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RESEARCH

Human diet in Mantua (Northern Italy): isotopic data on local communities dated from Copper Age to Middle Bronze Age

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Abstract
The Copper to Middle Bronze Ages are particularly significant times in Italian Protohistory, as they were marked by major dietary, social, and technological transformations. Stable isotope analysis has become a key tool in reconstructing past human diets. Although its application has expanded across the Italian Peninsula over the past decade, data for the Copper Age in northern Italy remain limited, and geographic coverage is still uneven. This study presents new isotopic evidence on 11 faunal specimens, and 101 humans from the province of Mantua (Lombardy), a region with a dense concentration of funerary contexts dating from the Copper Age to the Middle Bronze Age. The results reveal a consistent dietary pattern across the periods investigated, with protein intake derived predominantly from terrestrial animal sources and C_3 plants; no significant dietary differences were observed between sexes or age groups. The dietary continuity observed across nearly a millennium suggests that, despite broader socio-economic changes documented in the archaeological record, subsistence strategies in this region remained stable. The dietary homogeneity observed among buried individuals suggests consistent dietary practices within the funerary population. This study provides one of the first isotopic datasets from Northern Italy for the Copper Age and offers a new perspective on subsistence strategies in protohistoric Lombardy.

Keywords Northern Italy · Stable isotope analysis · Copper Age · Bronze Age · Diet reconstruction

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Introduction

The Copper to Middle Bronze Ages represent a period of profound transformation in Italy, marked by major technological innovations, shifts in subsistence strategies, and evolving social structures (Peroni 1996; Cazzella and Guidi 2011). The introduction and subsequent development of metallurgy acted as a catalyst for far-reaching changes in social organisation, exchange networks, and material culture (Dolfini 2020), while parallel developments in agricultural practices and animal husbandry strategies fundamentally reshaped protohistoric communities across the Po Plain and Alpine regions (De Marinis 1997, 1999; Cardarelli 2009). The development of metallurgy required new forms of labor specialisation, long-distance exchange networks for raw materials such as copper and tin, and potentially differential access to prestige goods (Dolfini 2014). Similarly, the diversification of animal exploitation strategies, including the adoption of secondary products such as milk and wool, as well as the use of animals for traction, likely impacted both the availability and distribution of food resources within communities (Sherratt 1983; Greenfield 2010; Tecchiati et al. 2020). The convergence of these innovations created new economic possibilities and social dynamics, making this period crucial for understanding the emergence of increasingly complex societies in the Italian peninsula (Cazzella and Guidi 2011; Bietti Sestieri 2015).

Despite the archaeological significance of these periods, our understanding of dietary practices and subsistence strategies remains incomplete, particularly due to the limited application of bioarchaeological methods in many key regions.

Stable isotope analysis of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) in human and animal bone collagen has proven to be a powerful tool for reconstructing past diets and has been increasingly applied to Italian protohistoric contexts over the past two decades (e.g., Tafuri et al. 2009, 2018; Varalli et al. 2015, 2016, 2022; Lai et al. 2017; De Angelis et al. 2019; Masotti et al. 2019; Arena et al. 2020; Rumolo et al. 2020; Bernardini et al. 2021; Skeates et al. 2021; Cortese et al. 2022; Romboni et al. 2022), revealing considerable regional dietary variability. Evidence of C_4 plant consumption has been documented at several northern Italian Bronze Age sites such as Olmo di Nogara and Dossetto di Nogara (Tafuri et al. 2018), while other contemporaneous communities, including Arano di Cellore and Ballabio, show exclusive reliance on C_3 resources (Varalli et al. 2016; Masotti et al. 2019). However, geographic and chronological coverage remains uneven; data for the Copper Age in Lombardy are particularly scarce, and the province of Mantua, despite its wealth of funerary contexts spanning the Copper to Middle Bronze Age, has not been systematically investigated from an isotopic perspective.

To contextualise the dietary evidence presented in this study, it is essential to first outline the broader archaeological framework of these periods in northern Italy, with particular attention to settlement patterns and funerary practices. In northern Italy, the Copper Age (CA) spans from the mid-4th millennium BCE to conventionally 2300/2200 BCE and is characterised by significant social and economic transformations, driven by advancements in metallurgy and animal husbandry (Cazzella and Guidi 2011). The ability to smelt metal not only introduced a new material but also led to increased resource exploitation, trade, and social complexity (Dolfini 2014, 2020; Marzatico 2021). These developments contributed to greater mobility, specialised pastoralism, and shifts in religious practices, including the rise of monumental tombs and ancestor worship, as evidenced by the appearance of anthropomorphic stone statues known as *statue menhir* (Leonardi 2012; Casini and Fossati 2021; Poggiani Keller and Baioni 2022). From a funerary perspective, regional differentiation is evident between Alpine and lowland contexts. In the Alpine and sub-Alpine regions, collective burials predominate, typically located in rock shelters and small caves (Barfield 2007; Baioni 2017). In contrast, the lowland Po Plain is characterised by the so-called *tombe a fossa* culture, featuring individual inhumations (Salzani and Tecchiati 2019). The most significant burial site, discovered in 1884 at Remedello Sotto (Brescia), contained hundreds of graves and played a pivotal role in defining the so-called *Remedello* funerary culture, a tradition that persisted for nearly a millennium before the emergence of the Bell Beaker phenomenon (de Marinis 2013). Remedello graves are simple pit burials, generally oriented NW-SE, with the deceased positioned on their left side with flexed limbs or in the *Rückenhocker* position (supine, with the head turned to the left and the legs bent towards the left). Grave goods in male burials include polished greenstone axes, flint daggers and arrowheads, and, occasionally, copper axes and daggers, all of which signify the adult male as a warrior (de Marinis 2010). Pottery finds are difficult to classify due to limited evidence and the poor standardisation (Longhi 2010); only in a few cases where sex determination was possible for individuals interred with ceramic vessels, they were female. Recent scientific excavations have considerably expanded the available dataset for analysing Copper Age funerary practices in the Po Valley (Longhi 2021). The present study includes three Copper Age necropolises from the province of Mantua, Fontanella Mantovana, San Giorgio Valdaro and Valdaro – Rosignoli, which exemplify this cultural framework and provide new opportunities to investigate dietary practices during this period.

The Bronze Age in northern Italy conventionally began around 2200 BCE, and its development in the region is well-documented thanks to numerous discoveries in pile-dwelling settlements, primarily located near pre-Alpine and Alpine lakes across eastern Lombardy, western Veneto, and Trentino (De Marinis 2007; Leonardi et al. 2015; Rapi 2020; Baioni et al. 2021). Chronologies based on metal finds, radiocarbon-calibrated dendrochronological dating, and scientific excavations at Lake Garda settlements (e.g., Desenzano – Lavagnone; Polpenazze – Lucone) have allowed for the differentiation of three main periods: the Early Bronze Age (EBA, 2200–1600 BCE), the Middle Bronze Age (MBA, 1600–1300 BCE), and the Late Bronze Age (LBA, 1300–1150 BCE) (Rapi et al. 2019; Baioni et al. 2025; Martinelli 2025). During the Early Bronze Age, settlements were typically small pile-dwellings (up to one hectare) located along lake shores, over water, or in periodically flooded lowlands (Rapi et al. 2019; Baioni et al. 2025). At the EBA/MBA transition, however, there was a significant expansion into the plains, eventually extending beyond the natural barrier of the Po River. This phenomenon is associated with a substantial demographic increase linked to improved agricultural practices and resource exploitation (De Marinis 1997). It also coincides with the emergence of a new settlement model in the Po plain: the *Terramare*, dryland pile-dwelling villages surrounded by embankments, which experienced a rapid decline around 1150 BCE (De Marinis 1997; Cardarelli 2009; Cremaschi et al. 2016).

An important agricultural innovation during the Bronze Age was the introduction and cultivation of millet, a C_4 plants that seems to appear in northern Italy from the first half of the II millennium BCE onwards (Filipović et al. 2020), though their adoption was spatially uneven across the region (Tafuri et al. 2009, 2018; Rottoli 2005; Varalli et al. 2015, 2022). Regarding the Middle Bronze Age, which in this region is characterised by the so-called *Polada* culture, our knowledge of the funerary practices remains limited, with known sites located in areas where settlement patterns are not yet fully understood. The earliest burials, dating to the earliest phase of the Early Bronze Age, have been found in rock shelters in the pre-Alpine and Alpine regions (e.g., Trento, Brescia). These burials exhibit some variability but are generally characterised by crouched inhumations, often covered by low stone mounds and accompanied by modest grave goods, mainly ornaments such as discoidal beads, *Dentalium* shell tubes, animal canines, and sporadically ceramic vessels (De Marinis 2003; Barfield 2007). In the pile-dwelling settlements, no necropolises have been identified, and reliable data on burial practices are entirely lacking. However, the discovery of numerous skulls and long bones within these settlements suggests that human remains, possibly those of ancestors or enemies, were preserved within the settlements themselves (Baioni 2000; Salzani et al. 2015). Until recently, only three cemeteries from the advanced phase of the Early Bronze Age were known, all located in the plains: Sorbara (Mantua), Arano di Cellore and Valserà (Verona), where the deceased were buried in pits in a crouched lateral position (Baioni 2000; Salzani et al. 2015). The discovery of additional funerary contexts in the Mantua area has shown that, in a later phase of the Early Bronze Age, a shift occurred from crouched lateral burials to extended supine burials, a practice that subsequently became standard in the Middle Bronze Age (De Marinis 2003). This study examines five Bronze Age funerary contexts from the Mantua area, San Giorgio – Valdaro (EBA and MBA), Valdaro – Corte Tridolo, San Giorgio – Viale Europa, San Giorgio – Via Marconi, and Goito-Strada Calliera-Sacca, as well as the settlement of San Giorgio – Castiona, which provides the faunal baseline for dietary reconstruction.

The Mantua region provides an ideal context for such an investigation. Recent archaeological discoveries have significantly expanded the dataset of funerary contexts from this area, providing a rare opportunity to examine dietary continuity and change across nearly a millennium of cultural transformations. The region's strategic position in the Po Plain, combined with its dense concentration of well-preserved burial sites, makes it an ideal case study for understanding subsistence strategies during these pivotal periods. This study presents stable carbon and nitrogen isotope data from 11 faunal specimens and 101 human individuals from multiple burial sites in the province of Mantua, providing one of the first comprehensive isotopic datasets for the Copper Age in northern Italy (Fig. 1). The primary aims of this study are to: (i) characterise the dietary baseline for Copper to Middle Bronze Age populations in this area; (ii) investigate whether documented social and economic transformations correlate with detectable dietary changes; (iii) examine potential intra-community dietary variation based on biological sex, age, or other factors; (iv) compare dietary practices in Mantua with other contemporary northern Italian communities to assess regional variability and broader patterns.

Archaeological contexts

This study examines individuals from three Copper Age cemeteries (Fontanella Mantovana, San Giorgio Valdaro, and Valdaro – Rosignoli), five funerary contexts dated to the Early and Middle Bronze Age (San Giorgio – Viale Europa; San Giorgio – Via Marconi; San Giorgio Valdaro; Valdaro – Corte Tridolo; Goito, Strada Calliera-Sacca) and one settlement (San Giorgio – Castiona). All sites are located in close proximity to one another in the province of Mantua.

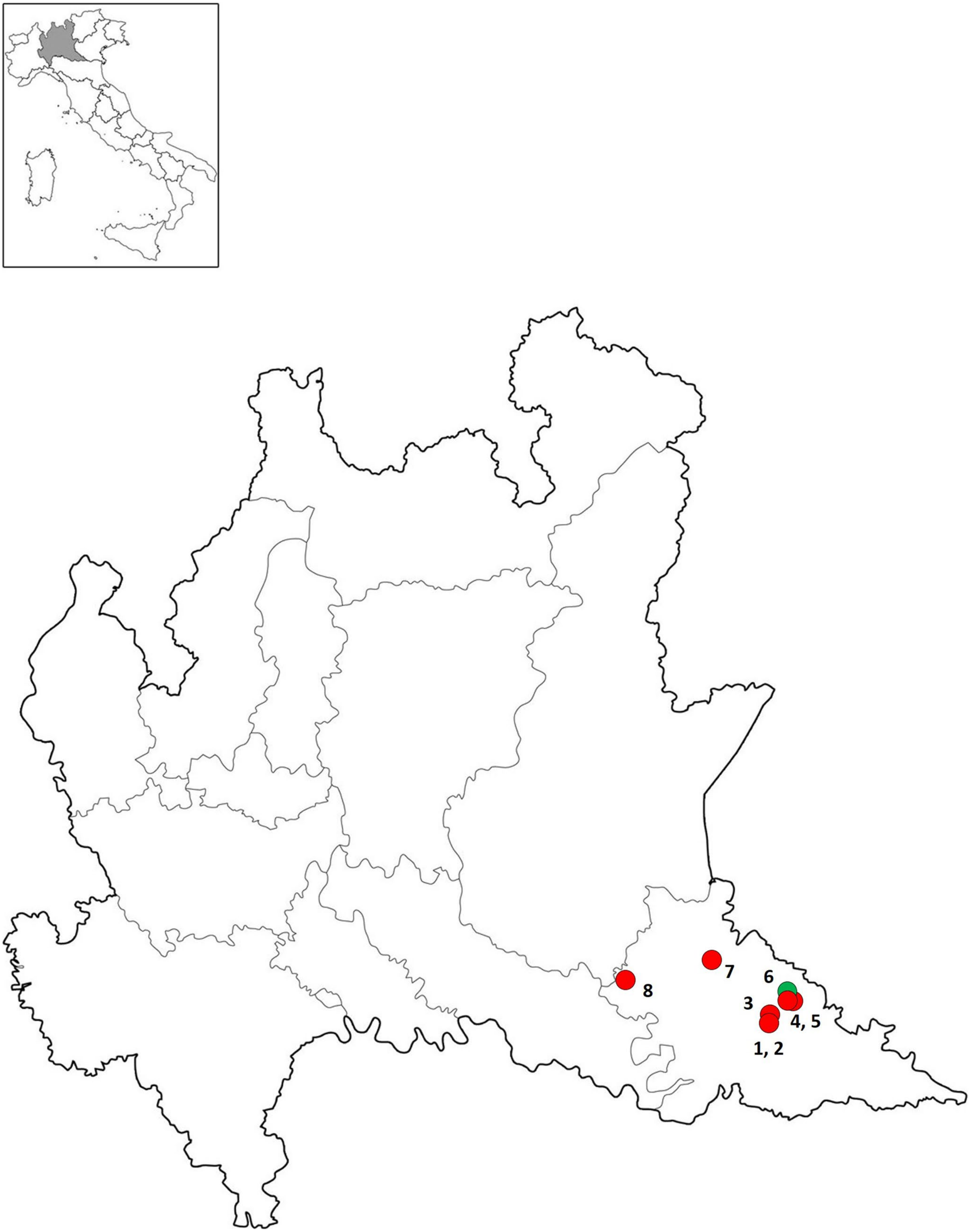

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Fig. 1 Site details, with necropolises in red and settlement in green. (1) Valdaro – Corte Tridolo (Early Bronze Age), (2) Valdaro – Rosignoli (Copper Age), (3) San Giorgio Valdaro (Copper Age - Middle Bronze Age), (4) San Giorgio – Viale Europa (Early Bronze Age), (5) San Giorgio - Via Marconi (Early Bronze Age), (6) San Giorgio – Castiona (Early Bronze Age), (7) Goito - Strada Calliera-Sacca (Early Bronze Age), (8) Fontanella Mantovana (Copper Age)

With the exception of Fontanella Mantovana and San Giorgio – Viale Europa, all other sites are unpublished, and the archaeological data derive from excavation documentation.

Fontanella Mantovana (Casalromano)

The necropolis, located in the municipality of Casalromano between the valleys of the Gambara and Oglio rivers, was discovered and excavated between 1888 and 1891 (Acanfora 1956). Information about the site is limited, as no detailed plan or documentation of grave distribution is available. A total of 36 flat graves were uncovered, with skeletons predominantly found in a crouched position, occasionally supine. Only 13 burials were preserved, extracted along with the surrounding soil and stored in wooden cases. When present, grave goods included ceramic vessels, flint daggers, axes, and arrowheads, as well as copper artifacts such as daggers and awls (Zampa 1890; Acanfora 1956; Corrain and Gallo 1967; Salzani 1978).

San Giorgio Valdaro (San Giorgio Bigarello)

The archaeological excavation carried out in the Valdaro area (2006–2007) revealed significant evidence spanning from Late Prehistory to the Roman period. Among the most remarkable discoveries were 22 prehistoric burials, dated between the Final Neolithic and the Bronze Age, distributed across Sectors I and III (**Supplementary Fig. 1**). One of the most extraordinary finds is the double burial, known as the "Lovers of Valdaro", in which two individuals were found interlocked in a crouched position, accompanied by a set of flint weapons, and dated to the Late Neolithic. Particularly noteworthy for the Bronze Age, some burials in Sector I have been dated to the Early Bronze Age, while in Sector III, individuals buried in a crouched position date to the Final Neolithic–Early Bronze Age, whereas those laid in a supine position belong to the Middle Bronze Age. Only five graves contained grave goods, mainly ceramics and flint artifacts. Among them, grave 17 stands out as an infant burial with an exceptionally rich assemblage of perforated shells and a marine shell pendant. In 2017, another large necropolis was uncovered at Valdaro, consisting of approximately 45 burials, all inhumations within NW-SE oriented pits. The deceased were placed in a flexed position on their left side or in the *Rückenhocker* position, regardless of sex. Three undisturbed graves (grave 29, grave 111, and grave 112) contained manipulated skeletal remains, suggesting secondary burial practices. Flint daggers, both simple-based and tanged, were identified in 17 male burials, with eight of these graves also containing one or more flint arrowheads. When sex determination was possible, ceramic vessels, present in 13 burials, were consistently associated with female individuals, except for grave 29, which contained two ceramic vessels alongside a flint dagger. However, given the presence of manipulated bones in this grave, the ceramics may have been offerings rather than part of the original grave goods. Ongoing radiocarbon dating is expected to clarify the necropolis's diachronic development, as it represents a key site for the study of Copper Age funerary practices in northern Italy.

Valdaro – Rosignoli (Mantua)

At Valdaro, a second, smaller necropolis was investigated in 2018 on the Rosignoli property. This burial ground contained eight inhumations, all within simple pit graves-oriented E-W. In this necropolis, burial positions were more variable: two individuals were flexed on their right side with the head facing west (grave 1; grave 3); two were flexed on their left side, with the skull oriented west and the face turned north (grave 4; grave 8); two were flexed on their left side with the head to the east (grave 5; grave 6); and one individual was supine, with the skull positioned westward (grave 7). Grave goods included ceramic vessels, ornaments such as multiple discoid beads from a necklace, flint arrowheads, and a flint dagger. The latter, in terms of typology, is comparable to artifacts associated with the Remedello culture.

Valdaro – Corte Tridolo (Mantua)

During the 2010 excavation campaigns, several burials were uncovered in the industrial area of Valdaro, near the locality of Corte Tridolo in the municipality of Mantua. These consisted of a cluster of five simple pit graves, oriented N-S or NW-SE, with the individuals buried in a supine position. These burials were attributed to the Neolithic period. In 2017 a new rescue excavation was conducted a short distance from the previously described necropolis. On this occasion, two additional burials were discovered, characterised by a grave assemblage that included metal artifacts (copper daggers and a horn handle), which allowed their chronological attribution to the advanced Early Bronze Age (EBA II-III).

San Giorgio – Viale Europa (San Giorgio Bigarello)

In 2013 preventive archaeological excavations in San Giorgio (Viale Europa) uncovered artifacts dating from the Neolithic to the modern age, primarily related to agricultural activity. For the Bronze Age, a circular structure approximately 11 m in diameter was identified, bordered by a shallow ditch, possibly a funerary or ritual enclosure with an entrance. The ditch contained only a few ceramic fragments and flint flakes. To the west of the structure, three burials were discovered, including a double burial, with individuals laid in a supine position and oriented N-S. Not all the graves contained grave goods (Castagna 2023). Of particular interest is grave 4, which contained two individuals (**Supplementary Fig. 2**): an adult woman (35–50 years old) and a child approximately 6–7 years old, both buried in a supine position (Lamanna 2019). The woman was adorned with a necklace featuring a finely incised crescent-shaped copper sheet pendant, a discoid bone bead, and a shell from the *Cerithium* genus. The subadult was accompanied by a double-spiral pendant. These artifacts find parallels in funerary and settlement contexts from the Early Bronze Age in the Lake Garda region, western Switzerland, and Bavaria, further supporting the existence of close connections between these areas during prehistory (David-Elbiali and David 2009).

San Giorgio – Via Marconi (San Giorgio Bigarello)

In 2005, a preventive archaeological survey was conducted on a 2,000 m² plot of land in San Giorgio, designated for commercial and residential use. The excavations revealed burials dating from the Protohistoric period to the Middle Ages. An important protohistoric discovery consists of a ring-shaped structure containing three vessels positioned according to the cardinal points (N-W-S); the vessel oriented to the east was not found, likely removed at a later date. At the center of this structure, an inhumation burial was located, oriented W-E, suggesting the presence of a low tumulus with a ditch and funerary markers (**Supplementary Fig. 3**). The burial was completely disturbed, with the skeleton lacking anatomical connections, indicating an ancient violation. Radiocarbon dating placed the individual in the advanced Early Bronze Age.

Strada Calliera-Sacca (Goito)

Strada Calliera-Sacca necropolis, located in the municipality of Goito, excavated in 2021, consists of seven inhumation burials in simple graves, oriented east-west. All the skeletons were laid in a supine position, with both upper and lower limbs extended and the skull facing east. Grave 3 also contained a bronze dagger, which, based on its typology, can be dated to the full phases of the Early Bronze Age. These burials are the first to feature the supine deposition of the deceased, marking a shift from the earlier practice of crouched burial, as observed in cemeteries such as Sorbara and Arano di Cellore. Supine deposition would later become the standard during the Middle Bronze Age, when inhumations in simple pits, generally oriented east-west or southeast-northwest, became common.

San Giorgio – Castiona (San Giorgio Bigarello)

The settlement of San Giorgio – Castiona was identified in 2009. The usage layers were no longer present in situ, having been destroyed over millennia of land use, but it was possible to investigate dozens of pits, many of which contained pottery and faunal remains (**Supplementary Fig. 4**). Based on the typology of the materials, the settlement can be dated to the latest phase of the Early Bronze Age, a period during which the Polada communities began to occupy the plains north of the Po River.

Materials and methods

In recent decades, isotopic analyses have become a fundamental tool for reconstructing human diets, offering new insights into the dietary habits of ancient populations. Specifically, the analysis of carbon and nitrogen stable isotopes provides direct information on food sources and ecological interactions (DeNiro 1985; Ambrose 1990; Unkovich et al. 2001; Marshall et al. 2007). This analysis measures the proportion of ^{13}C and ^{15}N isotopes relative to established international standards (Vienna Pee Dee Belemnite for carbon and atmospheric nitrogen for nitrogen) using the δ notation. The δ is defined with the equation (Coplen 2011):

$$\delta\, {}^{i}E_{RM} = \delta\, {}^{i/j}E_{RM} = \frac{\left(\frac{{}^{i}E}{{}^{j}E}\right)_{s}}{\left(\frac{{}^{i}E}{{}^{j}E}\right)_{RM}} - 1$$

where $\left(\frac{{}^{i}E}{{}^{j}E}\right)_{s}$ and $\left(\frac{{}^{i}E}{{}^{j}E}\right)_{RM}$ are the ratios between the abundance of the less abundant isotope, ${}^{i}E$, to the most abundant isotope, ${}^{j}E$, present in the substance *s* of interest and in a reference material RM (i.e., the international standard).

$\delta^{13}C$ and $\delta^{15}N$ values indicate individuals' trophic position within the food web, reflecting the protein intake from their diet along with some influence from other nutrients (DeNiro 1985; Schoeninger and DeNiro 1984; Jim et al. 2007; Froehle et al. 2010; Warinner and Tuross 2009). The relationship between consumers and resources follows a pattern where consumers typically exhibit higher carbon and nitrogen values than their food sources (DeNiro 1985; Schwarcz and Schoeninger 2011). Different values of the offset between diet and collagen/body have been proposed to trace the value of the animal diet. The offset values for carbon and nitrogen are influenced by the trophic level, metabolism, physiology and climatic-environmental factors (Ambrose and Norr 1993; Hedges and Van Klinken 2002; O'Connell et al. 2012; O'Connell 2017). Currently, the generally accepted offsets for human diet-collagen analysis are $+4.8 \pm 0.5‰$ for $\delta^{13}C$ and for diet-body $+5.5 \pm 0.5‰$ for $\delta^{15}N$ (Schulting et al. 2022).

Carbon and nitrogen stable isotope analysis have been performed on 11 faunal remains belonging both to domesticated and wild animals (*Ovis* vel *Capra*, *Bos taurus*, *Sus domesticus*, *Cervus elaphus*) dated to the Early Bronze Age and 101 human remains dated from the Copper Age to the Middle Bronze Age. Faunal remains come from a nearby settlement site, called San Giorgio – Castiona, in the municipality of San Giorgio Bigarello; human remains belong to different burial areas located in different municipalities (Casalromano, San Giorgio Bigarello, Mantua, and Goito; see **Supplementary Materials 1**, **Table A and Table B**).

Concerning fauna, we selected only adult individuals. Conversely, human remains belong to different age classes: 52 individuals are adults, 7 adolescents, 10 subadults, 9 infants and 23 indeterminable; specifically, we have 27 males, 20 females and 54 indeterminable.

Among human remains, 81 samples date back to the Copper Age, 14 to the Early Bronze Age, and 6 to the Middle Bronze Age.

Collagen was obtained from the cortical bones of both humans and animal remains. The process took place at the Centre of Molecular Anthropology for Ancient DNA Studies of the University of Rome "Tor Vergata", and at the Laboratory of Isotope Geochemistry of the University of Parma. Longin's protocol (1971), which was adjusted by Brown et al. (1988), was applied to all materials. Initially, the cortical bone underwent thorough cleaning via surface abrasion. Subsequently, approximately 250 mg of bone was subjected to the extraction protocol, with a modern bovine sample serving as a benchmark. This involved demineralisation in HCl 0.6 M, followed by rinsing with bi-distilled water and gelatinization. To enhance collagen concentration, an ultrafiltration step using 30 kDa Amicon Ultra-4 Centrifugal Filter Units with Ultracel membranes (Millipore) was employed before lyophilisation. Carbon and nitrogen stable isotope ratios within the collagen were analysed using advanced equipment: a Delta V Advantage (Thermo Scientific, Bremen, Germany), hyphenated with the Thermo Fisher Flash HT plus Elemental Analyzer at the Laboratory of Isotope Geochemistry of the University of Parma, and a Delta Plus XP isotope ratio mass spectrometer connected to a Flash 1112 Elemental Analyzer via a Conflow IV interface (Thermo Scientific, Milan, Italy) at Fondazione Edmund Mach. Cross-checks were performed between the two laboratories, repeating some measurements, to check for possible systematic errors in the calibration of the isotopic data. The check allowed us to establish that the values obtained in the two laboratories are comparable. By conducting replicate analyses against the PDB standard for $\delta^{13}C$ and AIR for $\delta^{15}N$, the prediction errors were estimated to be within $\pm 0.2‰$ for $\delta^{13}C$ and $\pm 0.3‰$ for $\delta^{15}N$. Additionally, the samples were assessed against established criteria to determine carbon and nitrogen percentages, atomic C/N ratios, and collagen yields (DeNiro 1985; Ambrose 1990; van Klinken 1999). Preservation of the extracted collagen was evaluated based on carbon and nitrogen contents falling between 15 and 45% and 5–15%, respectively, as well as C/N ratios ranging from 2.9 to 3.6 (DeNiro 1985; Ambrose 1990).

Moreover, statistical comparisons between demographic groups (e.g., sex, age class) were performed using the Wilcoxon-Mann-Whitney test, due to the small sample sizes and potential deviations; for chronological comparisons between Copper Age and Bronze Age individuals, a t-test was applied, given the larger sample sizes.

We employed, also, a Bayesian mixed model using FRUITS v3.1 (Fernandes et al. 2014) to analyse the human diet. The software offers a probabilistic approach to quantifying dietary components, integrating information on food macronutrients, as well as elemental and isotopic composition in its calculations.

The model requires the specification of consumer isotope values, source isotope values, diet-to-collagen isotopic offsets, and macronutrient routing parameters. The mean isotopic values of humans served as the consumer data, and all estimated offset values were inputted into FRUITS with uncertainties of 0.5‰ for carbon and 1‰ for nitrogen (Fernandes et al. 2015; Fernandes 2016).

Three resources (plants, faunal products and freshwater fish) have been identified as food groups in the model. Plants category utilised data obtained from protohistoric sites located in northern and central Italy (Cortese et al. 2024). The reference dataset included both cereals and legumes: 46 samples of barley (*Hordeum vulgare*), 23 of bread wheat (*Triticum aestivum*), 30 of emmer (*Triticum monococcum/dicoccum*), and 81 samples of broad bean (*Vicia faba*). The inclusion of legumes is particularly important for the Fruits model, as nitrogen-fixing plants like *Vicia faba* typically exhibit lower $\delta^{15}N$ values compared to non-leguminous crops, and their presence in the baseline better reflects the diversity of plant foods potentially consumed in protohistoric diets.

Faunal products values are derived from specimens analysed in this study (see **Supplementary Materials 1**, **Table B**), whereas freshwater fish data were obtained from published literature due to the absence of suitable fish remains from the study sites. The freshwater fish baseline comprises four samples of pike (*Esox lucius*) from the Late Bronze Age site of Chindrieux, Switzerland (Varalli et al. 2021). While we acknowledge the chronological and geographic distance between these reference samples and our study area, pike (*Esox lucius*) is a top predator species native to the Po Plain and Alpine lake systems during the periods under investigation, and the Chindrieux samples represent the most robust published dataset available for northern Italian/Alpine freshwater systems from comparable lacustrine environments. The scarcity of isotopic data for prehistoric freshwater fish from Italy represents a broader gap in the archaeological record that limits dietary reconstructions across the region.

Estimated offset values were entered into FRUITS with associated uncertainties of ±0.5‰ for carbon and ±1‰ for nitrogen (Fernandes et al. 2015; Fernandes 2016). For the $\delta^{15}N$ diet-to-collagen offset, we applied 4.0±1.0‰, representing an intermediate estimate within the 3–5‰ trophic enrichment range documented between diet and collagen (Hedges and Reynard 2007). This value accommodates current debates on nitrogen isotope fractionation, allowing the model to explore possible enrichment values between 3–4‰ and the higher 6‰ proposed by O'Connell et al. (2012). For $\delta^{13}C$, a diet-to-collagen offset of 0.9±0.5‰ was used, consistent with controlled feeding experiments that report carbon isotope fractionation of approximately 0.8–1.0‰ (Styring et al. 2017). Macronutrient routing parameters were set following established FRUITS protocols (Fernandes et al. 2014, 2015), assuming that 74% ± 4% of dietary protein and 26% ± 0% of dietary energy contribute to collagen carbon, while 100% ± 0% of dietary protein contributes to collagen nitrogen. Estimations of source values, along with the assessment of energy and protein content in each food group, were computed following methodologies outlined in Fernandes et al. (2015), Knipper et al. (2020), and Varalli et al. (2021) (refer to **Supplementary Materials 2**, **Table E.1-E.8**, for specifics).

Results

Isotope data were successfully obtained for all samples of fauna, except for one specimen of *Sus domesticus*; concerning human remains, data were obtained for 85 out of 101 samples. Indeed, the preservation of the remains was not always optimal, due to the high acidity of the soil.

Faunal remains (n=10) show $\delta^{13}C$ values ranging between −22.4‰ and −17.3‰ (median −21.5‰), and from 4.2‰ to 6.7‰ (median 5.8‰) for $\delta^{15}N$, consistent with terrestrial C_3 plants consumption. One specimen (*Bos taurus*) shows elevated $\delta^{13}C$, potentially linked to C_4 plant intake. Nevertheless, considering that it concerns only a single individual, it would be speculative to make any hypotheses. There are no significant differences between the values of domesticated and wild animals, indicating a rather similar typology of food provisioning, suggesting a diet based on resources typical of a temperate environment. It should be noted that faunal samples are available only from the Early Bronze Age context of San Giorgio – Castiona. No faunal remains associated with burials were recovered from the Copper Age or Middle Bronze Age sites. Consequently, the same faunal baseline has been applied across all periods for comparative purposes, with the inherent assumption that the local terrestrial herbivore baseline remained relatively stable over time. While period-specific faunal data would be ideal, geographic coherence was prioritised over chronological precision, as spatial variation in isotopic baselines can be substantial even between nearby contemporaneous sites in environmentally heterogeneous regions. Moreover, archaeozoological data from the Mantua region indicates substantial continuity in subsistence strategies across the Copper to Middle Bronze Ages, with agro-pastoral economies consistently dominating the lowland Po Plain (De Marinis 1997; Cardarelli 2009).

Human remains (n=85) values range between −21.1‰ and −19.0‰ (median −20.5‰) for $\delta^{13}C$ and between 8‰ and 12.1‰ (median 9.3‰) for $\delta^{15}N$. Human bone collagen $\delta^{15}N$ values are consistently higher than those of terrestrial herbivores, with a mean trophic offset of $\Delta^{15}N_{h\text{-}f}$ = 3.9±0.3‰. This offset is consistent with a diet in which animal protein (meat and/or dairy products) constitutes a substantial proportion of total protein intake, with the remainder derived from terrestrial C_3 plants. The $\delta^{13}C$ values, combined with the absence of elevated $\delta^{15}N$ values characteristic of aquatic food webs, indicate no evident contribution from freshwater or marine resources.

Carbon and nitrogen stable isotope values are shown in Fig. 2**A-D** and listed in **Supplementary Materials 1** (see Table A and Table B).

The isotopic data grouped by archaeological site show relatively consistent $\delta^{13}C$ and $\delta^{15}N$ values, despite the geographical and chronological variability. This pattern, summarised in Table 1, which reports the range and median values of $\delta^{13}C$ and $\delta^{15}N$ for each site, suggests dietary homogeneity across sites and periods. Minor variations in $\delta^{15}N$ are observable, particularly in the Middle Bronze Age. However, these differences may be partially influenced

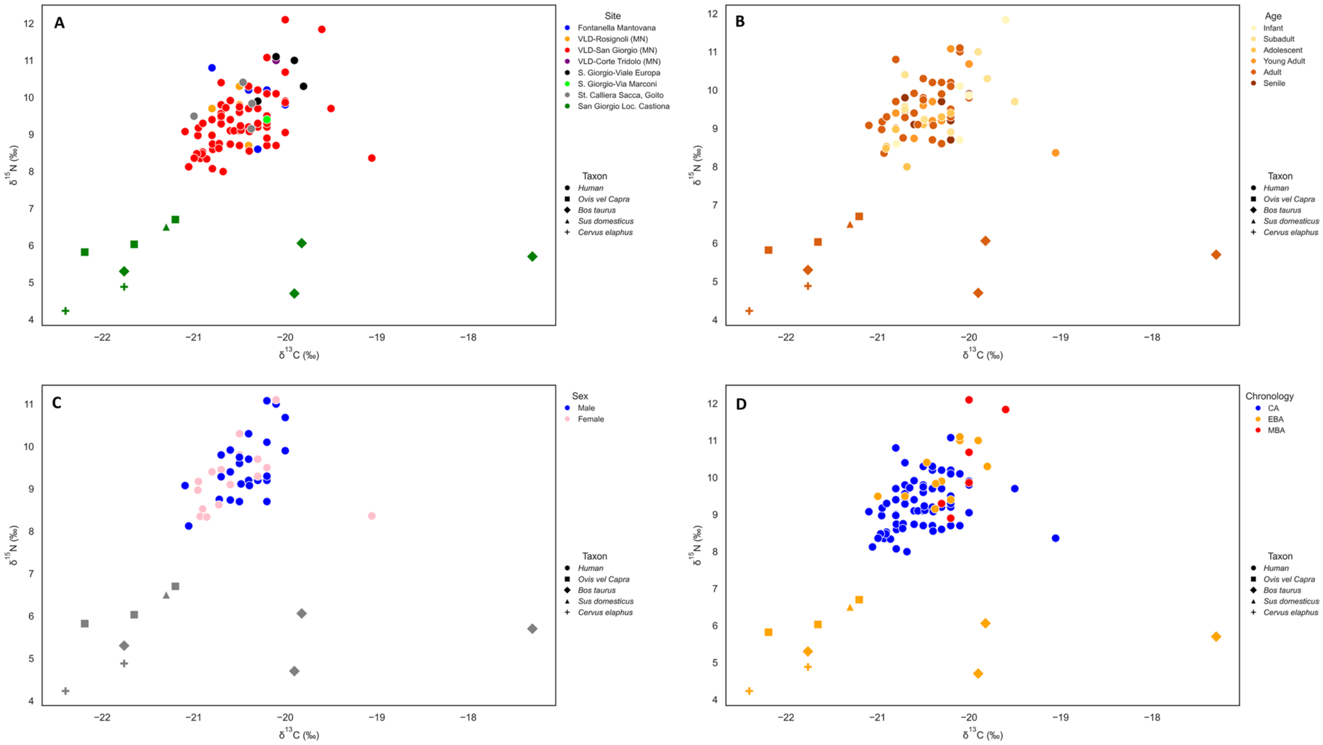

Fig. 2 Isotopic data from faunal and human remains: **A**) data grouped by archaeological site; **B**) data grouped by age category; **C**) data grouped by sex; **D**) data grouped by chronological periods

Table 1 δ^{13}C and δ^{15}N values of human samples for each investigated site

Sites	Number of samples	Period	δ^{13}C			$\delta^{15}N$		
			min	max	median	Min	max	median
Fontanella Mantovana	5	CA	-20.8‰	-20.0‰	-20.3‰	8.6‰	10.8‰	10.2‰
VLD - Rosignoli	6	CA	-20.8‰	-20.4‰	-20.5‰	8.7‰	10.3‰	9.4‰
VLD – San Giorgio	57	CA	-21.1‰	-19.1‰	-20.5‰	8.0‰	11.1‰	9.2‰
VLD – San Giorgio	1	EBA	-20.7‰			9.5‰		
VLD – San Giorgio	6	MBA	-20.3‰	-19.6‰	-20.0‰	8.9‰	12.1‰	10.3‰
VLD – Corte Tridolo	1	EBA	-20.1‰			11.0‰		
S. Giorgio – v.le Europa	4	EBA	-20.3‰	-19.6	-20.0‰	8.9‰	12.1‰	10.6‰
S. Giorgio – Via Marconi	1	EBA	-20.2‰			9.4‰		
Goito, St. Calliera -Sacca	4	EBA	-21.0‰	-20.4‰	-20.4‰	9.2‰	10.4‰	9.7‰

by the age composition of the individuals analysed, as the majority of Middle Bronze Age samples consist of young individuals. While physiological factors have been shown to influence δ^{15}N values in specific contexts such as infancy and weaning (Fuller et al. 2006), the extent to which age-related metabolic differences affect bone collagen δ^{15}N values in juveniles and adolescents beyond the weaning period remains uncertain (Waters-Rist and Katzenberg 2010). Other factors, such as differences in dietary composition or protein sources between age groups, may also contribute to the observed variation.

A Wilcoxon-Mann-Whitney test was applied to assess whether statistically significant differences existed between demographic groups. Adults and young individuals (δ^{13}C *p-value*: 0.4; δ^{15}N *p-value*: 0.6), as well as male and female individuals (δ^{13}C *p-value*: 0.1; δ^{15}N *p-value*: 0.3), have statistically similar values, suggesting no differences in the diet, except for infants, whose higher nitrogen values are related to the breastfeeding effect (Fuller et al. 2006; Tsutaya and Yoneda 2015). Similarly, there are no discernible differences in access to resources based on sex. Intra-site analyses by sex and age were not systematically conducted due to insufficient sample sizes within individual sites ($n<5$ for most sites). Among the seven sites analysed, only Valdaro San Giorgio (Copper Age) contained sufficient individuals for statistical testing. Within this site, no significant differences were detected between males and females (δ^{13}C $p=0.2$; δ^{15}N $p=0.2$) or between adults and young individuals ($\delta^{13}C$ $p=0.5$; $\delta^{15}N$ $p=0.5$), consistent with the absence of demographic patterning observed at the regional level. The pooled analytical approach therefore maximizes statistical power while providing the most robust assessment of dietary patterns across the study region.

Given the disparity in the number of samples from the Copper Age compared to those from the Middle and Early Bronze Age, for the statistical investigation we considered the samples from the two Bronze Age periods together. The human dataset includes 5 infants (age 0–6 years) and 8 subadults (age 6–12 years), to avoid potential confounding effects related to breastfeeding (Fuller et al. 2006) and growth-related metabolic differences (Waters-Rist and Katzenberg 2010), these individuals were excluded from statistical comparisons between chronological periods. The t-test was applied to assess whether there were significant differences in $\delta^{13}C$ and $\delta^{15}N$ values between the Copper Age and Bronze Age individuals (see details in **Supplementary Materials 1**, **Table C1**). The results suggest that the differences in both carbon and nitrogen isotope values do not show levels of statistical significance ($\delta^{13}C$ *p-value*: 0.1; $\delta^{15}N$ *p-value*: 0.1).

Although the mean $\delta^{15}N$ values are slightly higher in the Bronze Age group (10.1‰) compared to the Copper Age (9.2‰), and $\delta^{13}C$ values slightly less negative (-20.3‰ vs. -20.5‰), these shifts are modest and may reflect subtle changes in dietary practices, resource availability, or demographic composition, rather than clear chronological trends. The lack of statistical significance supports the overall interpretation of dietary continuity across the periods, while also acknowledging potential variation that may warrant further investigation with larger, more balanced sample sets.

Discussion

The province of Mantua is abundant in necropolises dating back to the Copper and Bronze Ages. Notably, Valdaro is considered one of the largest funerary areas in the protohistoric period of Lombardy. Unfortunately, no faunal remains associated with the burials were discovered in the analysed necropolises. Consequently, to reconstruct the ecological baseline for the analysed samples, it was necessary to rely on faunal remains from the site of San Giorgio – Castiona.

The analysed fauna, dated to the Early Bronze Age, indicates a diet primarily based on C_3 plants. The $\delta^{13}C$ values are consistent with those reported from other sites of Northern Italy, with the exception of certain specimens from Arano di Cellore, Mereto, and Olmo di Nogara, where there is evidence of millet consumption (Varalli et al. 2015, 2022; Tafuri et al. 2018; Masotti et al. 2019). The nitrogen values similarly align well with contemporary contexts in northern Italy (Varalli et al. 2015, 2016, 2022; Tafuri et al. 2018; Masotti et al. 2019). The elevated $\delta^{15}N$ values, compared to those obtained in Central and Southern Italy (e.g., De Angelis et al. 2019; Arena et al. 2020; Rumolo et al. 2020; Cortese et al. 2022; Romboni et al. 2022), may be attributable not only to the local habitat but also to the possibility that the analysed faunal remains consumed fertilised plants (Bogaard et al. 2007, 2013). It should be acknowledged, however, that the reasons for higher-than-normal nitrogen values in fauna may be manifold and not solely related to the consumption of manured plants; factors such as grazing in high-altitude pastures, grassland environments, or neighboring locations with similar isotopic signatures, as well as stabling on nitrogen-enriched soils such as marshy or arid areas and water scarcity, may also play a role (Ambrose 1991; Tafuri et al. 2009; Groß-Schmölders et al. 2021).

Concerning human remains, the isotopic data reveal consistent dietary patterns across all sites investigated. The human $\delta^{13}C$ values closely match the herbivore baseline from San Giorgio – Castiona, as reflected in the minimal carbon offsets ($\Delta^{13}C_{h\text{-}f}$ = 0.2–0.9‰, Table 2). This indicates that both humans and animals consumed resources from the same terrestrial C_3 ecosystem, consistent with the dietary patterns observed at other contemporary northern Italian Bronze Age sites such as Arano di Cellore, Ballabio, and Grotta del Pertuso, where C_3 plants dominated subsistence strategies (Tafuri et al. 2009; Varalli et al. 2016, 2022; Masotti et al. 2019). In contrast, significant C_4 plant consumption has been documented at other contemporary sites, such as Bovolone, Dossetto di Nogara, La Vallona di Ostiglia, Olmo di Nogara, and Sedegliano Dossetto di Nogara (Tafuri et al. 2018; Varalli et al. 2022), but no such evidence emerges from our assemblages. The nitrogen isotope values show greater variability and are systematically enriched relative to herbivores, yielding human-animal offsets ($\Delta^{15}N_{h\text{-}f}$) ranging from 3.7 to 5.5‰ across sites (Table 2). These values clearly indicate trophic level enrichment consistent with animal protein consumption. This is based on the principle

Table 2 Offsets calculated using regional faunal baseline from San Giorgio – Loc. Castiona. For sites with $n=1$, standard errors could not be calculated

Site	Number of humans	$\Delta^{13}C$	$\Delta^{15}N$
Fontanella Mantovana	5	0.6±0.5‰	4.4±0.5‰
VLD – Rosignoli	5	0.3±0.5‰	3.9±0.4‰
VLD – San Giorgio (CA)	57	0.4±0.5‰	3.7±0.3‰
VLD – San Giorgio (EBA)	1	0.2‰	4‰
VLD – San Giorgio (MBA)	6	0.9±0.5‰	4.9±0.6‰
VLD – Corte Tridolo	1	0.8‰	5.5‰
S. Giorgio – Viale Europa	4	0.9±0.5‰	5.1±0.4‰
S. Giorgio – Via Marconi	1	0.7‰	3.9‰
St. Calliera Sacca, Goito	4	0.4±0.6‰	4.2±0.4‰

that each trophic level is associated with a $\delta^{15}N$ enrichment, indicating that humans occupied a higher trophic position than herbivores (O'Connel et al. 2012; Schulting et al. 2022).

The range of $\Delta^{15}N_{h\text{-}f}$ values suggests some variability in the relative contributions of animal versus plant protein between sites (e.g., Valdaro – Corte Tridolo, S. Giorgio – Viale Europa, San Giorgio Valdaro – CA), possibly reflecting subtle differences in access to animal resources or local subsistence strategies. Regarding freshwater fish consumption, while the proximity to watercourses makes this resource potentially available, the human $\delta^{15}N$ values provide no clear isotopic signature of significant freshwater fish intake.

Moreover, regarding the $\Delta^{15}N$ diet-collagen offset, it is important to acknowledge ongoing debate surrounding the diet-collagen nitrogen offset used in dietary models. O'Connell et al. (2012) estimated a $\Delta^{15}N$ diet-collagen of around 6‰ based on controlled dietary studies, higher than the traditionally assumed 3–4‰ in archaeological contexts. This implies that prehistoric human diets may have contained a lower proportion of animal protein than previously inferred. As Hedges and Reynard (2007) point out, applying a 3–4‰ offset often leads to estimates of 60–80% animal protein intake in prehistoric European farmers, values that are significantly higher than those observed in modern developed countries and roughly double those in developing countries. If a 6‰ offset is applied instead, the estimated contribution of animal protein would decrease by approximately one-third to one-half. In this study, we adopt a cautious approach by considering both scenarios in our interpretation. Our $\Delta^{15}N_{h\text{-}f}$ values range from 3.7 to 5.5‰ (Table 2), clearly indicating consumption of animal protein. However, discerning the exact percentage contribution of animal protein to the diet based solely on these qualitative isotopic offsets is unreliable, particularly given the ongoing debate between the traditional 3–4‰ and the higher 6‰ diet-collagen offset. Given the uncertainties inherent in both approaches, we interpret our isotopic data as indicating a mixed subsistence economy in which animal protein was important but not necessarily predominant, with substantial contributions from C_3 plant sources (cereals and legumes) alongside animal products. This interpretation is consistent with the archaeozoological evidence from contemporary sites in the region, which documents mixed farming economies with both crop cultivation and animal husbandry (De Grossi Mazzorin and Riedel 1997; Cattani and Marchesini 2010; Bietti Sestieri 2015). The application of the FRUITS Bayesian mixing model allows us to move beyond simple offset-based interpretation and obtain more concrete quantitative estimates of dietary proportions, accounting for the complexities and uncertainties inherent in isotope-to-diet reconstruction.

As above-mentioned, there is no dietary differentiation by sex or age observed in our dataset. This absence has important implications for understanding social organisation in protohistoric Mantua. Dietary homogeneity is particularly noteworthy given the archaeological evidence for social differentiation in burial practices, especially the Copper Age warrior burials with weapons and status goods, that suggests an emerging social hierarchy and gendered roles within these communities (de Marinis 2010; Longhi 2010; Bietti Sestieri 2015). Our isotopic data demonstrate that such social differentiation did not translate into differential dietary access. To the best of our knowledge, evidence for differential access to resources based on gender or age has only been found in a few Italian protohistoric contexts (e.g., Tafuri et al. 2009, 2018; Masotti et al. 2019; Varalli et al. 2022), despite the fact that numerous studies have discussed social differentiation during the Copper and Bronze Age (e.g., Peroni 1996; Pedrotti 1998; Cazzella and Guidi 2011). Nevertheless, interpreting the absence of significant dietary differences requires caution. While our data demonstrate dietary homogeneity among buried individuals, this pattern cannot, by itself, be taken as evidence of egalitarian or non-stratified societies. It is likely that access to formal funerary rites was restricted to a privileged minority (Cocchi Genik 2014). This interpretation is also suggested by the demographic composition of the largest cemetery, excavated in 2017 at San Giorgio Valdaro, where the proportion of subadults is far lower than expected, given the high rates of infant and child mortality typical of pre-modern societies (Goodman and Armelagos 1989; De Marinis 2003), indicating that the human sample recovered from the site does not provide a reliable reflection of the community's demographic structure.

Accordingly, Bayesian mixed model (Fernandes et al. 2014) has been used to probabilistically reconstruct the human diet of each archaeological site, accounting for the contribution of multiple food sources. The models included infants, whose isotopic composition reflects the dietary habits of the adult female population and, consequently, of the broader community (Fuller et al. 2006; Tsutaya and Yoneda 2015). The box plots obtained for the Copper Age sites of Fontanella Mantovana, Valdaro – Rosignoli, and San Giorgio Valdaro (Fig. 3A-C) confirm significant animal protein consumption (62–65%), followed by plant resources (30–35%) and freshwater fish (3–4%) (see details in **Supplementary Materials 2**, **Table E.1-E.3**). Similarly, the models applied to the Bronze Age sites of Valdaro – Corte Tridolo, San Giorgio Valdaro, San Giorgio – Viale Europa, San Giorgio – Via Marconi, and the necropolis of Goito in

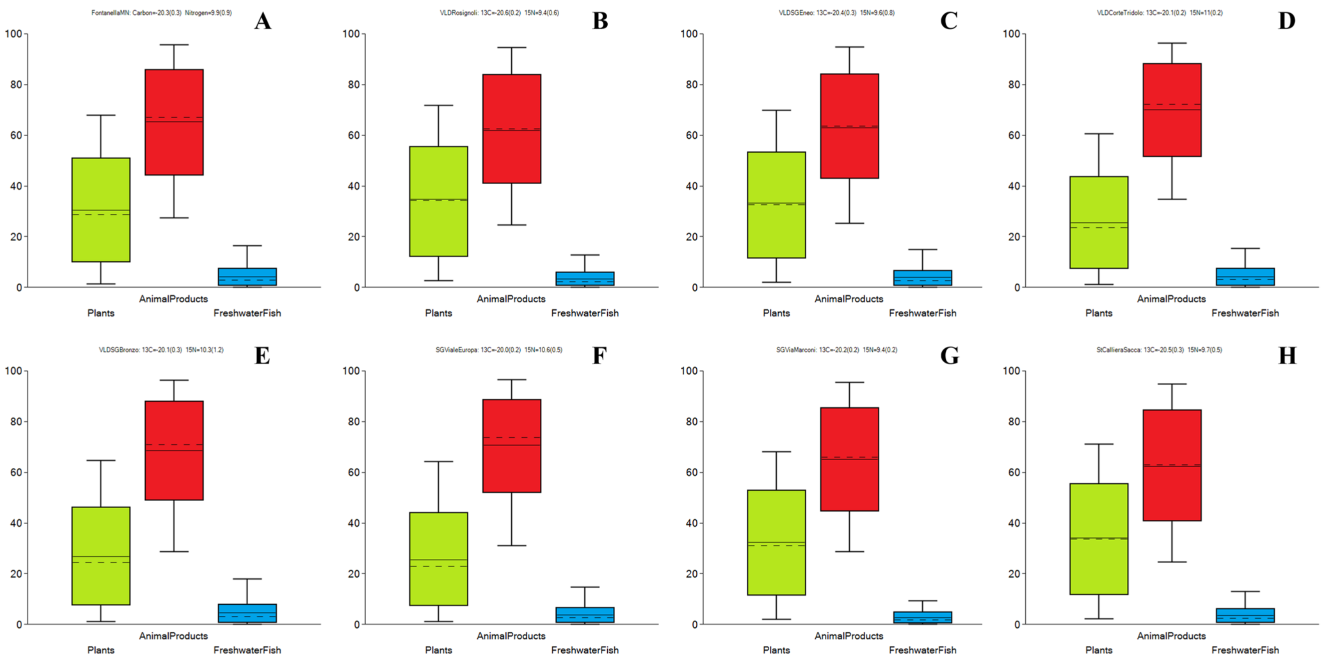

Fig. 3 Estimated contributions of plants, animal products, and freshwater fish to the diets of individuals using the Bayesian model FRUITS: (**A**) Fontanella Mantovana, (**B**) Valdaro – Rosignoli, (**C**) Valdaro San Giorgio (Copper Age), (**D**) Valdaro – Corte Tridolo, (**E**) Valdaro – S. Giorgio (Early-Middle Bronze Age), (**F**) San Giorgio – Viale Europa, (**G**) San Giorgio – Via Marconi, (**H**) necropolis of Goito in Strada Calliera-Sacca

Strada Calliera-Sacca (Fig. 3D-H) suggest a predominant consumption of terrestrial animal protein (62–71%), followed by plant resources (25–34%) with occasional intake of freshwater fish (3–5%). These results suggest dietary continuity across the Copper and Bronze Ages (see details in **Supplementary Materials 2**, **Table E.4-E.8**).

Although the FRUITS model provides a probabilistic framework for estimating dietary contributions, its application in this study should be interpreted with caution due to several methodological limitations. The same faunal assemblage was used as a baseline for both Copper and Bronze Age individuals due to the lack of associated animal remains from the funerary contexts; however, these specimens derive from a nearby settlement within the same geomorphological area, which minimises potential ecological bias. Similarly, the plant isotopic baseline was derived from published northern and central Italian datasets (Cortese et al. 2024), representing the most comparable values currently available. Given these constraints, the results should be viewed as indicative rather than absolute, providing an analytical tool to explore dietary trends and evaluate the relative importance of terrestrial animals versus plant resources. Future work incorporating local plant and faunal isotopic baselines will allow for a more refined interpretation.

Importantly, the evidence for a diet dominated by terrestrial animal protein and C_3 plants is strongly supported by multiple lines of archaeological evidence from northern Italy. Archaeozoological studies from contemporaneous sites in the Po Plain document intensive livestock management systems characteristic of the region's agro-pastoral economy (de Marinis 1997). During the Copper Age, faunal assemblages from northern Italian sites show a prevalence of ovicaprines with limited representation of wild fauna, reflecting an economy already oriented toward domestic animal husbandry (Catttani, Marchesini 2010; Maini 2010). This pattern intensifies during the Bronze Age, when archaeozoological data from Terramare settlements reveal that domestic species, particularly *Bos taurus*, followed by *Ovis* vel *Capra* and *Sus domesticus*, constituted over 85% of faunal assemblages, with hunting relegated to a marginal role (Cattani and Marchesini 2010; De Grossi Mazzorin and Riedel 1997). The dominance of cattle, exploited for traction, secondary products, and meat, alongside significant sheep/goat herding for wool and dairy production, aligns with the elevated $\delta^{15}N$ values observed in our human sample, consistent with substantial consumption of animal protein from managed herds (Sabatini et al. 2018; Trentacoste et al. 2018). Archaeobotanical evidence from Bronze Age sites across northern Italy confirms the widespread cultivation of cereals and legumes (Mercuri et al. 2006; Rottoli and Castiglioni 2009) confirming the important role of cereal agriculture in the analysed periods. The low consumption of freshwater fish highlighted in our data, despite the proximity of study sites to lacustrine and riverine environments, is consistent with broader patterns documented in other contemporaneous contexts: although fishing was practiced, it appears to have played a marginal economic role compared to agro-pastoral production (Fiorentino et al. 2004). This terrestrial focus of subsistence strategies reflects a widespread pattern in Po Plain economies, where intensive agricultural and pastoral systems dominated resource exploitation (Cardarelli 2009; Bietti Sestieri 2015; Trentacoste et al. 2018).

Finally, a striking pattern in our dataset is the complete absence of millet consumption, even among Middle Bronze Age individuals. This is surprising given the regional context: the Valdaro area and the site of Olmo di Nogara are less than 50 km apart, yet at the Olmo di Nogara site, evidence of C_4 plant consumption exists as early as the Middle Bronze Age (Tafuri et al. 2018). Similarly, in northern Italy, the earliest evidence of millet consumption dates back to the Early Bronze Age (Tafuri et al. 2018). The absence of millet in our sample may reflect the uneven distribution of millet cultivation across the Po Plain (Varalli et al. 2015). However, it should be noted that the limited number of Middle Bronze Age individuals analysed may also contribute to this pattern. The regional variability in millet adoption likely depended on a combination of local environmental conditions, agricultural choices, and exchange networks. The proximity between Valdaro and Olmo di Nogara therefore suggests that millet use was shaped by more than geographic distance alone, reflecting complex, community-specific subsistence strategies.

When examining Bronze Age isotopic data across the Italian Peninsula, a distinctive pattern emerges regarding millet use. At sites where C_4 plant signatures are present, they typically appear either exclusively in human skeletal remains or exclusively in faunal assemblages, suggesting differential allocation strategies (**Supplementary Materials 1 – Table D**). Olmo di Nogara stands out as the only site where both humans and domestic animals exhibit C_4 signatures (Tafuri et al. 2018). This pattern suggests that millet, when cultivated, may have been selectively allocated either for direct human consumption or as animal fodder depending on community-specific economic strategies and resource management priorities.

In the interest of transparency and to guide future research directions, we acknowledge several constraints in this study: (i) the absence of faunal remains in the funerary contexts required the use of comparative samples from a nearby settlement, which may not fully represent the local ecological baseline. While ideally each period would have contemporaneous faunal data, the geographic consistency of the baseline and evidence for subsistence continuity mitigate this limitation; (ii) collagen preservation varied, and only 85 out of 101 human samples provided usable data; (iii) the small number of individuals dating to the Middle Bronze Age limits our ability to detect potential dietary changes during this period. Despite these constraints, the analytical and interpretative approaches adopted here allow for a robust reconstruction of dietary patterns. Future isotopic research should continue to expand the dataset and integrate a broader range of archaeological contexts to improve our understanding of past lifeways.

Conclusion

The sites selected for this study span a broad chronological range, from the Copper Age to the Middle Bronze Age. These sites are geographically close to one another and provide a detailed picture of the dietary practices in protohistoric Lombardy. Furthermore, this study presents one of the first comprehensive isotopic datasets for the Copper, Early and Middle Bronze Age in northern Italy.

The data obtained reveal no significant differences between the Copper and Bronze Age periods and dietary patterns appear to have remained largely consistent across these two periods. The faunal remains analysed indicate a diet based on C_3 plants, and the consumption of manured plants by domesticated animals cannot be ruled out.

Human diets reflect a terrestrial environment, with a predominant consumption of animal proteins, followed by C_3 plants. The intake of freshwater fish appears to have been limited, despite the proximity to water sources. No clear differences emerged by sex or age, suggesting relatively homogeneous subsistence strategies within and between communities. However, these patterns reflect only those individuals granted access to formal burial and may not represent the broader living community (Cocchi Genik 2014; De Marinis 2003). A comparison with published literature indicates that the consumption of C_4 plants was not prevalent among the Bronze Age communities studied in this work, even though nearby archaeological contexts show clear evidence of millet consumption (e.g., Olmo di Nogara – Tafuri et al. 2018); nevertheless, the small sample size for the Middle Bronze Age ($n=6$) restricts definitive conclusions about temporal dietary shifts in the later period. The dietary continuity observed across the Copper to Middle Bronze Ages in our isotopic data finds corroboration in the archaeological record. The subsistence choices remained stable throughout these periods; this stability suggests that the economic foundations of Po Plain societies proved resilient and adaptable across subsequent cultural transitions (Bietti Sestieri 2015).

This study contributes meaningfully to the existing published data, enhancing our understanding of economic and dietary practices within a complex and dynamic panorama. Even though isotopic analyses have become conventionally applied across the majority of pre-protohistoric sites in Italy, it remains desirable to conduct studies on as many contexts as possible.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12520-026-02534-1.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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