to +4.8 ± 0.5‰, with a 74 ± 4% contribution from protein and a 26 ± 4% contribution from lipids and -carbohydrates, while the $\Delta^{15}N_{collagen-diet}$ offset was set to +5.5 ± 0.5‰, with a 100% contribution from proteins (Fernandes, 2016). Concentrations were calculated using the following offsets: for plants, $\Delta^{13}C_{protein-bulk} = -2‰$, $\Delta^{13}C_{carbohydrates-bulk} = +0.5‰$ and $\Delta^{15}N_{protein-bulk} = 0‰$, for terrestrial animals, $\Delta^{13}C_{protein-collagen} = -2‰$, $\Delta^{13}C_{lipids-collagen} = -8‰$ and $\Delta^{15}N_{protein-collagen} = 0‰$, and for marine and freshwater animals, $\Delta^{13}C_{protein-collagen} = -1‰$, $\Delta^{13}C_{lipids-collagen} = -7‰$ and $\Delta^{15}N_{protein-collagen} = +1.5‰$ (Soncin et al., 2021). ReSources was run using default parameters, except for: "model type" set to Individual targets (no shared info), the "include components" option selected, "optimal objective prior" deselected and "covariates model" set to "fixed intercept (cat. vars), fixed slope (num. vars)" (Tafuri et al., 2023).

Given the scarce evidence for fish consumption in Italy (Lightfoot et al., 2011; Lubell et al., 1994; Papathanasiou, 2003; Tafuri et al., 2023) and the lack of a reliable local baseline, we did not include freshwater and marine fish data when running this mixing model with ReSources. However, a test run using data from the literature (Garcia-Guixé et al., 2010; Salazar García, 2011; Lelli et al., 2012; Vika and Theodoropoulou,

2012) has been included as a supplementary file (Supplementary Data 4).

3. Results

Supplementary Data 2 shows the subsetted MAIA dataset used in this study, for a total of 776 humans ($\delta^{13}C$ of −18.77 ± 2.13‰, $\delta^{15}N$ of 8.98 ± 1.19‰), 373 terrestrial animals ($\delta^{13}C$ of −20.18 ± 1.46‰, $\delta^{15}N$ of 5.69 ± 1.78‰), 9 aquatic animals ($\delta^{13}C$ of −14.43 ± 5.90‰, $\delta^{15}N$ of 9.13 ± 2.62‰) and 432 C_3 plants ($\delta^{13}C$ of −23.62 ± 1.06‰, $\delta^{15}N$ of 2.08 ± 2.01‰). 32 out of the total C_3 plants available are pulses of the *Vicia* genus (Supplementary Data 2); however, their nitrogen values do not show a statistically significant difference from the other plant remains in the dataset (Supplementary Data 5). Table 1 summarises the human, animal and plant data divided by chronological periods, while more detailed descriptive statistics divided into Southern, Central and Northern Italy are available in Supplementary Data 6. Regarding the human dataset, the Copper Age presents the highest mean nitrogen values and the Iron Age the highest mean carbon values (Table 1).

Fig. 2a shows the distribution of carbon and nitrogen data for the Neolithic period, with 151 humans (from 33 sites), 98 terrestrial animals (from 21 sites) and 6 marine fish (from 1 site). The terrestrial animals have a mean $\delta^{13}C$ of −19.86 ± 2.55‰ and a mean $\delta^{15}N$ of 6.01 ± 1.92‰. The marine animals have a mean $\delta^{13}C$ of −10.33 ± 0.50‰ and a mean $\delta^{15}N$ of 8.42 ± 2.60‰. The humans show a mean value of −19.96 ± 0.73‰ for $\delta^{13}C$ and 8.86 ± 0.88‰ for $\delta^{15}N$ (Table 1).

For the Copper Age period (Figs. 2b), 183 humans (from 25 sites), 96 terrestrial animals (from 12 sites) and 20 C_3 plants (from two sites) have

Table 1

Descriptive statistics of the human, animal and plant data divided by chronological period.

Species	Period	n°	Mean δ^{13}C	1SD δ^{13}C	Min δ^{13}C	Max δ^{13}C	Median δ^{13}C	Mean δ^{15}N	1SD δ^{15}N	Min δ^{15}N	Max δ^{15}N	Median δ^{15}N
Human	Neolithic	151	−19.96	0.73	−22.00	−18.20	−19.90	8.86	0.88	6.90	11.77	8.80
Human	Copper Age	183	−19.87	0.64	−21.30	−17.50	−20.00	9.38	1.25	6.00	13.10	9.40
Human	Bronze Age	318	−18.77	1.85	−20.90	−12.50	−19.25	8.89	1.38	3.70	12.30	8.70
Human	Iron Age	124	−15.72	2.38	−21.20	−11.60	−15.68	8.77	0.70	6.90	10.20	8.76
Domesticated Herbivore	Neolithic	61	−20.21	1.10	−23.93	−16.70	−20.30	5.99	1.81	3.20	11.70	5.80
Domesticated Herbivore	Copper Age	61	−20.49	0.69	−21.90	−18.60	−20.50	5.89	1.89	2.80	9.95	5.30
Domesticated Herbivore	Bronze Age	96	−20.08	1.32	−22.50	−14.90	−20.42	5.13	1.58	1.90	9.00	4.95
Domesticated Omnivore	Neolithic	22	−20.75	0.50	−21.80	−19.74	−20.80	6.22	1.58	3.60	9.40	6.25
Domesticated Omnivore	Copper Age	15	−20.63	0.82	−21.60	−19.30	−21.00	5.69	1.75	3.00	10.30	5.30
Domesticated Omnivore	Bronze Age	55	−19.30	2.58	−21.70	−11.00	−20.37	6.01	1.67	2.90	9.70	5.80
Domesticated Omnivore	Iron Age	4	−20.25	1.01	−21.30	−19.00	−20.35	6.35	1.18	5.50	8.00	5.95
Wild Herbivore	Neolithic	13	−21.11	0.61	−22.40	−20.30	−21.10	4.69	1.32	3.35	8.68	4.30
Wild Herbivore	Copper Age	10	−21.64	0.42	−22.40	−20.60	−21.60	4.63	1.53	2.70	8.40	4.50
Wild Herbivore	Bronze Age	21	−20.25	1.16	−22.40	−17.40	−20.47	5.03	1.58	1.40	8.50	4.90
Wild Omnivore	Neolithic	2	−20.05	0.55	−20.60	−19.50	−20.05	5.75	1.65	4.10	7.40	5.75
Wild Omnivore	Copper Age	10	−19.47	0.81	−21.00	−18.50	−19.20	7.80	1.53	3.90	9.60	8.05
Wild Omnivore	Bronze Age	3	−19.50	0.71	−20.50	−19.00	−19.00	7.73	0.21	7.50	8.00	7.70
Marine Fish	Neolithic	6	−10.33	0.50	−11.00	−9.60	−10.40	8.42	2.60	3.60	10.90	9.75
Freshwater Fish	Bronze Age	3	−22.63	1.72	−24.70	−20.50	−22.70	10.57	2.00	7.90	12.70	11.10
C$_3$ Plant	Copper Age	20	−24.13	2.29	−30.80	−20.30	−24.60	3.12	2.81	−0.90	7.90	1.70
C$_3$ Plant	Bronze Age	50	−24.03	1.25	−27.40	−20.40	−24.00	3.28	2.74	0.10	9.90	2.05
C$_3$ Plant	Iron Age	362	−23.53	0.89	−25.70	−20.80	−23.60	1.86	1.74	−4.20	8.40	1.65

n = number of isotopic data. SD = standard deviation.

been analysed (Table 1).

Terrestrial animals have a mean δ^{13}C of −20.52 ± 0.86‰ and a mean δ^{15}N of 5.93 ± 1.94‰. The humans show a mean value of −19.87 ± 0.64‰ for δ^{13}C and 9.38 ± 1.25‰ for δ^{15}N. C$_3$ plants have a mean δ^{13}C of −24.13 ± 2.29‰ and a mean δ^{15}N of 3.12 ± 2.81‰. As reported in Table 2, this period shows the lowest variability in terms of human carbon values.

The Bronze Age (Fig. 2c) has the most extensive body of data in this study, with 318 human data (from 34 sites), 175 terrestrial animals (from 21 sites), 3 freshwater fish (from one site) and 50 plant data (from two sites).

The terrestrial animals have a mean δ^{13}C of −19.85 ± 1.84‰ and a mean δ^{15}N of 5.44 ± 1.67‰. The freshwater animals show a mean δ^{13}C of −22.63 ± 1.72‰ and a mean δ^{15}N of 10.57 ± 2.00‰. C$_3$ plants have a mean δ^{13}C of −24.03 ± 1.25‰ and a mean δ^{15}N of 3.28 ± 2.74‰. The humans show a mean value of −18.77 ± 1.85‰ for δ^{13}C and 8.89 ± 1.38‰ for δ^{15}N. This period shows the highest variability for human nitrogen values (Fig. 2 and Table 2).

For the Iron Age (Fig. 2d), the period with the lowest amount of human data analysed, we used data from 124 humans (from three sites) and 362 C$_3$ plants (from one site). Only 4 terrestrial animals from one site are available.

C$_3$ plants have a mean δ^{13}C of −23.53 ± 0.89‰ and a mean δ^{15}N of 1.86 ± 1.79‰. The humans have a mean δ^{13}C of −15.72 ± 2.38‰ and a mean δ^{15}N of 8.77 ± 0.70‰ (Table 1). Terrestrial animals have a mean δ^{13}C of −20.25 ± 1.01‰ and a mean δ^{15}N of 6.35 ± 1.18‰. As shown in Fig. 2 and reported in Table 2, this period shows the highest variability

in human carbon values and the lowest for nitrogen values.

4. Discussion

By collating more than 700 human isotopic data (Supplementary Data 2), our study provides a review of subsistence practices in Italy between the Neolithic and Iron Age.

A preliminary investigation has been conducted to analyse the extent to which the isotopic signal is linked to dietary choices and how much is instead influenced by environmental factors. Aridity levels and temperatures can influence carbon and nitrogen fractionations, reflecting higher or lower isotopic ratios depending on the surrounding ecosystem (Hedges et al., 2004; Nielsen-Marsh et al., 2007; Nielsen-Marsh and Hedges, 2000). However, no high-resolution evidence is available to take into account the different precipitation and temperature estimates for all the sites included in this study, with only some exceptions available (e.g. Fiorentino et al., 2013).

Therefore, by comparing isotopic data between humans, terrestrial animals and plants, we can test for environmental impact on the isotopic signal, since we can assume that the animals would mirror the local ecosystem, which is directly influenced by climatic and environmental factors (Parkinson et al., 2023). For this analysis, we included both wild and domesticated animals, as not enough isotopic evidence was available from wild animals alone to fully explore the dataset; moreover, the two groups present statistically similar isotopic data (Wilcoxon rank-sum test, *p* value = 0.06884 and W = 10646 for δ^{13}C and *p* value = 0.3613 and W = 9957 for δ^{15}N). We employed a locally estimated
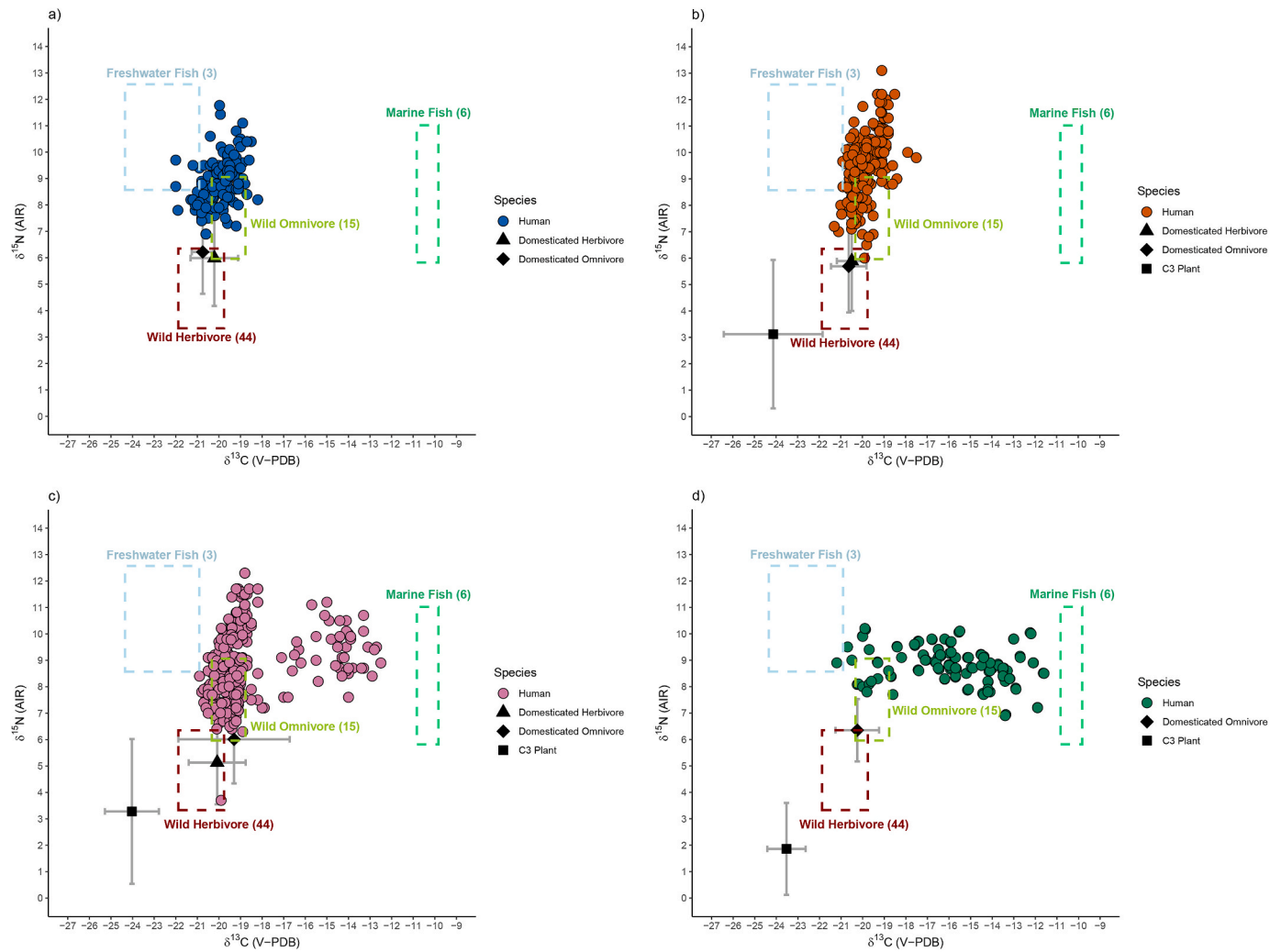
Fig. 2. Neolithic (**a**), Copper Age (**b**), Bronze Age (**c**) and Iron Age (**d**) human, animal and plant δ^{13}C and δ^{15}N data for Italy. Bars represent 1SD. Rectangles represent mean $\pm$ 1SD for collagen isotopic data used across all time periods.

Table 2
Variance matrix for human δ^{13}C and δ^{15}N values according to chronological periods.

Period	Variance in δ^{13}C values	Variance in δ^{15}N values
Neolithic	0.542	0.773
Copper Age	0.410	1.559
Bronze Age	3.421	1.918
Iron Age	5.683	0.484

scatterplot smoothing (LOESS) of the isotopic data, with no assumption about the underlying structure of the data (Fig. 3). We can, therefore, observe isotopic curves and how they vary in time between humans, animals and plants. Human and animal trends shown in Fig. 3 differ from each other, suggesting that the human isotopic signal available for prehistoric Italy represents dietary choices and is not a mere reflection of the environment people lived in. The human dataset is characterised by a nitrogen signal consistent with a terrestrial diet. The slight increase in human δ^{15}N values towards the third millennium BCE in Central and Southern Italy, highlighted by the LOESS regression and independent from the animal signal particularly for Southern Italy (Fig. 3), might be explained by the introduction or intensification of secondary product use (Dolfini, 2020), as displayed by the Wilcoxon rank-sum test (Supplementary Data 7). Human δ^{13}C values, on the other hand, are relatively stable until 2000 BCE, when the isotopic signal increases

significantly for Northern Italy at the beginning of the second millennium BCE when millets were presumably introduced (Tafuri et al., 2009, 2018; Varalli et al., 2022). This increase is not visible in the animal dataset, suggesting that millets were almost exclusively adopted for human subsistence rather than being the result of the consumption of animals fed with C_4 plants. The restricted quantity of plant samples, instead, does not allow for an interpretation of the data. However, we notice variation in the nitrogen values of plant data, which cannot be explained through diagenetic alteration (no strong correlation is found in this dataset between C:N ratios and δ^{15}N values, $R^2 = 0.1303$, and between %N and δ^{15}N values, $R^2 = 0.0160$; after Szpak and Chiou, 2020), further, such variation is observed in plants (Bogaard et al., 2007, 2013) often as a reflection of differences in crop management.

When comparing Later Prehistory periods in pairs, using a Wilcoxon rank-sum test (Supplementary Data 7), we can observe significant differences (p value < 0.05) in carbon values across all periods, except for the Neolithic-Copper Age comparison. This suggests that similar typologies of plants (with a C_3 pathway) were consumed in the Peninsula before the introduction of new crops. With the Bronze Age and the introduction of millets, δ^{13}C values spiked as people in northern regions were consuming more ^{13}C enriched crops. Nitrogen values, instead, are statistically similar (Wilcoxon rank-sum test, p value < 0.05; Supplementary Data 7) across all of Later Prehistory in Italy, except for the Copper Age, possibly because, as previously suggested, people were relying on a wider selection of animal resources, such as secondary
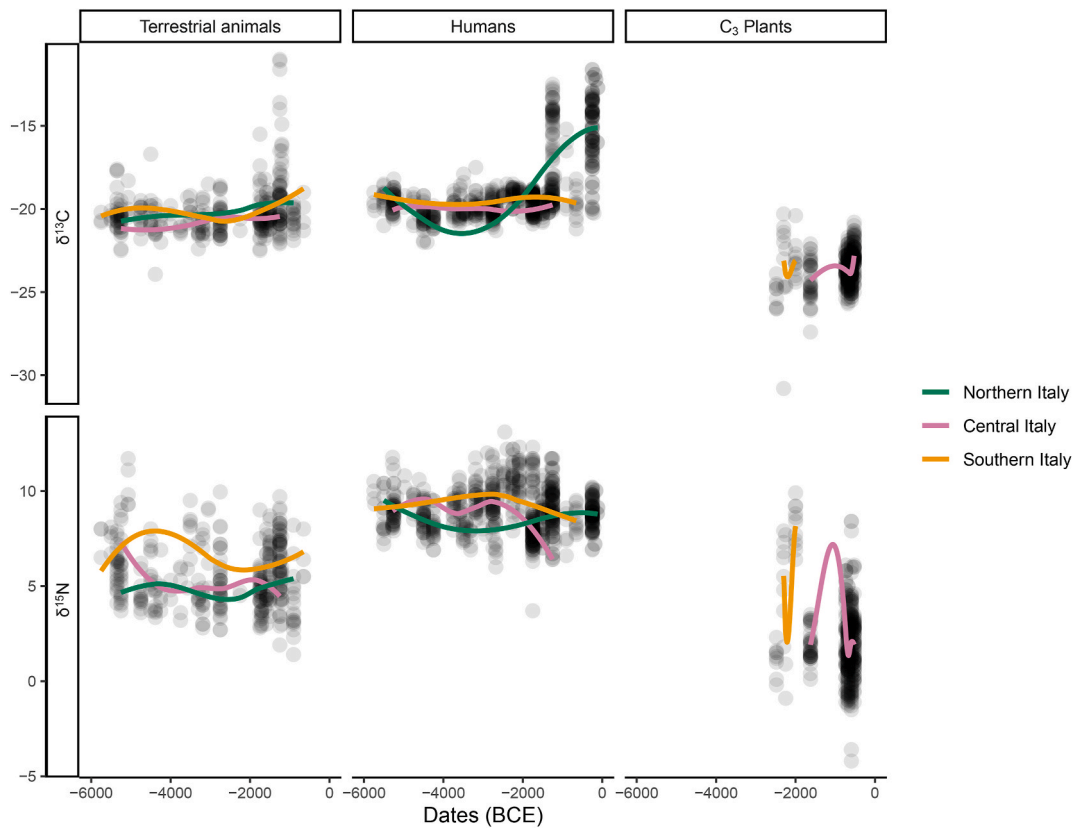
Fig. 3. LOESS plot showing variations in $\delta^{13}C$ and $\delta^{15}N$ for humans, (wild and domesticated, omnivore and herbivore) terrestrial animals and C_3 plants according to time (BCE) and geographical position. The x-axis has been built from calibrated dates (when available) and inferred chronological attributions calculated as a mean value of the overall range (when ^{14}C dates were not provided in the original text).

products (Dolfini, 2020).

A more detailed analysis of each archaeological period is presented hereafter, aided by a Bayesian approach to visualise the geographical variability of dietary choices that characterised the Italian Peninsula during Later Prehistory, obtained using the AverageR tool available in IsoMemo (Cubas et al., 2020). Different scales are used in the maps (Figs. 4–6) in order to better visualise isotopic variations in each specific period. The data discussed hereafter mirrors the history of research in Italy and is naturally subject to gaps either in geographical or chronological terms.

In the Neolithic, we observe a clustering of the isotopic data (Fig. 2a) consistent with the idea of a "Neolithic package" being introduced and adopted throughout the Peninsula. Subsistence strategies focused on C_3 plants and terrestrial resources, with probably very limited consumption of aquatic species. Fish consumption has been scarcely observed in Italy, and more broadly in the Mediterranean, even when studying coastal populations (Lightfoot et al., 2011; Lubell et al., 1994; Papathanasiou, 2003; Tafuri et al., 2023). Several explanations for this evidence have been proposed, among which the hypothesis that fishing was only employed once terrestrial resources were low due to the high energetic demand of the activity and the greater risks implied (Galili et al., 2004). Moreover, it has been found that fish in the Mediterranean Sea present less enriched nitrogen values compared to the Atlantic Ocean (Craig et al., 2013; Cubas et al., 2019), which could make marine fish "invisible" when using stable nitrogen isotopes. It was also noted that much of the Mediterranean coast was characterised by marshy lagoons and, therefore, the fish living in their proximity most likely exhibited a mixed freshwater-marine signal, which is similar to the terrestrial one, making it difficult to detect its consumption (Tafuri et al., 2023). Regarding

animal management, we observe higher variation in the domesticated herbivores (e.g. *Bos taurus*, *Ovis/Capra*) as opposed to the domesticated omnivores (e.g. *Sus scrofa*) (Fig. 2a), suggesting a more closely supervised feeding strategy for the latter, while herbivores were possibly still left free to roam a wider environment and were therefore feeding on a variety of plants. Earlier studies show more variability for omnivores than herbivores (Zavodny et al., 2014, 2015), however, they only focused on samples from South-Eastern Italy. This dataset instead includes animal samples from the Tyrrhenian coast as well.

A general similarity in isotopic patterns between humans and terrestrial animals can be inferred from the Bayesian model (Fig. 4). This trend mostly follows a latitudinal gradient, with lower carbon and nitrogen values in Northern Italy and higher values in the south (Supplementary Data 8). Therefore, this isotopic pattern can be attributed to environmental factors rather than dietary and organisational choices made by the communities for themselves or the animals they were farming. Such a broad approach, like Bayesian modelling, can hide more nuanced patterns that are only visible when analysing single sites. However, it allows us to observe larger and more widely applicable phenomena. Most notably, from both the latitudinal gradient in the model (Fig. 4; Supplementary Data 8) and the narrow distribution of nitrogen values for humans in the scatter plot (Fig. 2a), we can note the strong reliance that Neolithic communities had on their natural surroundings, with no evidence of a systematic application of farming techniques (such as manuring or irrigation) that could otherwise mask the latitudinal gradient and increase the variability of isotopic data. The Neolithic also shows the lowest variance (Table 2) for $\delta^{15}N$, if we exclude the Iron Age, whose scarcity of data does not allow for an unbiased comparison.
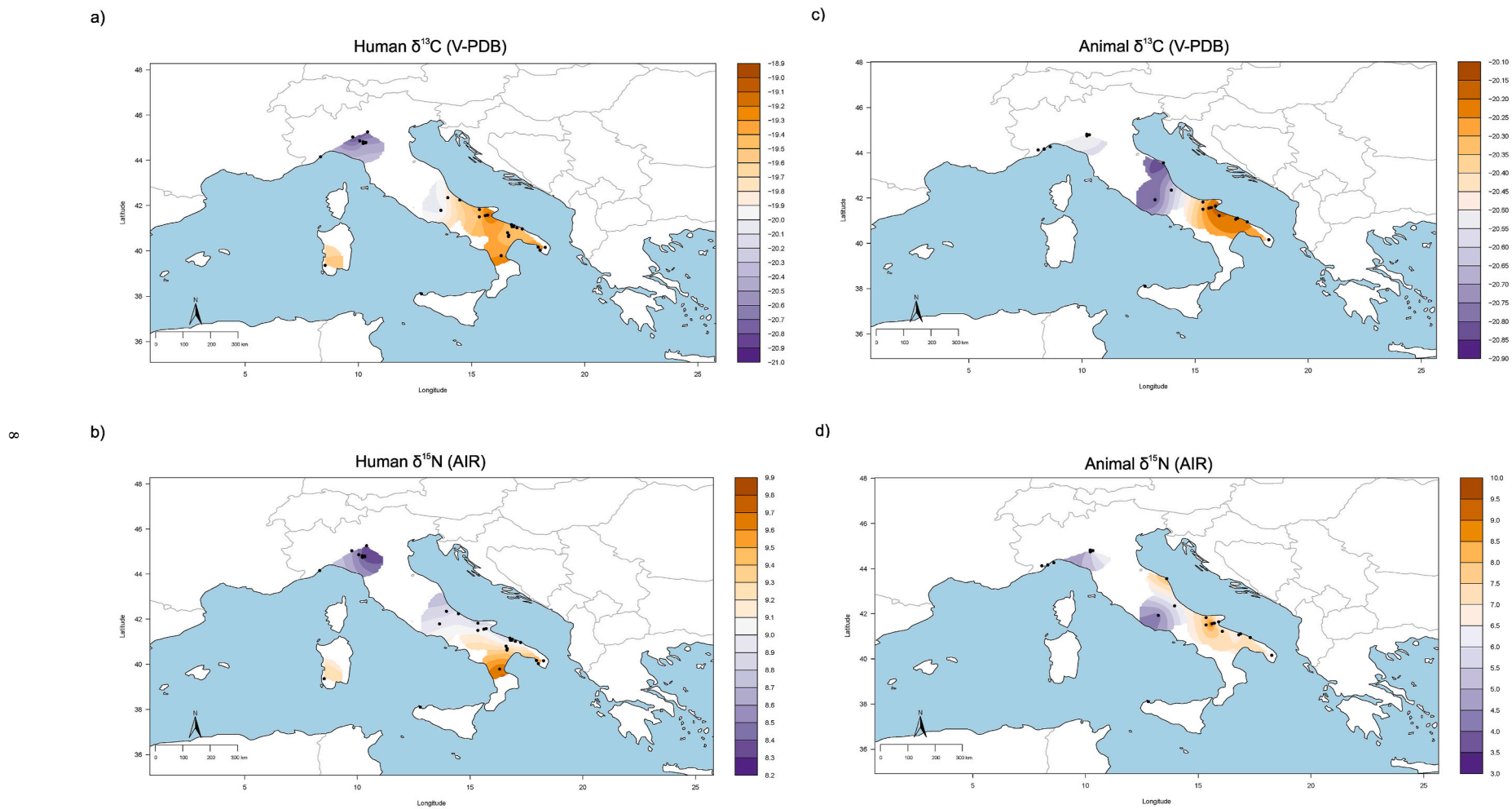
Fig. 4. Bayesian maps showing the distribution of δ^{13}C (**a,c**) and δ^{15}N (**b,d**) in humans (**a,b**) and terrestrial animals (**c,d**) for the Neolithic period. The maps were created using the AverageR tool in IsoMemo (Cubas et al., 2020).
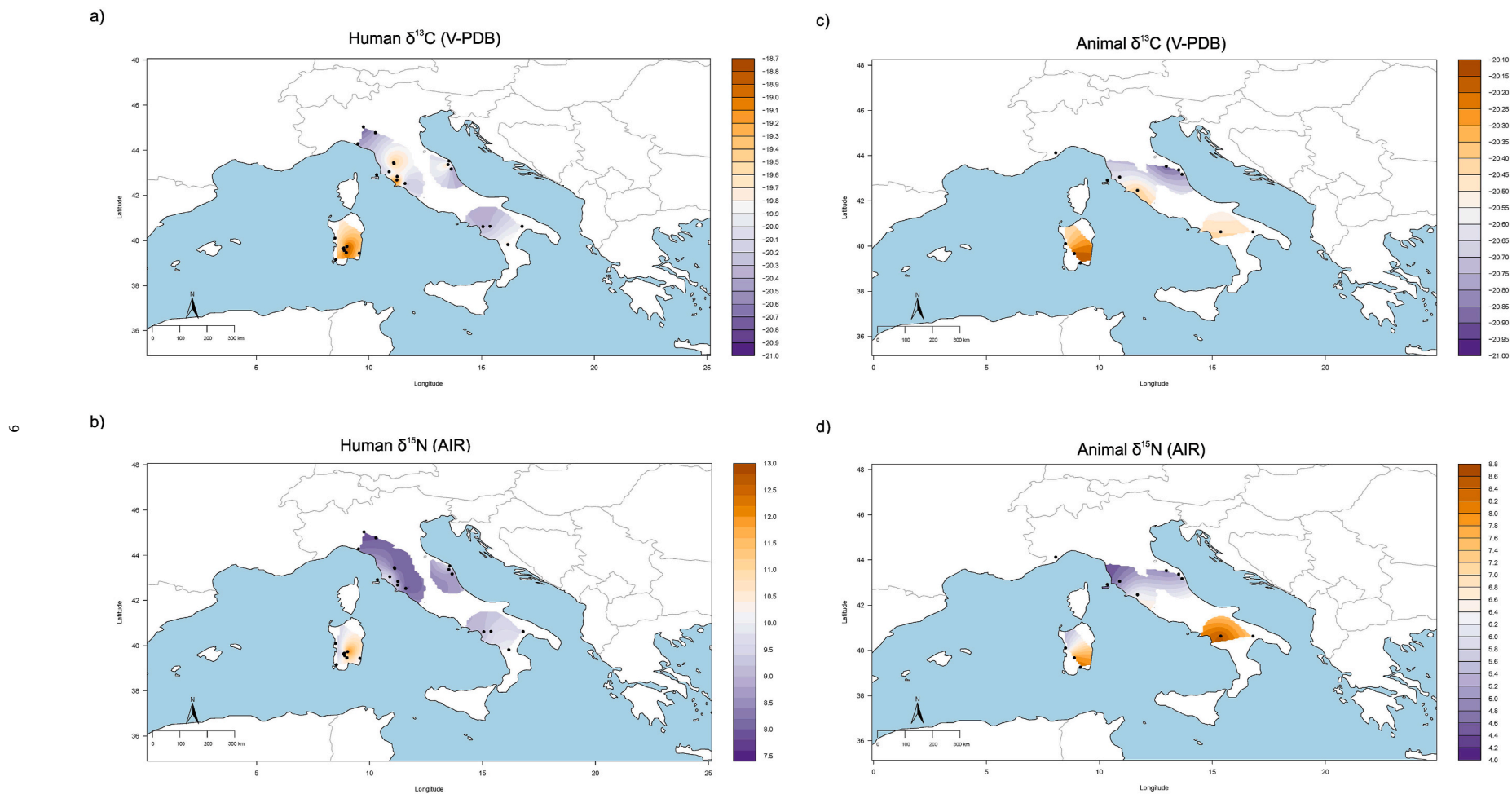
Fig. 5. Bayesian maps showing the distribution of δ^{13}C (**a,c**) and δ^{15}N (**b,d**) in humans (**a,b**) and terrestrial animals (**c,d**) for the Copper Age. The maps were created using the AverageR tool in IsoMemo (Cubas et al., 2020).
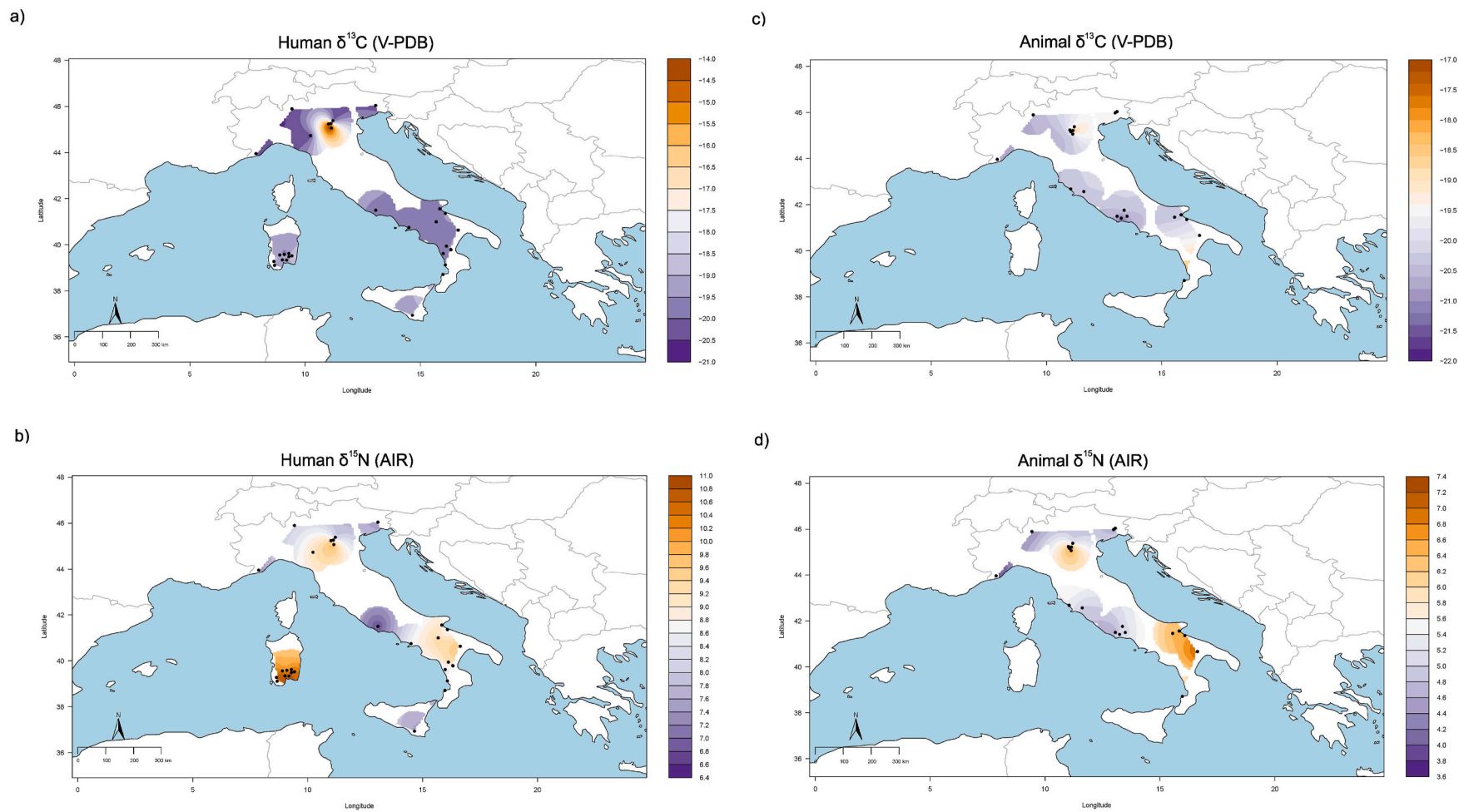
Fig. 6. Bayesian maps showing the distribution of δ^{13}C (**a,c**) and δ^{15}N (**b,d**) in humans (**a,b**) and terrestrial animals (**c,d**) for the Bronze Age. The maps were created using the AverageR tool in IsoMemo (Cubas et al., 2020).

Similarly to the Neolithic, the Copper Age carbon and nitrogen data are consistent with the consumption of terrestrial proteins and C_3 plants (Fig. 2b). However, an increased geographical variation is visible compared to the previous period (Supplementary Data 8). During the Copper Age, different communities occupied a variety of landscapes and, therefore, exploited their respective environments according to more nuanced choices. Previous studies report differences in the source of proteins (animals vs legumes) chosen by different groups across Italy, with a significant reliance on animal consumption observed in some areas, particularly in the northern portion of central Italy (De Angelis et al., 2019), while other sites present lower nitrogen values, consistent with a diet centred around plant proteins (Bernardini et al., 2021). Such differences in land exploitation and dietary choices reflect the variability generally observed during the Copper Age in terms of community management, with several small and dispersed settlements occupying different ecological niches (Dolfini, 2015). This is reflected in the greater variability visible for δ^{15}N values (Table 2), which mirrors the exploitation of different environments and the diverse food choices that varied according to the preferences of each community. Furthermore, even though the variance in δ^{13}C values appears lower than for the Neolithic (Table 2), when we observe how isotopic values are geographically distributed (Fig. 5; Supplementary Data 8), we can perceive that differences in food consumption were connected to human preferences and choices, rather than environmental factors. This diversity is also supported by the variability in archaeological findings (Cocchi Genick, 2011; Dolfini, 2015). Variations in isotopic values could also be connected, to some extent, to the kin-based differences, for example as visible in Central Italian sites of the Rinaldone culture (Bernardini et al., 2021).

In Europe, the Bronze Age was characterised by the spread of a new "package" of cultural features: a widespread increase in social complexity, increased urbanisation and a diffused use of standardised objects (e.g. wheel-made pottery). This set of traits was first observed in the Aegean - long integrated into the Mesopotamian and Levantine network - but soon spread to Italy, starting from the south, by 2500 BCE, and in the rest of Europe, assuming specific characteristics depending on the region (Heyd, 2013). These cultural differences are also reflected in the dietary choices of the Italian population, with a marked variability visible from the isotopic record (Figs. 2c and 6). The high carbon values visible in certain areas of the north (notably, the Po plain) are an indicator of the introduction of new crops (millets) that took place during the Bronze Age (Tafuri et al., 2009, 2018; Carra, 2012; Varalli et al., 2022). The humans available for the Bronze Age can be divided into two groups: one pointing to the exclusive exploitation of C_3 plants (characterised by lower carbon values) and the other showing a significant consumption of C_4 plants (with higher carbon values). These groups follow a regional pattern, with higher values in Northern Italy and lower ones in the south. However, only parts of Northern Italy (e.g. Bovolone and Olmo di Nogara; Tafuri et al., 2018) were interested by this phenomenon, while the rest of the area was still majorly relying on C_3 plants (Fig. 6; Supplementary Data 8). The higher carbon values are primarily visible in humans and, partially, among domesticated omnivores, supporting the idea of C_4 plants being used for human consumption and, less extensively, as animal fodder (Tafuri et al., 2009). Herbivores, on the other hand, present lower δ^{13}C, not compatible with millet consumption, suggesting that this group of animals mainly relied on wheat and C_3 vegetation.

No millet grains from Italian archaeological sites have been directly studied through stable isotope analysis yet. Moreover, the reasons behind the introduction of millet in Northern Italy are still being discussed. Its cultivation may have been used as a "buffer crop" to support primary crops (wheat and barley) during the periods of increasing aridity that characterised those centuries (Kirleis et al., 2022). Moreover, millet glumes are high in silica (Lu et al., 2009), which allows the grain to be stored for an extended period of time without spoiling (Kirleis et al., 2022). The introduction of millet has been connected to the intensive exploitation of the area, which was ongoing during the Bronze Age due to the demographic increase and economic development brought about by the Terramara culture (Cremaschi et al., 2016). Connections to Central Europe might have also facilitated the spread of this new crop (Varalli et al., 2022).

The Iron Age dataset is the most restricted in this study. This can be attributed to the current state of archaeological research in Italy, as well as to the funeral practices of the period. In fact, the Italian Iron Age was characterised by the widespread use of cremation (already started in the Middle/Late Bronze Age), which hinders stable isotope analyses as high temperatures degrade collagen molecules (Bozec and Odlyha, 2011). The only data available comes from two archaeological sites in Northern Italy, one on the eastern and one on the western coast, and one in Southern Italy. Both Northern sites point to a noticeable consumption of C_4 plants by humans, with evidence for Seminario Vescovile of a "predominantly C_4 diet", as some individuals present δ^{13}C values higher than $-12‰$ (Lightfoot et al., 2013; Wang et al., 2019). By this time, millet was widely used in Europe, with isotopic evidence of C_4 plants being included in human diets (δ^{13}C $\geq -18‰$) available for several modern countries, e.g. Switzerland (Knipper et al., 2017; Moghaddam et al., 2016, 2018; Varalli et al., 2021), Croatia (Zavodny et al., 2017) and Bulgaria (Keenleyside et al., 2006). Individuals buried in the Southern Italian site of Pontecagnano, on the other end, show a major reliance on C_3 plants (Supplementary Data 2, 6, 8), with millets mostly implemented in subadult diets (not included in this review; Riccomi et al., 2024). This period shows the lowest variability in terms of nitrogen values (Table 2), suggesting the presence of a homogeneous system centred around the consumption of terrestrial resources, probably relying on animal proteins in particular (Fig. 2d), even though archaeological evidence suggests a political system characterised by more independent settlements (Sestieri, 1997).

By exploring isotopic patterns from the Neolithic to the Iron Age (Figs. 2 and 4-6), we observe that the diet of prehistoric individuals remains, for the most part, stable (Fig. 7). People were generally eating terrestrial animals and C_3 plants. As previously discussed, there is no evidence of aquatic animal consumption throughout the whole Peninsula. We observe some isolated changes, notably the introduction of millets in Northern Italy during the Bronze Age characterised by increasing δ^{13}C values (Figs. 6 and 7b). The Bronze Age also shows the highest variability in terms of δ^{15}N values, pointing to a more diversified set of protein sources (Table 2 and Fig. 7a).

The major question about the economy of Later Prehistory human communities is the extent to which animals and secondary products were consumed. Sherratt's "Secondary Products Revolution" model (1981) argued that Neolithic people only used domesticated animals for meat; "secondary products" such as milk, wool and traction were only used from the Copper Age onwards. This model has been debated since then, with much nuance and complexity added as new data become available. During the development of agricultural practices, prehistoric communities from Italy, as well as the Middle East and Europe in general, had access to several animal species suitable for human consumption. Among domesticated species, cattle, sheep, goats and pigs can be considered, plus wild game such as red deer, wild boars and hare (Achino et al., 2021; Martín et al., 2023; Trentacoste et al., 2018). However, the extent to which they were consumed is still under debate. By analysing bone collagen through stable isotope analysis, we are not able to differentiate between meat and secondary product consumption. However, other techniques, such as lipid residue analysis and aDNA analysis of dental calculus, have demonstrated the presence of dairy products in Italy since the Neolithic period (Salque et al., 2012; Debono Spiteri et al., 2016; Quagliariello et al., 2022). Though isotopic analysis cannot distinguish between meat use and milk use, one corollary is that Neolithic groups may have kept relatively small herds (Robb, 2007); if pastoralism was extended in later periods, consumption of all animal products relative to plant-based foods would presumably rise.

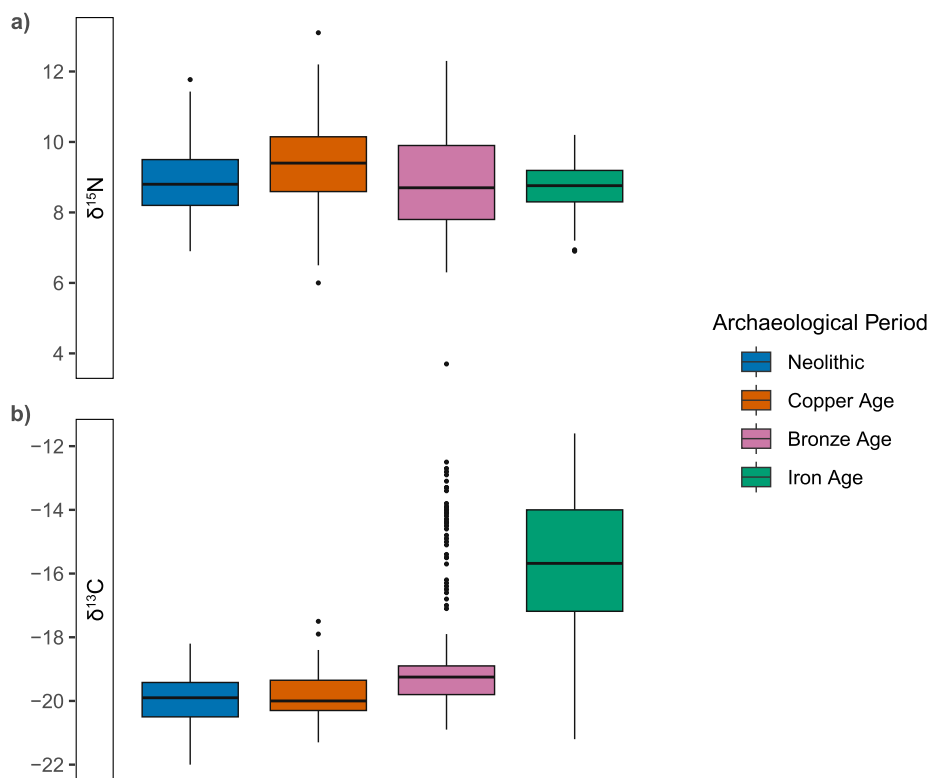Was meat the primary source of proteins in the diet? Or were people

Fig. 7. Boxplot of human δ^{15}N (**a**) and δ^{13}C (**b**) data from the Neolithic to the Iron Age. We included: 151 individuals from 33 sites for the Neolithic; 183 individuals from 25 sites for the Copper Age; 318 individuals from 30 sites for the Bronze Age; 124 individuals from 3 sites for the Iron Age. The horizontal lines represent the median, the boxes represent a 68% credible interval and the whiskers represent a 95% credible interval.
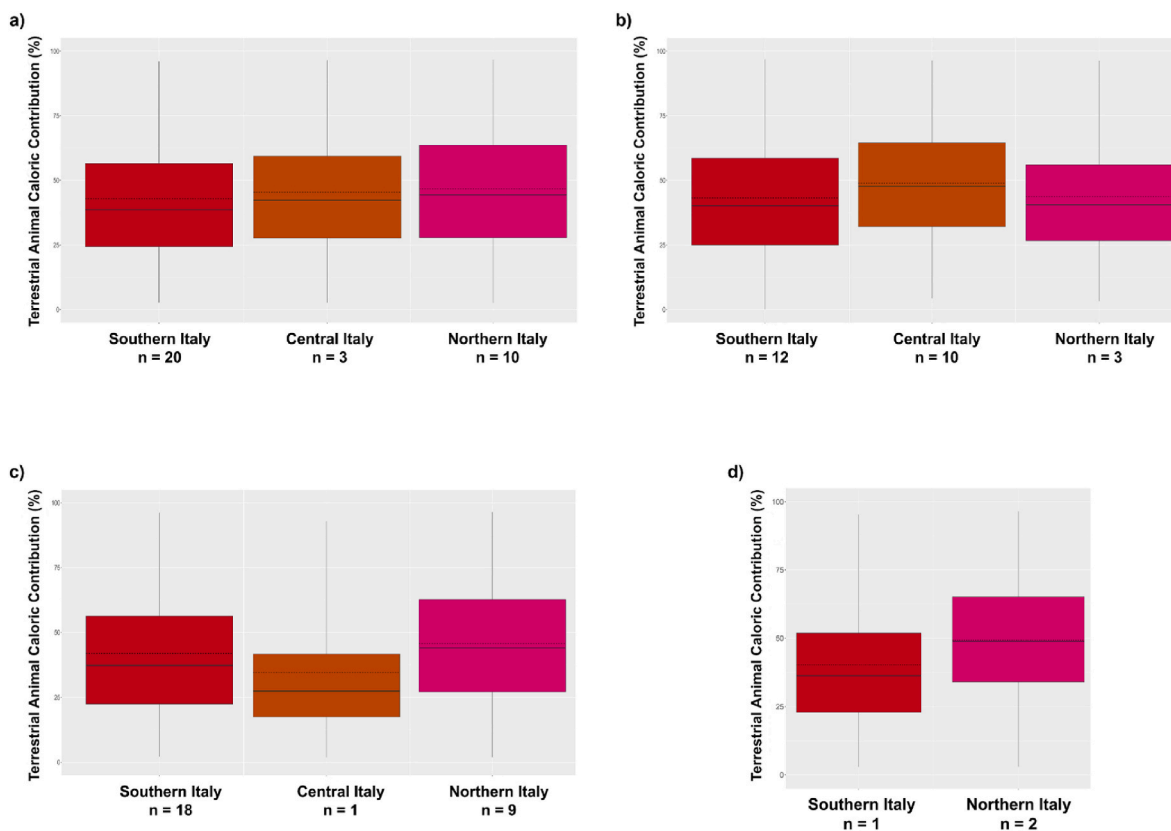

Fig. 8. Boxplots representing the terrestrial animal caloric contribution (%) in the diet of Neolithic (**a**), Copper Age (**b**), Bronze Age (**c**) and Iron Age (**d**) humans divided by geographical location. Boxes represent a 68% credible interval, whiskers represent a 95% credible interval. Horizontal continuous lines represent the median (50th percentile). Dashed horizontal lines represent the mean. The number of sites analysed for each location and period is reported. The plots were created using ReSources (Sołtysiak and Fernandes, 2021; see Supplementary Data 9).

mostly relying on grains, legumes and vegetables? Did the consumption of animal proteins vary over time?

We applied a Bayesian mixing model to the $\delta^{13}C$ and $\delta^{15}N$ data to quantify the caloric contribution of terrestrial animals to the diet of prehistoric Italian communities. Fig. 8 shows the estimations of terrestrial animal consumption across prehistoric Italy, with general stability in the relative contributions of plant and animal food to the diet. On average, 44% of the calories consumed by the individuals under analysis were derived from terrestrial animal products (Supplementary Data 9). Therefore, we can hypothesise that animal proteins were an important part of the diet of these communities and animals were generally accessible to the population. Plants were not the only energy source for prehistoric human groups living on the Italian Peninsula, and some variability in the percentage of animals consumed can be observed. Except for the Iron Age, whose scarcity of data does not allow for objective analysis, the Copper Age shows the highest percentage of animal-derived calories, reaching a mean of 45.5%, as already visible from the $\delta^{15}N$ data (Table 1), which was the highest in this study and might confirm the strong pastoral vocation of Copper Age communities (Dolfini, 2020; Bernardini et al., 2021). The Bronze Age, instead, shows the lowest percentage (43%). However, only one archaeological site is available for Central Italy during this time period, which may alter the results reported here.

Geographical differences can be observed, with sites from Southern Italy showing the lowest values across all periods except for the Bronze Age, whose data distribution (with only one site available for Central

Italy) could misrepresent the contribution of animal and plant protein to the diet. With an average terrestrial animal consumption of 42.5%, the diet of Southern Italian populations still appears strongly based on terrestrial animal products, even though meat and secondary products probably played a more prominent role in the subsistence practices of Northern and Central regions (Supplementary Data 9).

Southern Italy during the Iron Age exhibits a peculiar high reliance on grain (Fig. 8d). Pontecagnano is, in fact, an Etruscan urban site with well-established interactions with Greeks and Phoenicians (Cerchiai et al., 2018; Pellegrino and Rossi, 2011, 2020). As a class-based urban settlement, it probably relied more on grains than, for example, pastoralism.

The outcome of this analysis may change when more data is made available, as we are aware that a lower contribution of animal products might be expected in agrarian societies (Sołtysiak and Fernandes, 2021). Currently, we lack data from C_4 plants, shellfish and freshwater fish. Moreover, the results obtained provide wide uncertainties (Fig. 8) that account for a probable diverse scenario throughout the Peninsula. Nevertheless, these results agree with previously published studies on both Europe (Hedges and Reynard, 2007) and Italy. Specifically, archaeological sites from Southeastern Italy show that calories derived from terrestrial animal proteins constitute, on average, 40% of the diet of Neolithic populations (Tafuri et al., 2023). For Central Italy, a predominant consumption of livestock has been suggested (Scorrano et al., 2019). Copper Age and Bronze Age data from Central Italy point to a major reliance on plants, without excluding animal product
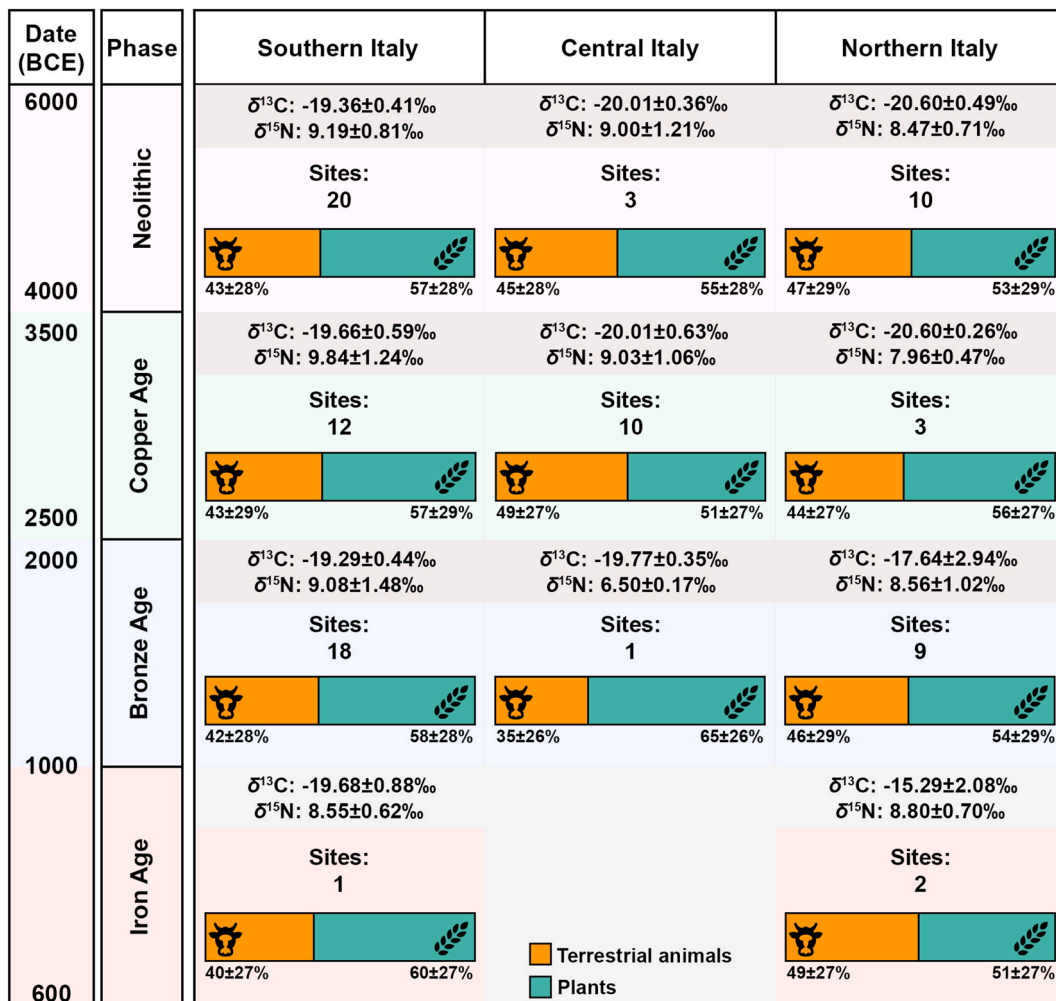
Fig. 9. Schematic representation of chronological information, isotopic data and terrestrial animal vs C_3 plant consumption from the Neolithic to the Iron Age. The percentages refer to the mean ± 1SD of terrestrial animal and plant consumption calculated using ReSources (Sołtysiak and Fernandes, 2021).

consumption, which agrees with our findings of decreasing consumption of terrestrial animals throughout Later Prehistory (Romboni et al., 2023).

Following Sherratt, 1981, we would expect an increase in the percentage of animals consumed since the "Secondary Products Revolution", as people had access to both meat and dairy products. However, our data (Figs. 8 and 9) do not show a clear rise in animal consumption during the Copper or Bronze Age. On the contrary, an increasing contribution of plant-based foods can be observed in Central and Southern Italy since the Copper Age. We can suppose that the introduction of secondary products may have changed how people interacted with animals without changing their overall nutrition. For example, it was now possible to consume dairy products instead of slaughtering animals for their meat. Ploughing, in particular, represented a way to improve agricultural techniques, therefore making cereal consumption more accessible, which appears to translate well in the distribution of the isotopic data presented here (Fig. 9).

5. Conclusions

This paper presents the first comprehensive meta-analysis of carbon and nitrogen stable isotopes for the Italian Peninsula during Later Prehistory, summarised in Fig. 9. By collating 1590 data, we reviewed diachronic variations in dietary patterns in Italy.

The results of this isotope-based approach highlighted the human driving force behind many dietary transformations and the extent to which food represents a means to explore broader contexts. By observing a human dietary pattern generally independent from the animal one (Fig. 3), we recognise that environmental factors are not the only reason for communities to modify their habits. Moreover, the regional variations visible in Fig. 9 can be traced back to the heterogeneous geography of the Peninsula, which causes a diverse distribution of natural resources and, therefore, different farming strategies according to the territory. Social and cultural factors also play an important role, as the circumstances around the introduction of millets during the Bronze Age, which were predominantly used for human consumption, suggest. On the other hand, after analysing this extensive set of data, we can conclude that the introduction of dairy products during the "Secondary Products Revolution" did not mean a definite increase in animal protein consumption but, most probably, a shift in subsistence practices, as an example, one in which secondary sources substitute meat as opposed to integrating it, *de facto* not changing the isoscapes obtained.

As several areas are still isotopically unexplored, new studies might modify these conclusions. Yet, this diachronic review highlighted different trends linked to events from the Neolithic to the Iron Age.

- During the Neolithic, the introduction of a shared "package" of domesticated plant and animal resources triggered a similarity in foodways shared throughout Italy (Fig. 2; Fig. 4).
- The Copper Age was characterised by nucleated settlements that had different access to food resources, reflected in the diverse isoscapes (Fig. 2; Fig. 5).
- While Europe was invested in important cultural innovations, which resulted in overall cultural homogeneity during the Bronze Age, a degree of heterogeneity can be observed in Italy. In particular, during this period, we see the introduction of new crops, such as millet, in the north (Fig. 2; Fig. 6).
- Millet consumption was confirmed during the Iron Age, at least in Northern Italy. However, more data are needed to explore the Peninsula more thoroughly (Fig. 2).

In conclusion, this study demonstrated the relevance of analysing a broad set of isotopic data. The combination of data plotting and Bayesian models made it possible to explore foodways across a variety of cultural landscapes over a span of 6000 years. What is strikingly emerging from this study is the overall homogeneity, through a wide

chronological frame, of food practices in Italy (Fig. 9). Over the course of several millennia, notwithstanding plausible local variations, the dietary *habitus* of prehistoric communities is composed of a relatively balanced contribution of both animal and plant proteins, which seems to be hardly affected by environmental constraints or technological innovations. We hypothesise that this does not reflect the absence of change, but could instead proves how different farming strategies are not always visible in the isotopic record. However, when bulk data are analysed at the site level or through an inter-site analysis within a limited area of investigation, interesting discontinuities become visible, suggesting local traditions and overall complexity (Tafuri et al., 2023). More in general, bulk stable isotope data cannot reflect minor variations in the diet - which calls for a progression of studies through improved techniques (e.g. Compound-Specific Isotope Analysis of Amino Acids). Therefore, the output of this paper can be beneficial in directing future research in the stable isotope field, as many gaps are still present, both temporally and spatially.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2024.109056.

Data availability

The data used in this study are available in the article and its Supplementary Data. The MAIA dataset is available at https://pandoradata.earth/dataset/maia.

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