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Animal Management Strategies in Bronze Age Italy. Integrating Isotopes, Zooms, Bioarchaeology and Land Use Modelling

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Abstract – Animal management strategies in Bronze Age Italy. Integrating isotopes, ZooMS, bioarchaeology and land use modelling. – The reconstruction of animal management practices is crucial for understanding prehistoric societies, their subsistence economies, and their relationships with the environment. Recent advances in biomolecular and biogeochemical research have provided key methodological tools for addressing these questions, which are particularly relevant for the study of emerging complex societies, such as those of 2nd millennium BCE Italy. In this study, we apply an integrated research protocol combining zooarchaeology, ZooMS, and strontium, oxygen, and carbon isotope analyses to investigate husbandry practices at three key Italian Bronze Age sites – Solarolo-via Ordiere, Montarice, and Coppa Nevigata – each located within distinct ecosystems. Our results indicate that Bronze Age communities developed diversified management strategies adapted to local ecological conditions, aimed at maximising primary production. Marked differences emerge between lowland systems (the Po and Tavoliere plains), characterised by residential management of domestic herbivores, and the hilly areas of Central Italy (Marche region), where transhumance were likely employed to prevent overgrazing and consequent soil erosion in the immediate hinterland of settlements. Furthermore, isotopic evidence indicates the integration of cultivated C_4 plants (likely broomcorn millet) into animal diets, and documents mobility of livestock individuals at both local and long-distance scales.

Riassunto – Strategie di gestione animale nell'età del Bronzo italiana. Un'integrazione tra dati isotopici, ZooMS, bioarcheologia e modellazione di sfruttamento del territorio. – La ricostruzione delle pratiche di gestione degli animali è fondamentale per la ricostruzione delle società preistoriche, le loro economie di sussistenza e i loro rapporti con l'ambiente. I recenti progressi nella ricerca biomolecolare e biogeochimica hanno fornito nuovi strumenti metodologici per affrontare queste questioni, particolarmente rilevanti per lo studio delle società complesse, come quelle dell'Italia del II millennio a.C.

In questo studio applichiamo un protocollo di ricerca integrato che combina dati archeozoologici, ZooMS e isotopici dello stronzio, dell'ossigeno e del carbonio per indagare le pratiche di allevamento in tre importanti siti italiani dell'età del Bronzo – Solarolo-via Ordiere, Montarice e Coppa Nevigata – ciascuno situato in ecosistemi distinti. I risultati indicano che tali comunità svilupparono strategie di gestione diversificate, adattate alle condizioni ecologiche locali, con l'obiettivo di massimizzare la produzione primaria. Emergono differenze marcate tra i sistemi di pianura (la pianura Padana e il Tavoliere), caratterizzati da una gestione stanziale degli erbivori domestici, e le aree collinari dell'Italia centrale (area medio-adriatica), dove si ricorreva probabilmente alla transumanza per prevenire il pascolamento intensivo e la conseguente erosione del suolo nell'immediato hinterland degli insediamenti.

Inoltre, le evidenze isotopiche indicano l'integrazione di piante coltivate a metabolismo C_4 (probabilmente il miglio) nella dieta degli animali e documentano la mobilità dei capi di bestiame sia su scala locale, sia su lunga distanza.

Parole chiave: Età del bronzo, strategie di gestione animale, analisi isotopiche.

Keywords: Bronze Age, Animal Management Strategies, Isotope Analysis.

INTRODUCTION

The analysis of husbandry practices represents a fundamental step in the reconstruction of the primary economy, land use, and cultural adaptations of ancient communities to their ecosystems. Zooarchaeological methods provide a wide range of data for this purpose, including the relative frequencies of domestic and wild taxa, the proportions of major food-producing species (caprines, cattle, and pigs), sex ratios, age-at-death profiles, as well as estimates of body mass.

In recent decades, advances in biomolecular archaeology have substantially expanded the interpretive potential of zooarchaeological assemblages. While ancient DNA (aDNA) and ZooMS (Zooarchaeology by Mass Spectrometry) primarily address genetic relationships and taxonomic identification, isotope analyses contribute complementary information by investigating animal diet, mobility, and seasonality. These methods offer a means to investigate how herds were managed across landscapes and seasons, how animals were integrated into agricultural systems and how pastoral practices responded to environmental changes and socio-economical demands.

Given the importance of integrating these methods in the most standardised, replicable and efficient way, here we present a general overview of the isotopic methods and protocols that can be applied to faunal assemblages, and illustrate the potential of this approach applied to three key Italian Bronze Age contexts: Solarolo-via Ordiere (Ravenna province, Northern Italy), Montarice (Ancona province, Middle Adriatic coast), and Coppa Nevigata (Foggia province, Tavoliere plain)[1]. The sites were selected based on several criteria: (1) the availability of extensive archaeological documentation; (2) the substantial presence of domestic faunal remains; (3) a well-defined and consistent chronological framework spanning the Middle to Recent Bronze Age (MBA-RBA); and (4) their distribution across distinct climatic and ecological settings, enabling a more robust comparative analysis. The new results are then discussed in relation to available environmental data and land-use models, with the aim of contextualising animal management strategies within the territories and ecological niches occupied by these settlements.

1. THE IMPORTANCE OF ANIMAL HUSBANDRY IN THE CONTEXT OF BRONZE AGE ITALY

The 2nd millennium BCE witnessed a marked increase in the number of sites across Europe and the Mediterranean. This phenomenon is also clearly observable in the various regions of Italy (Cardarelli *et al.* in this volume). In parallel, assuming that an increased density of archaeological evidence reflects a phase of population pressure (Drennan *et al.* 2015), kernel density estimation (KDE) and summed probability distributions (SPDs) of calibrated radiocarbon dates from the Italian territory indicate dramatic expansions during the Early Bronze Age (2200-1700 BCE) and a phase of consolidation during the Middle Bronze Age (1700-1350 BCE) (Palmisano *et al.* 2021; Parkinson *et al.* 2021).

This pattern is partly attributable to the low visibility of settlements in the preceding 3rd millennium, which were often occupied for relatively short periods and left ephemeral archaeological traces, at least in the alluvial plain zones. However, the proliferation of evidence (i.e., sites) in the earliest phases of the Bronze Age (2200 BCE onwards) also reflects a generalized stabilization of settlements, organization of production and demographic expansion (Peroni 1996). From the Middle Bronze Age, communities began to develop a more effective relationship with their environment, stabilizing the productive potential of both agriculture and animal husbandry and creating a more conspicuous food surplus. This sustained production was supported by several strategies, such as crop rotation, renovation of soil fertility through periods of fallow, ploughing, manuring and drainage/irrigation systems (Cremaschi 2009a, 2009b; Mercuri-Sadori-Uzquiano Ollero 2011; Cattani 2021). This is particularly visible and well-documented in the framework of the Terramare system in the Po plain (Cardarelli 2010 and references therein).

Population can increase substantially in a given region when mortality decreases and/or natality rates rise. In general, increased food availability reduces the risk of malnutrition and, consequently, lowers infant mortality rates, while also enhancing female fertility and overall birth rates (Chamberlain 2007). A systematic evaluation of palaeopathological markers from 868 burials ranging from the EBA and advanced MBA in the Po Plain showed a drastic decrease in markers of metabolic disease and nutritional stress at the transition to the MBA, coinciding with the emergence of the Terramare cycle (Capecci *et al.* 2024: 122-123). This trend has been interpreted as the result of improved living conditions and nutritional patterns during the Terramare period, likely linked to a substantial increase in food production and availability. As noted above, this increased food availability derived from the application of more effective agro-pastoral practices, improved food storage and preservation methods, and greater investment in animal-derived products, all of which contributed to a more secure, balanced, and protein-rich diet.

Beyond demographic expansion, the Bronze Age witnessed an unprecedented development of exchange networks, both in terms of the intensity and diversity of exchanged goods and the geographical extent of maritime and terrestrial connections. Livestock presumably constituted a significant component of exchange and gift econ-

[1] The analyses presented in this study constitute part of a broader dataset generated within the framework of the HERDS project, which includes a larger number of Bronze and Iron Age sites distributed across different regions of Italy (Cardarelli *et al.* in this volume). The results discussed here should therefore be considered preliminary. A comprehensive analysis and a broader discussion of animal management strategies during the Bronze Age will be presented in future publications.

omies. For example, a recent study on pigs documented the introduction of an italic mtDNA haplogroup into palatial and post-palatial contexts in the Peloponnese, suggesting preferential connectivity between Central Mediterranean and Aegean societies (Meiri *et al.* 2019).

With regard to mobility, last years' isotopic research has focused predominantly on human individuals, while animals have largely been treated as proxies for establishing the local isotopic baselines. In contrast, fewer studies have specifically investigated patterns of livestock management, which appear of great relevance for the understanding of past societies.

Transhumance, in particular, occupies a central position in theoretical debates concerning the formation of the *Civiltà Appenninica*, since the work of Salvatore Maria Puglisi (Puglisi 1959). According to the scholar, the widespread evidence of implements used in the processing of animal-derived products indicates that pastoralism and transhumance were structural components of communities settled along both the eastern and western sides of the Apennine mountain chain. In his view, the seasonal movement of sheep and goat herds towards Apennine upland pastures represented the principal mechanism of interaction and cultural transmission, facilitating the development of a peninsular koine. However, this and similar hypotheses centred on animal mobility still require empirical cross-validation (see also Carrer-Migliavacca 2019). Here we argue that isotope analysis can provide a substantial contribution toward this objective.

2. THE USE OF ISOTOPE DATA TO INTERPRET ANIMAL MANAGEMENT STRATEGIES AND ECOLOGY

Isotope analysis has become a central tool for investigating animal management strategies and ecological interactions in archaeological contexts. Four isotopic systems are most commonly employed for this purpose: carbon ($\delta^{13}C$), nitrogen ($\delta^{15}N$), oxygen ($\delta^{18}O$), and strontium ($^{87}Sr/^{86}Sr$). Together, these isotopic ratios reflect the composition of the animal diets and drinking water, as well as the characteristics of the soils and underlying geolithology in which food resources grew.

More specifically, $\delta^{13}C$ and $\delta^{15}N$ values are primarily influenced by dietary inputs (e.g. the consumption of C_3 and/or C_4 plants and the level of protein intake), while also being modulated by broader ecological parameters, such as soil exposure, precipitation rates, and soil organic matter content. $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values are largely controlled by local geolithology and water composition and temperature, respectively, therefore providing insights into animal provenance and potential mobility across seasons or different life stages.

The type and interpretative value of isotopic data depend on sampling and analytical protocols. Analyses of $\delta^{13}C$ and $\delta^{15}N$ generally require preservation of organic components, most commonly collagen, which can be extracted from either bone or dentine. In contrast, $^{87}Sr/^{86}Sr$, $\delta^{13}C$ and $\delta^{18}O$ are preferentially measured on tooth enamel.

For both tooth enamel and dentine, sampling may be conducted either in bulk or using sequential methods, as described in detail below. Tooth enamel, in particular, represents an optimal substrate for isotopic analysis, as it undergoes minimal (or none) remodelling during the individual's lifetime and is relatively resistant to chemical diagenesis in post-depositional environments. Sequential sampling involves the extraction of a series of samples starting from the earliest formed ('older') portions of enamel and progressing along the tooth growth axis[2]. This approach allows isotopic variation to be tracked throughout the developmental stage of the tooth, reflecting changes in diet, water intake, or mobility across the seasons.

2.1 STRONTIUM

Strontium is one of the most widely used tracers of mobility and provenance in archaeological and palaeoecological research, with applications to investigate movements of humans and animals, exchange networks and animal trade (e.g. Lee-Thorp 2008; Montgomery 2010). In nature Sr has four isotopes (^{84}Sr, ^{86}Sr, ^{87}Sr, ^{88}Sr), of which ^{87}Sr

[2] For example, the third molar (M3) crowns of sheep/goat forms at 9-12 months of age and is completed around 18-22 months of the individual's life. In cattle, M3 crown formation begins 6-9 months after birth and is completed around 18-24 months of the individual's life (Barone 2001).

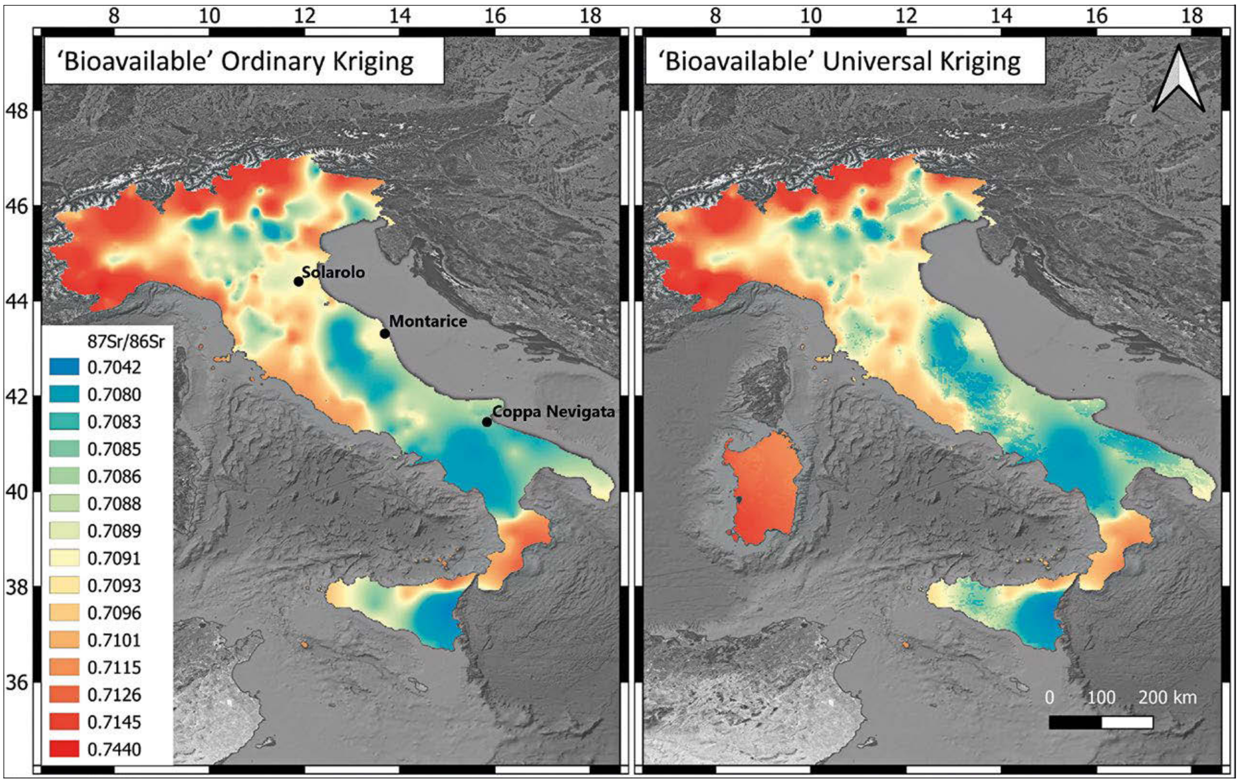

Fig. 1. $^{87}Sr/^{86}Sr$ isoscape of Italy, using different geostatistical models (Ordinary and Universal Kriging; after Lugli *et al.* 2022).

$^{87}Sr/^{86}Sr$ isoscape del territorio italiano, ottenuto con i due metodi geostatistici (Ordinary and Universal Kriging; Lugli et al. 2022).

is radiogenic, produced by the beta-decay of ^{87}Rb. Because of this, the $^{87}Sr/^{86}Sr$ ratio varies across the landscape mainly as a function of bedrock type, initial Rb/Sr ratio and geological age. Older, Rb-rich rocks tend over time to yield higher (more radiogenic) $^{87}Sr/^{86}Sr$ ratios.

Strontium enters the ecosystem through weathering of bedrock, moving from rocks to soils and waters and subsequently into plants and animals as 'bioavailable' strontium (Evans *et al.* 2010). Notably, the $^{87}Sr/^{86}Sr$ signal is transferred from bedrock to soil/water, plants and tissues with negligible isotopic fractionation. In mammals, Sr substitutes for Ca in mineralized tissues, recording the isotopic composition of local food and water consumed during tissue formation. Tooth enamel is particularly important because it forms at different lifetimes without subsequent remodelling and is more resistant than bone to alteration in post depositional settings.

An important step in Sr based mobility studies is establishing the local bioavailable Sr baseline (the '*isoscape*'). Bedrock values can differ from the Sr that enters the food chain, which might reflect a mixture of sources including weathered bedrock, groundwater, atmospheric inputs and rainfall (Price *et al.* 2002; Bentley 2006). For this reason, local baselines are built using modern plants and waters and archaeological fauna/microfauna with limited home ranges. Once established, these baselines allow the $^{87}Sr/^{86}Sr$ values of animal enamel to be evaluated: values consistent with the baseline suggest local life, while differences may indicate non-local origin or seasonal movements (i.e. transhumance).

The reliability of such interpretations depends strongly on the spatial resolution and quality of the isoscape. Recent work has substantially expanded the Sr dataset for the Italian territory, enabling the construction of a national isoscape based on 1,831 measurements derived from plants, modern and archaeological animals, snails, soils, and waters (fig. 1) (Lugli *et al.* 2022). Nevertheless, the assessment of the 'local signatures' can be challenging, as each type of environmental source is characterized by its benefits and limitations (Holt *et al.* 2021; Spies *et al.* 2025). Therefore, besides the comparison of animal *vs* environment Sr signatures, it is important to evaluate the internal distribution of faunal data, to identify internal variability and potential outliers, indicative of mobility.

Since 2022, additional studies have further enriched the Italian strontium isoscape, although gaps remain. Northern, Central, and Southeastern Italy are well covered, whereas the Middle Adriatic coast, Sicily, and Sardinia require further refinement. Nowadays, isoscapes are built with increasingly sophisticated geostatistical and machine learning approaches and are widely used to predict $^{87}Sr/^{86}Sr$ across regions to strengthen provenance assignments and mobility interpretations (Gigante *et al.* 2023; Holt *et al.* 2025; Lugli *et al.* 2022; Scaggion *et al.* 2025).

2.2 Oxygen

Oxygen occurs in a wide range of solid, liquid and gaseous compounds and has three naturally occurring stable isotopes: ^{16}O (99.76%), ^{17}O (0.0384%) and ^{18}O (0.205%). Because ^{16}O and ^{18}O are by far the most abundant isotopes, oxygen isotope studies most commonly focus on the $^{18}O/^{16}O$ ratios expressed as $\delta^{18}O$.

In geochemistry and bioarcheology, $\delta^{18}O$ is especially valuable because it links environmental water to animal tissues through well understood fractionation processes, making it useful for reconstructing climate and past environments, investigating drinking behaviour, and aspects of provenance and mobility (Pederzani-Britton, 2019).

Oxygen isotope compositions are typically reported using delta (δ) notation in per mill (‰). In delta notation, a sample isotope ratio is expressed relative to an international standard. For oxygen this is commonly VSMOW (Vienna Standard Mean Ocean Water) but could also be VPDB (Vienna Pee Dee Belemnite).

The general formula is:

– $\delta^{18}O$ (‰) = [(Rsample / Rstandard) − 1] × 1000

where R is the $^{18}O/^{16}O$ ratio.

Because different laboratories may use different reporting scales (SMOW vs VPDB for carbonates), it is important to always state the reference standard used when presenting $\delta^{18}O$ values.

In mammals, oxygen-isotope analysis is commonly performed on bioapatite, the mineral component of skeletal tissues such as tooth enamel and bone. Bioapatite contains oxygen in two ionic forms both suitable for isotopic measurements: phosphate (PO_4^{3-}) and carbonate (CO_3^{2-}) groups present within the apatite structure. Although phosphate is more abundant and more resistant to alteration, carbonate-based measurements are now widely used because they have shown to be equally accurate and precise, while being easier, faster and more cost-effective in analytical practice (Iacumin *et al.* 1996). Both phosphate and carbonate in bioapatite form in isotopic equilibrium with body water, but they undergo different fractionation pathways, which can introduce species-specific offsets (Iacumin *et al.* 1996). Oxygen isotope carbonate ($\delta^{18}Oc$) data (in SMOW ‰) can be converted in phosphate ($\delta^{18}Op$) values using the equation from Iacumin *et al*. (1996), i.e. $\delta^{18}Op = \delta^{18}Oc * 0.98-8.5$.

Mammalian body water oxygen derives primarily from drinking water but also from oxygen bound in organic food compounds and atmospheric O_2 inhaled during respiration (Lutz-Kolodny-Horowitz 1984). The $\delta^{18}O$ of these inputs varies geographically because meteoric water is shaped by multiple environmental parameters, including precipitation regime, humidity, continentality, altitude and latitude, which all depend on temperature differences (D'Angela and Longinelli 1990). In Italy, annual average precipitation $\delta^{18}O$ values are significantly negative in Alpine and upper Apennine areas and progressively increase towards the coasts and southern regions (fig. 2). For this reason, $\delta^{18}O$ is expected to vary significantly among the three selected sites.

In continental temperate climates, $\delta^{18}O$ typically shows a marked seasonal cycle: lower values in winter and higher values in summer in the Northern hemisphere (Pederzani-Britton 2019). If tooth enamel is sampled sequentially along the growth axis, these seasonal cycles can be preserved, enabling seasonal reconstructions relevant to ecology and herding strategies, detecting shifts in water sources or elevation movements. Ingested water isotope values ($\delta^{18}Ow$) can be calculated starting from $\delta^{18}Op$ using taxon-specific equations, e.g. for goats $\delta^{18}Ow = (\delta^{18}Op-24.1)/0.88$ (Huertas *et al.* 1995). Water values can be converted to air

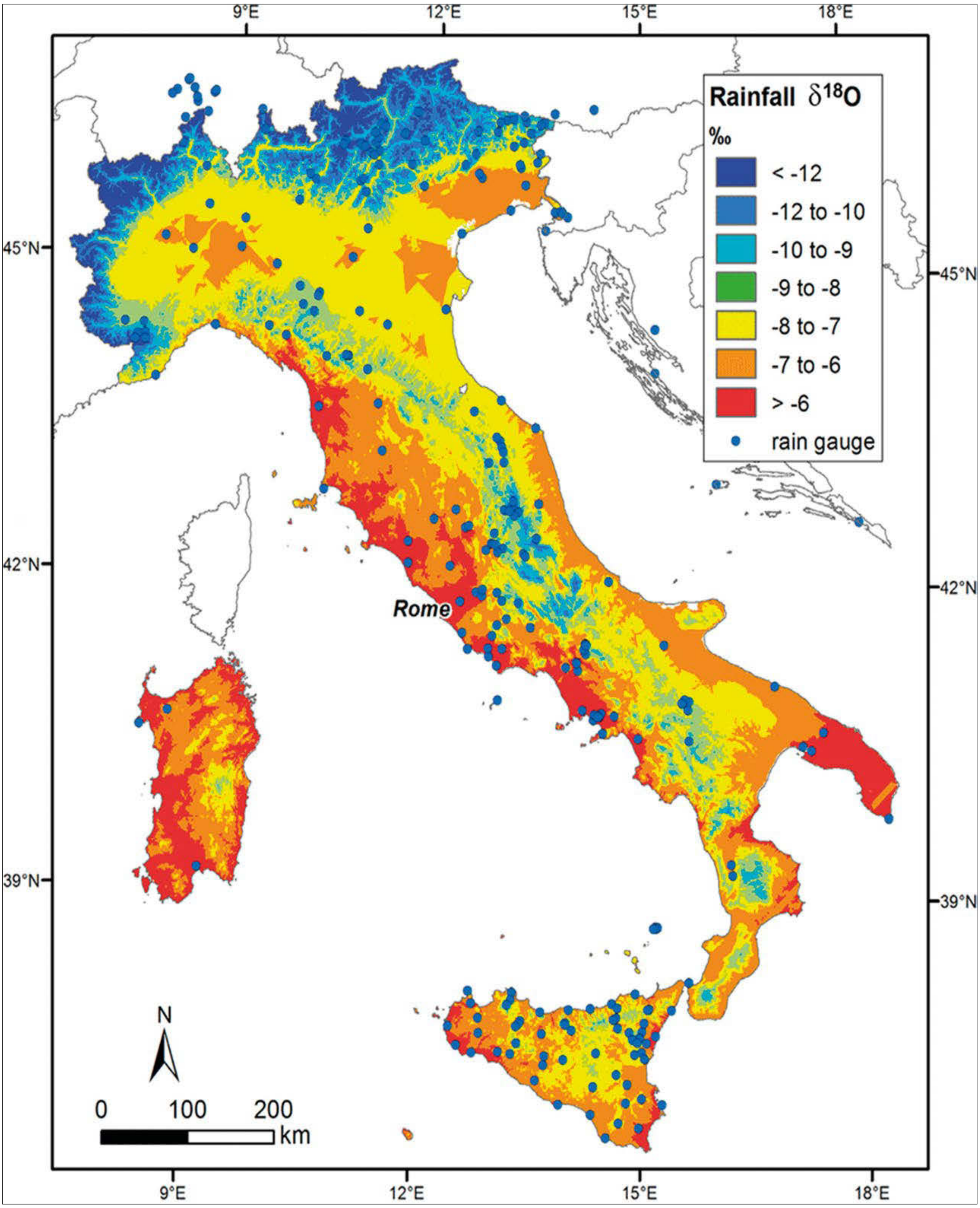

Fig. 2. Map of spatial distribution of average $\delta^{18}O$ (‰) of precipitation in Italy (data collected between 1971 and 2012; after Giustini *et al.* 2016).

Mappa di distribuzione dei valori medi di $\delta^{18}O$ (‰) delle precipitazioni in Italia (dati tra il 1971 e il 2012; da Giustini et al. 2016).

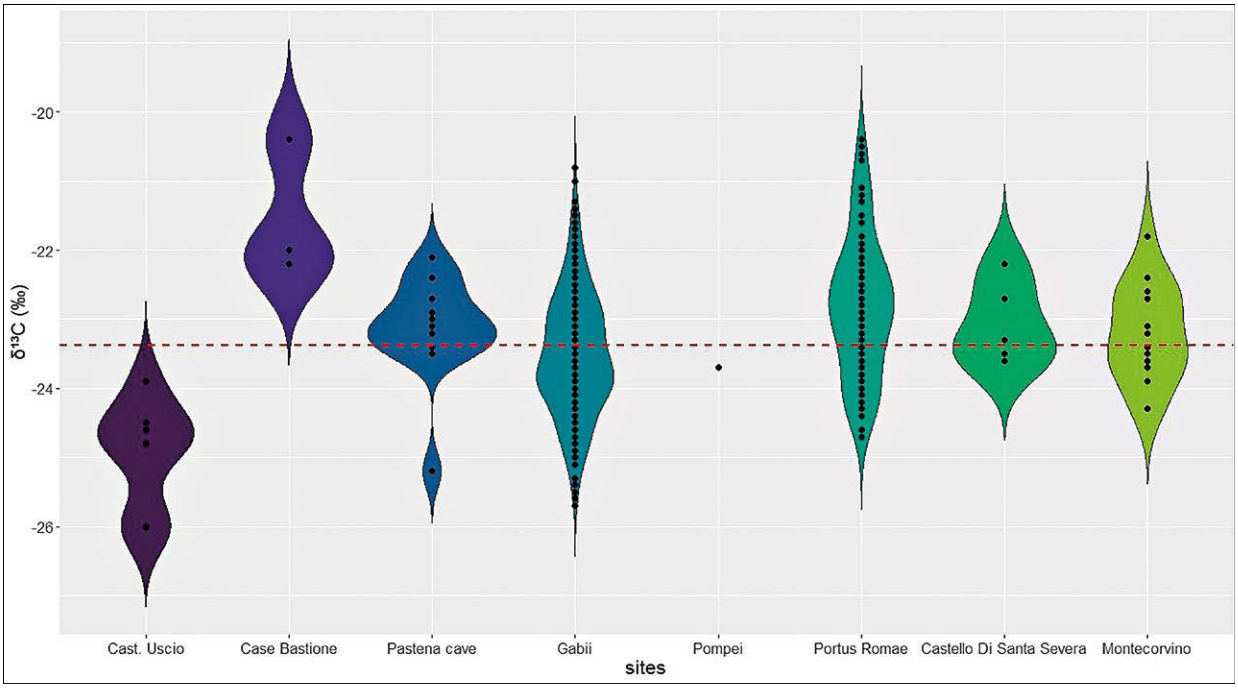

Fig. 3. $\delta^{13}C$ distributions of C_3-plant-grains (*Triticum* and *Hordeum* sp.) from various Italian sites (general dataset extracted from Depaermentier *et al.* 2025, and references therein).
*Distribuzione dei valori di $\delta^{13}C$ ottenuti da semi di piante C_3 (*Triticum *and* Hordeum *sp.) da vari siti archeologici italiani (dataset general estratto da Depaermentier et al. 2025 con bibliografia).*

temperature (T_{air}) using specific equations, e.g. $T_{air} = (\delta^{18}Ow+13.74)/0.53$ (equation for Europe, see Pryor *et al.* 2014).

In mobility and management studies, sequential enamel sampling is particularly informative: with incremental samples, seasonal patterns of $\delta^{18}O$ values can be observed and used to define interpretations of seasonal transhumance in livestock (see e.g. Balasse *et al.* 2002). $\delta^{18}O$ is also integrated into multi-isotope frameworks with strontium and carbon and used for the development of oxygen isoscapes to determine the expected spatial/environmental $\delta^{18}O$ variation.

2.3 Carbon

Carbon is a key element in the Earth biosphere and atmosphere, central to organic molecules and photosynthetic processes. It has two stable isotopes: ^{12}C (98.93%) and ^{13}C (1.07%) and a radioactive cosmogenic isotope, ^{14}C, widely used in geochronology. Because of their different weight, carbon isotopes fractionate during chemical and biological processes, producing systematic $\delta^{13}C$ differences across environments, plants and animal tissues. $\delta^{13}C$ is widely used in archaeological research for dietary and paleoenvironmental reconstructions.

Carbon isotopes are expressed as $\delta^{13}C$ in per mill (‰) using the delta notation reported relative to the VPDB (Vienna Pee Dee Belemnite) standard.

The general formula is:

– $\delta^{13}C$ (‰) = [(Rsample / Rstandard) − 1] × 1000

where R is the $^{13}C/^{12}C$ ratio.

A major reason $\delta^{13}C$ is so powerful in archaeological and ecological studies is that the $\delta^{13}C$ values of plants vary in Europe in a predictable way with photosynthetic pathways (O'Leary 1981). C_3 plants (Calvin cycle pathway) typically vary between -27 and -21‰ and are commonly distributed in temperate zones (Depaermentier *et al.* 2025). C_4 plants (Hatch-Slack pathway) typically vary from -14 to -10‰ and are more common in warmer (tropical/subtropical) settings. Because these ranges are distinct between C_3 and C_4 plants, $\delta^{13}C$ values can often distinguish grazing in C_4 grassland from browsing in C_3 woodlands and it can track feeding strategies of livestock (Still *et al.* 2003; Cerling *et al.* 2015).

Even in regions dominated by C_3 vegetation $\delta^{13}C$ values can still provide environmental infor-

Site	*Ovis aries*	*Capra hircus*	*Bos taurus*	*Sus domesticus*	Total N
Solarolo, via Ordiere (c. 1550-1450 BCE)	5		2	3	10
Montarice (c. 1450-1250 BCE)	6	2	2	2	12
Coppa Nevigata (c. 1650-1550 BCE)	1				1
Coppa Nevigata (c. 1450-1350 BCE)			1	1	2
Coppa Nevigata (c. 1250-1150 BCE)	3	2	1	2	8
Total N	15	4	6	8	33

Tab. 1. Tooth sample distribution for isotope analysis. Coppa Nevigata specimens are subdivided among the different chronological phases.

Distribuzione dei campioni dentali per l'analisi isotopica. I reperti di Coppa Nevigata sono suddivisi tra le diverse fasi cronologiche.

mation. One widely discussed mechanism is the so-called "canopy effect", which causes plants to be more depleted in ^{13}C due to factors such as reduced light intensity and re-assimilation of ^{13}C depleted CO_2 (Van der Merwe-Medina 1991).

Carbon isotopes are measured on bone or dentine collagen (organic component) and the carbonate group (CO_3^{2-}) in bioapatite of bones and teeth (mineral component). Isotopic fractionation occurs in both tissues. Relative to the average diet, collagen $\delta^{13}C$ is typically about +5‰ more positive, while apatite carbonate is about +9 to +14‰ more positive, with fractionation varying with factors such as body mass (Lee-Thorp 2008). These tissues do not record identical dietary information. Collagen and apatite carbonate reflect different macronutrients pools. Collagen tends to reflect primarily the protein portion of the diet while apatite carbonate tends to reflect the energy component (carbohydrates and lipids and, only secondarily, protein). Because the relative importance of protein vs energy differs among herbivores, carnivores and omnivores, the relationship between collagen and apatite carbonate $\delta^{13}C$ can vary with trophic ecology (DeSantis *et al.* 2022)[3].

In animal management studies, $\delta^{13}C$ is particularly informative when combined with oxygen (and often strontium) and when applied at higher spatial resolution. $\delta^{13}C$ in enamel can identify seasonal foddering (e.g. switching between C_3 pasture and C_4 crop products). Intra-tooth sequential sampling can also capture diet changes and when interpreted together with $\delta^{18}O$ help evaluate seasonal mobility and land use. As with oxygen, the mineralization of enamel can introduce a damping effect of the original input signals, therefore inverse models might be necessary to reconstruct precisely the timing and amplitude of dietary changes.

A recent Europe-wide synthesis of $\delta^{13}C$ values measured on archaeobotanical macroremains of C_3 and C_4 plants has reported mean values of approximately −23‰ and −10‰, respectively (Depaermentier *et al.* 2025). In Italy, analyses of *Triticum* and *Hordeum* grains (C_3) from a range of ecological and chronological contexts (from the Copper Age to the sixteenth century CE) revealed values ranging between −26.0‰ and −20.4‰, with a mean of −23.4‰ (fig. 3). Established equations used to compare $\delta^{13}C$ values between a C_3 plant-based diet and the carbonate fraction of tooth enamel account for a systematic enrichment of approximately +13/14‰ (depending on the animal species) in tooth enamel bioapatite relative to the ingested plant material (Cerling-Harris 1999; Lee-Thorp-Van der Merwe 1991). In other words, a domestic animal consuming exclusively C_3 plants in the Italian geographic context should display enamel $\delta^{13}C$ values of approximately −10.4‰ to −9.4‰, depending on the species. Higher values usually indicate the inclusion of C_4 plants in the diet. Estimates of the proportion of C_4 plants in the diet follow linear mixing model equations with two end-members.

[3] Moreover, due to collagen turnover in bone, $\delta^{13}C$ values measured in bone collagen reflect an average of the bone remodelling time window of an individual's life. In contrast, $\delta^{13}C$ values measured in dental enamel apatite – which does not undergo remodeling during the individual's lifetime – represent a more restricted time frame, corresponding to the period of tooth formation.

3. MATERIALS

In this study, we focus on the animal management strategies employed by Middle and Recent Bronze Age communities, analysing three case studies from present-day Italy, each situated in distinct ecological niches (tab. 1). Samples were collected from well-dated archaeological layers.

The teeth from Solarolo-via Ordiere come from MBA2 layers of the settlement (c. 1550-1450 BCE). The teeth selected from Montarice belong to the MBA3-RBA1 phase (c. 1450-1250 BCE). The teeth from Coppa Nevigata are attributed to different chronological phases of the site (Protoapennine: c. 1650-1550 BCE; Apennine: c.1450-1350 BCE; Subapennine: 1250-1150 BCE).

Selected materials were first subjected to zooarchaeological analysis in order to identify pig, cattle and caprine specimens. The 18 caprine specimens were subsequently analysed using ZooMS to distinguish *Ovis* from *Capra*. Site and context descriptions are provided in the following sections. The sampling strategy was designed to assess the extent to which ecological factors influenced husbandry practices in different environments, exploring potential relationships with other aspects of land use and food production, particularly agriculture. Overall, we generated 90 $^{87}Sr/^{86}Sr$, 322 $\delta^{18}O$, and 322 $\delta^{13}C$ new data.

4. METHODS

4.1 Zooarchaeology by Mass Spectrometry (ZooMS)

ZooMS analyses were performed to determine the taxonomic assignment of 18 caprine hemimandibles by targeting diagnostic collagen peptide markers distinguishing *Capra* and *Ovis* (Buckley *et al.* 2010).

Sampling and collagen extraction followed established protocols (Buckley *et al.* 2009; Welker *et al.* 2015), with minor modifications. Approximately 40-60 mg bone chips were taken from each specimen and demineralised in 500µL 0.6M HCl for 48h at 4°C. Following demineralisation, the supernatant was removed and samples were rinsed twice in 200µL HPLC-grade water and twice in 200µL 50mM ammonium bicarbonate (AmBic), discarding the liquid fraction after each rinse and ensuring that the final AmBic aliquot reached a pH>7.5. After adding 200µL 50mM AmBic, the acid insoluble fraction of collagen was denatured at 65°C for 1h and digested in 2µL of 0.5µg/µL trypsin solution incubated at 37°C overnight. Enzymatic digestion was stopped by adding 10% trifluoroacetic acid (TFA, aqueous solution) until pH<2 was reached. Peptide digests were then purified using C_{18} tips, dried and stored at -18°C.

MALDI-TOF-MS analyses were performed using an Ultraflextreme instrument (Bruker-Daltonics) at the BIO-MS laboratory of Universidad Pablo de Olavide (Seville, Spain). The digested collagen samples were reconstituted in 0.1% TFA and mixed with a-cyano-hydroxycinnamic acid as matrix. Finally, a 0.8 mL aliquot of the sample-matrix mixture was spotted onto the sample plate, and the solvent was allowed to evaporate. MALDI-TOF peptide fingerprint spectra were obtained in positive ion reflectron mode, averaging 3000 laser shots (355 nm Nd:YAG laser). The mass spectrometer was calibrated with standard compounds in the mass range m/z 500-3500 Da.

Resulting spectra were processed in mMass v5.5.0 (Niedermeyer-Strohalm 2012) applying baseline correction (precision: 100; relative offset: 100), peak picking (S/N ratio: 3.5), and removing common contaminants' peaks (e.g., keratin peptides). No collagen peaks were detected in procedural blanks, excluding the possibility of interference in the analysis. Once processed, replicates for each sample were averaged and taxonomic identification was conducted by comparing identified peaks against published peptide markers (BioArCh, v2024). Markers were considered valid with a tolerance of ±0.6Da.

4.2 Sampling for isotope analysis

Lower third molars (M3) were selected for analysis, as these teeth have a generally uniform growth rate within the same species (they form approximately between the first and the second year of life, see note 1). Pigs were sampled in bulk (minimum 7 mg of enamel), while herbivores (sheep, goats and cattle) were subjected to sequential sampling (minimum 1.12 mg of enamel powder).

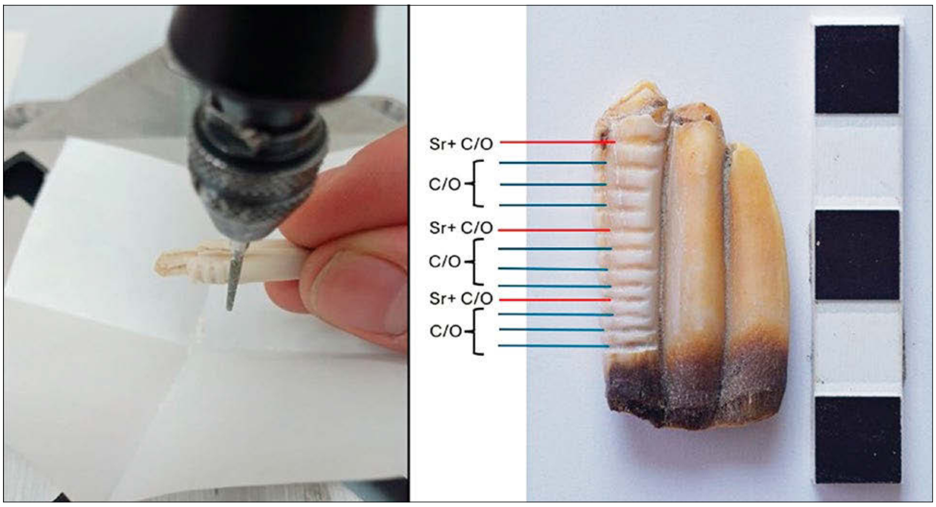

Fig. 4. Left: collection of enamel powder using sequential parallel plane sampling. Right: diagram of the sequential sampling strategy. The blue lines represent samples for C and O isotope analysis, while the red lines represent samples for Sr, C and O analysis.

A sinistra: operazioni di campionamento di polvere di smalto dentario con campionamento piano-parallelo. A destra: schema della strategia di campionamento sequenziale. Le linee blu rappresentano i campioni prelevati per le analisi di C e O, mentre le linee rosse per il campionamento per l'analisi di Sr, C, e O.

Sequential sampling – now well established for multi-isotopic work on herbivore teeth (Balasse 2002; Tornero *et al.* 2018; Chazin-Gordon-Knudson. 2019; Isaakidou *et al.* 2019; Messana *et al.* 2023; Trentacoste *et al.* 2020, 2023) – allows for extremely high temporal resolution of isotopic variations. If we consider the M3 to be formed between the first and the second year after birth, it is possible to detect variations that have occurred over approximately one year of the animal's life, at a nearly monthly rate. Sequential sampling is particularly well-suited to selenodont teeth, typical of bovids, which exhibit a crescent-shaped crown composed of multiple columns and a considerable crown height when unworn. For bunodont teeth (such as those of pigs), one enamel subsample was taken for $^{87}Sr/^{86}Sr$ analysis and a separate subsample for $\delta^{18}O$ and $\delta^{13}C$ analyses. Consequently, isotopic values obtained from bulk pig teeth represent averages over the period of tooth formation rather than discrete signals, as captured by sequential sampling.

A column-mounted drill was used to sample the sequence of herbivore enamel (fig. 4). Parallel sampling was conducted along the tooth column, starting from the apex of the dental crown and progressing toward the enamel-root junction. Following surface cleaning, twelve parallel samples were taken for carbon and oxygen, and three for strontium, from each tooth. The first strontium (Sr) enamel sample was taken at the same layer as the first carbon (C) and oxygen (O) sample, the second at the layer of the fifth C and O sample, and the third at the layer of the ninth C and O sample[4].

To minimize contamination, the work surface, drill tip, tooth surface and the operator's hands were cleaned and sterilized with denatured ethanol after the collection of each sample. Enamel powder was obtained by abrading the tooth surface with diamond tips of various thicknesses and collected in *Eppendorf* tubes for subsequent preparation, including chemical separation of strontium. Each sample taken was weighed using a high-precision balance. In addition, the distance between the sample and the enamel-root junction of each tooth was measured using a caliper, allowing precise spatial positioning of the sample along the tooth crown and enabling accurate representation of the isotopic variations during interpretation and graphical representation.

[4] The larger number of carbon and oxygen samples relative to strontium is justified by the higher analytical costs associated with Sr isotope analysis. This strategy is routinely adopted in isotopic studies (e.g., Chazin 2019; Trentacoste *et al.* 2020, 2023).

4.3 Analytical procedures

Oxygen and carbon isotope ratios were measured on 270 samples of carbonate moiety of tooth enamel at the Centro Interdipartimentale Grandi Strumenti (CIGS) of the University of Modena and Reggio Emilia (UNIMORE) according to Armaroli *et al.* (2025). Sample powders (~3 mg) were reacted for 2 h at 50 °C with +100% phosphoric acid. Isotope ratios were determined on liberated CO_2 by continuous flow IRMS (Elementar precisION) coupled to an equilibration system (Elementar isoFLOW). Repeated analyses of NBS18 and NBS19 reference materials showed a precision (1SD) of ±0.1‰ for $\delta^{13}C$ and ± 0.2‰ for $\delta^{18}O$. C-O values are expressed in ‰ against VPDB. Oxygen and carbon isotope ratios were measured on a second set of 52 samples at the Dept of Earth Sciences of Sapienza – University of Rome, using an automatic gas preparation and introduction system (ThemoFisher Gas Bench II), on line with a ThemoFisher DeltaV IRMS.

The $^{87}Sr/^{86}Sr$ isotope ratio was determined *via* solution MC-ICPMS. Specifically, enamel samples (~ 2 mg) were digested with suprapur nitric acid and processed through extraction chromatography columns filled with Eichron Sr-resin at the MeGic lab of the Department of Chemical and Geological Sciences of UNIMORE. Sr solutions were measured at the Neptune MC-ICPMS housed at the CIGS, following the analytical procedure described in Argentino *et al.* (2021).

Data were statistically processed using the "R" (Version 4.0.5) software and subsequently interpreted, including through comparison with the isoscape currently available for Italy and built by Lugli *et al*. (2022) with regard to the $^{87}Sr/^{86}Sr$ isotopic values.

5. CASE STUDY 1: SOLAROLO-VIA ORDIERE (RAVENNA)

Recent research carried out at the archaeological site of Solarolo-via Ordiere (RA) has significantly expanded our knowledge of Bronze Age settlements in northern Italy, offering new opportunities for comparison with regions traditionally included within the Terramare cultural area. Extending settlement analysis to the Romagna area allowed the reconstruction of productive practices (animal husbandry and agriculture) and cultural interactions among Bronze Age village communities (Carra *et al.* 2023; Maini-Curci 2013; Debandi-Maini 2021).

The settlement of Solarolo-via Ordiere is organized into several residential areas separated by watercourses or depressed zones, distributed over a total surface of approximately 7 ha. Based on surface finds and investigations carried out through trenches, coring, and excavation areas, the site was occupied from the Middle Bronze Age (advanced MBA1 phase) to the end of the Recent Bronze Age (advanced RBA2 phase), with rare elements attributable to the Final Bronze Age (Cattani 2009).

The village developed along the banks of an ancient palaeochannel of the Santerno River, approximately 25 m wide and 11 m deep, showing clear evidence of artificial regularization of the inner side. Excavation campaigns mainly focused on Sector 1, corresponding to a 10×50 m transect crossing the southern residential area of the settlement from south to north. This area, covering approximately 8,000 m², is located on the right bank of the river. Estimates of population size and simulations of agricultural and pastoral production were calculated exclusively on the basis of this intensively investigated area, identified as a residential zone. Other investigated sectors could correspond to different use destinations, like enclosures for animals or complementary infrastructures.

Excavation of Sector 1 revealed, starting from the riverbank, a 15 m-wide strip extending northwards that appears to be devoid of residential structures, bordered by large tree stumps and a palisade beyond which evidence of huts distributed over several phases emerges (Cattani *et al.* 2018). The earliest phase consists of raised structures supported by vertical posts, while a later phase includes a structure with a floor made of redeposited silt. Both structures belong to the MBA2 phase, approximately dated between the mid-16th and mid-15th centuries BCE. In the northern part of Sector 1, excavation uncovered a thicker and better-preserved stratigraphic sequence extending the chronology to the advanced Middle Bronze Age and the initial phase of the Recent Bronze Age, corresponding to the period from the mid-15th to the end of the 13th century BCE (Cattani *et al.* 2019).

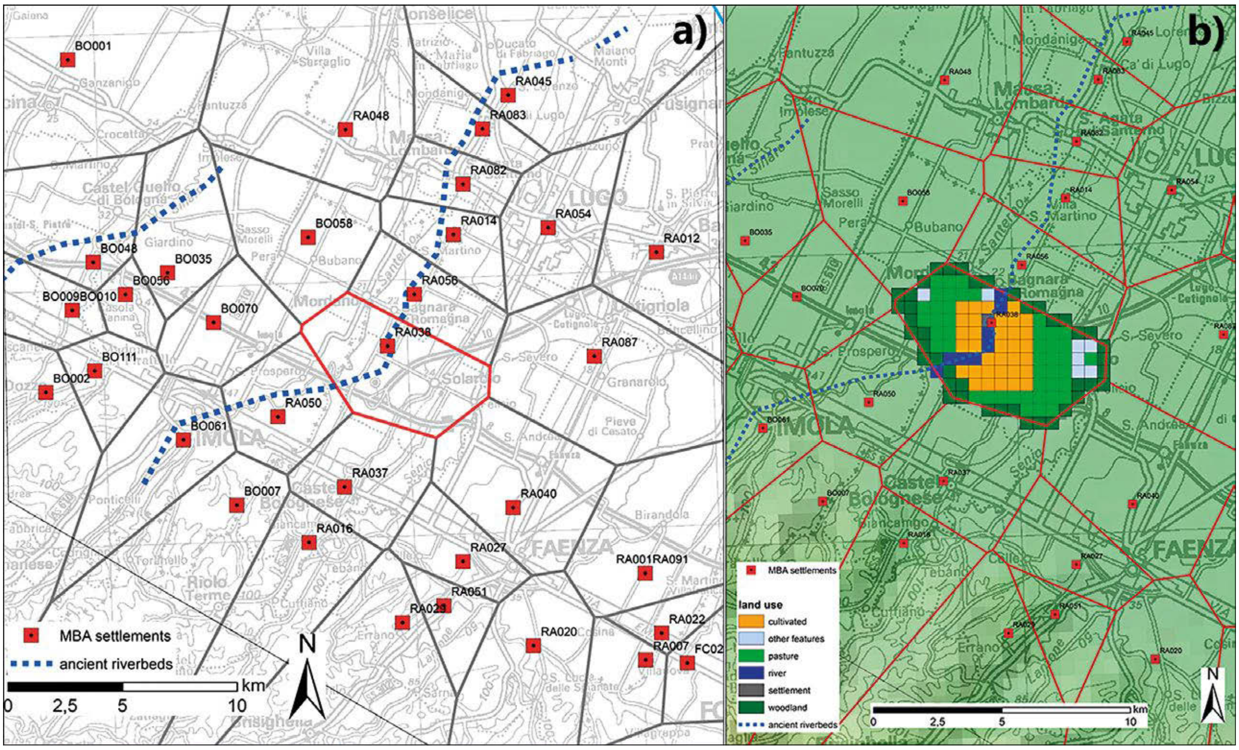

Fig. 5. a) Thiessen polygon model, applied to the MBA settlement pattern in the hinterland of Solarolo (RA038); b) simulation of land-use (30% cultivated areas; 30% pasture; 30% woodland: 10% other uses) for the territory controlled by Solarolo.
a) Modello con poligoni di Thiessen, applicato al territorio dell'hinterland di Solarolo (RA038); b) simulazione di utilizzi del suolo (30% aree coltivate; 30% pascoli; 30% aree boschive; 10% altri usi) per il territorio controllato dal sito di Solarolo.

5.1 Analysis of the territory associated with the Solarolo settlement

The availability of resources – derived from crop cultivation, gathering of other plant species, animal husbandry, and secondarily from wild resources – was assessed through an analysis of the territory and landscape characteristics surrounding the Solarolo settlement (Carra-Cattani-Debandi 2021).

The first necessary step in this analysis is the identification of the area hypothetically exploited by the village community. In the case of Solarolo, located in the middle plain and lacking significant topographical constraints, the territory pertaining to the settlement can be delineated using Thiessen polygons (fig. 5a). The only uncontrollable bias is the possible presence of other settlements not yet identified, which would reduce the territory attributable to the village. Based on current research, the area calculated using this method amounts to approximately 3,200 ha (32 km²). Even assuming a smaller extent, the land available for subsistence appears more than sufficient (Debandi 2021).

An alternative approach involves estimating population size based on the settlement core area of 0.8 ha, corresponding to approximately 150 individuals, and calculating the amount of land required to sustain them using parameters of agricultural productivity and protein acquisition from animals or other products. Simulations applied to Middle Bronze Age settlements in the plains generally use a territorial subdivision into four land-use categories with similar proportions: approximately 30% arable land, 30% pasture, and 30% woodland (both coppiced and high forest), plus an additional 10% allocated to other uses (rivers, settlement areas, cemeteries) (fig. 5b) (Debandi 2021). This approach also indicates a wide potential availability of productive land (see Debandi *et al.* in this volume).

5.2 Archaeobotanical investigations

Archaeobotanical data confirm that by the Bronze Age, cereal cultivation had become well established and that cereals, once processed into food products, likely constituted approximately 70% of individual dietary intake (Carra-Cattani-Debandi 2012).

The abundant multicropping cereal production at Solarolo included traditional winter-sown cultivars (*Triticum monoccocum*, *T. diccocum*, *T. aestivum*, *T. timopheevii*, *Hordeum*), with particular emphasis on high-yield species (in terms of grain size and weight) or those offering greater resistance and storability due to robust glumes (*Triticum spelta*) (Carra 2009; Carra 2012; Carra *et al.* 2023). Spring-sown small-grain cereals such as millet (*Panicum miliaceum*) and foxtail millet (*Setaria italica*) were also introduced, reaching a proportion of 22% for millet in MBA layers. This high diversity reflects deliberate planning aimed at ensuring productivity. Millet cultivation could alternate with more soil-demanding cereals or replace failed crops under specific conditions (Kirleis-Filipović-Dal Corso 2022), given its short growing cycle, summer maturation, and high resistance to drought and high temperatures.

The high proportion of millet identified in the Solarolo assemblage confirms a multicropping strategy focused on agricultural productivity and aimed at guaranteeing a substantial subsistence base and significant anthropogenic impact on the landscape.

Pollen analyses of samples taken from layers predating settlement establishment already document human presence, with open areas designated to agricultural activities (cereal and hemp cultivation) and animal husbandry (meadows/pastures), reaching 60% of the spectrum. 40% of the pollen spectrum indicates the proportion of arboreal landscape, characterized by coniferous and deciduous broadleaf forests, particularly oak woodland. A natural watercourse flowed through the area where the settlement would later develop, bordered by hygrophilous vegetation and associated with wetlands of varying degrees of stagnation. Spontaneous anthropogenic indicators (7.0%), including ruderal and nitrophilous plants, are well represented both qualitatively and quantitatively. Cultivated plants show moderate values (3.7%), represented mainly by cereals (3.3%) – notably barley/*Hordeum* (2.6%) and oat-wheat/*Avena-Triticum* (0.7%) – alongside a low percentage of hemp/*Cannabis sativa* (0.4%) (Pancaldi 2016).

With the village's beginning, a marked intensification of anthropogenic pressure across the area is evident, confirmed by a decline in forest cover due to woodland clearance for residential structures and the expansion of cereal fields (barley, oat-wheat, spelt). Wetland plant taxa show an overall decrease; however, there is a notable increase in herbaceous species and the introduction of new taxa, possibly linked to the network of channels and ditches separating the different settlement zones. Meadow and pasture areas intended for livestock breeding further expanded.

5.3 Zooarchaeological investigations

Zooarchaeological analyses at the site of Solarolo-via Ordiere provide clear evidence of a highly structured and specialized animal economy during the Middle Bronze Age 2 (MBA2), a period spanning approximately one century. The faunal assemblage, comprising over 6,800 remains, is overwhelmingly dominated by domesticates (98%), indicating a fully developed agro-pastoral system. Preliminary investigations (Maini-Curci 2013) and more recent studies (Debandi-Maini 2021) identified a clear hierarchy among the exploited taxa. In a subsample of 2,249 identified specimens, aprines – mainly sheep and to a lesser extent goats – emerged. as the most abundant group (NISP 1,176; MNI 95), followed by pigs (NISP 651; MNI 67) and cattle (NISP 284; MNI 29). Wild species-including red deer (*Cervus elaphus*), roe deer (*Capreolus capreolus*), hare (*Lepus europaeus*), and wild boar (*Sus scrofa*)-are only sporadically represented and account for less than 2% of the total assemblage.

Within the flocks, a selective trend appears to favour animals with higher fibre (wool) productivity rather than body mass; similarly, the clear size separation between domestic pigs and wild boars reflects a high degree of human control over breeding and herd management.

Mortality profiles reveal distinct, species-specific exploitation strategies. Caprines were managed with a 'triple vocation' (meat, milk, and wool), and the 5:1 sheep-to-goat ratio-confirmed by both morphological observations and ZooMS analysis-points to an emphasis on high-quality meat and wool production. Pigs were raised exclusively for meat and fat, with rapid turnover: 50% of individuals were slaughtered within their first year, reflecting a strategy focused on intensive protein yield and efficient resource conversion. Cattle, despite their modest size, played a crucial role as draught animals; they were generally kept alive until 3-4 or even 6 years of age, before being slaughtered to maximize meat returns at low maintenance costs.

Quantitative estimates of livestock herds at Solarolo during the Middle Bronze Age indicate substantial numbers. Zooarchaeological results from sampled areas, combined with projections of the minimum number of animals present annually at the Via Ordiere settlement – based on the minimum number of individuals slaughtered (MNI) – suggest herds consisting of approximately 125 cattle, 208 caprines, and 133 pigs. These values correspond to the average derived from the two reference areas used for the zooarchaeological sample (Debandi-Maini 2021).

Faunal data from Solarolo suggests solid planning and organization of production. The effects of abundant food availability likely promoted the demographic growth characteristic of the Middle Bronze Age expansion phase. These results provide a robust baseline for integrating isotopic and biomolecular analyses aimed at refining mobility, diet, and herd management strategies.

6. CASE STUDY 2: MONTARICE (PORTO RECANATI-MACERATA)

During the Middle Bronze Age 3 and Recent Bronze Age (14th -13th BCE) the middle Adriatic region was characterized by a relatively dense settlement pattern, with sites widely distributed along the coastal zone, particularly in locations offering favourable natural landing places or in proximity to river estuaries, which would have provided suitable conditions for coastal access and anchorage: Riccione, Fano at the mouth of the Arzilla River, Ancona-Montagnolo, Ancona-Colle dei Cappuccini, Numana, Civitanova Bambozzi (Baldelli *et al.* 2005). The topographic setting of the Montarice site, which dates to the same period and lies approximately 1 km from the coast, close to the mouth of the Potenza River, clearly falls within this settlement pattern (De Neef-Paolini in this volume; De Neef-Paolini 2025; Paolini 2023). The excavations at Montarice were conducted in the 1970s by Delia Lollini. Recently, the site has been the subject of archaeological and geophysical surveys conducted by the University of Ghent (for further information, see De Neef, Paolini in this volume).

More generally, during Middle Bronze 3 and the Recent Bronze Age (Apennine and Subapennine *facies* – 14th and 13th centuries BCE), the Marche territory experienced a substantial and widespread occupation encompassing all ecological zones, from the Adriatic coast to the Apennine uplands. As evidenced by the location of many settlements, the river valleys crossing the region must have played a key role as communication routes. These corridors likely facilitated the movement of people and goods, as indicated by the presence of Aegean-type ceramics even in inland contexts: Cisterna di Tolentino, Fonte Marcosa at Moscosi di Cingoli, Jesi, Ancona Montagnolo, Treazzano di Monsampolo (Jones *et al.* 2014). The same routes may also have supported the seasonal movement of flocks and herds toward summer and winter pastures.

6.1 Zooarchaeological investigations

Zooarchaeological analysis at Montarice was carried out on a total of 1,383 faunal remains dated to the final stages of the Middle Bronze Age and the early phases of the Recent Bronze Age. Of these, 614 specimens (44.4%) were taxonomically identified to at least the genus level, while 769 (55.6%) remain undetermined (Maini, ongoing study). The assemblage is clearly dominated by domestic animals, which account for 83.2% of the identified sample (NISP = 511), suggesting a well-established agro-pastoral system. Wild taxa are only marginally represented, with 18 remains (2.9%), including cervids, wild boar, and hare, confirming the strong prevalence of domestic exploitation.

The principal domestic species at the site -pigs, caprines, and cattle- display a relatively balanced distribution, pointing to a diversified subsistence strategy with no clear dominance of one taxon over the others. These three groups account for the vast majority of the domestic assemblage, with pigs representing 37.2% of the identified remains (NISP = 185), caprines 36.0% (NISP = 179), and cattle 26.8% (NISP = 133). An additional 24 dog remains (*Canis familiaris*) and 8 equid remains-likely horses-bring the total number of identified domestic animal remains to 529.

Within the caprine group, although most specimens remain indeterminate at the species level, sheep appear to predominate over goats, with an estimated ratio of approximately 3:1, a trend also confirmed by ZooMS analyses.

Age-at-death data indicate a relatively balanced slaughtering pattern for all major domestic taxa, with a notable representation of adult individuals among pigs, caprines, and cattle (Maini, ongoing study). Young and sub-adult specimens are also present, particularly among pigs, likely reflecting the aim of obtaining higher-quality meat. Conversely, the predominance of mature animals-especially among cattle and caprines-may suggest a reliance on secondary products such as wool and labour, alongside meat exploitation. Milk was likely obtained from all three domestic species (sheep, goats, and cattle), although none appears to have been exploited exclusively for dairy production.

7. CASE STUDY 3. COPPA NEVIGATA (FOGGIA)

The Bronze Age fortified settlement of Coppa Nevigata, located south of the Gargano Promontory, is one of the most extensively explored Bronze Age sites in Italy. Located on the shore of the former coastal lagoon of Lago Salso, which connected it to the Adriatic Sea while offering protection from seaborne attacks, the site was continuously occupied for approximately one millennium (18th-8th centuries BCE; Cazzella-Recchia 2012; Recchia in this volume). Characterised by substantial defensive lines, repeatedly modified and rebuilt over time, the settlement was actively engaged, and likely specialised, in long-range maritime exchange networks, particularly with the eastern and northern Adriatic (Cazzella-Recchia 2018a; 2018b). The settlement retained the same location throughout its occupation, and the area enclosed by the fortifications, approximately 2.5 ha, remained relatively stable in extent. The surrounding territory was well suited to cereal cultivation and animal husbandry, while the lagoon environment provided additional resources. The settlement lay close to the mouth of the River Candelaro, which flowed into the lagoon, and benefitted from a nearby brackish spring.

7.1 Territorial control

Based on the size of the Bronze Age settlement enclosed by the fortifications (c. 2.5 ha) and ethnographic estimates of approximately 125 inhabitants per hectare, a population of around 300 individuals has been proposed for the Coppa Nevigata community.

Considering the relative incidence of domestic species and the crop types identified at the site, and applying a carrying-capacity model, the territory required to sustain the community's subsistence economy has been estimated at approximately 5 km². This area would have included arable fields located closer to the settlement, pastures, and a limited proportion of woodland, mainly oak, supporting pig husbandry and possibly some hunting activities (Cazzella-Recchia-Lucci 2021).

Estimates of herd and flock size in this model were not based directly on the NMI of faunal remains recovered for each phase, but on the assumption that a nuclear family slaughtered one pig per year. The total number of living animals, including those kept alive to ensure reproduction, was then extrapolated according to the relative proportions of species (1 pig = 3 cattle = 7 caprines).

In this picture the community was self-sufficient. The area under its political control has been hypothesised at approximately 40 km², defined by natural boundaries (the River Candelaro to the south and the Gargano promontory to the north) and by the absence of other coeval stable settlements (at least between the 16th and 11th centuries BCE) within this territory.

7.2 Environmental data and agricultural practices

A series of core drillings carried out in the vicinity of the site, from its margins into the lagoon, have provided stratigraphic data and pollen diagrams for the reconstruction of the environment and its transformations in relation to both climatic variation and anthropogenic impact, although the respective influence of these two factors is not always easily to disentangle. Additional data have emerged from new cores taken from the Lago di Salpi lagoon, once forming a single water body with the Lago Salso (Susini *et al.* 2023). For the Bronze Age (between 3600 and 3090 cal. yr BP), the Salso lagoon has been identified as a brackish environment characterised by Hydrobiidae spp. and Cerastoderma sp., with salinity values ranging between 25‰ and 18‰. In the later phase, a reduction in salinity (to c. 6‰) indicates a shift towards a salt-marsh environment (Caldara-Simone 2012).

Pollen diagrams (Di Rita *et al.* 2011), particularly from core C3, located 0.8 km from the site within the lagoon, indicate that from the Neolithic onwards the coastal Tavoliere was characterised by relatively open shrubland. Core C5, situated closer to the site, covers the phase 3500-3230 cal. yr BP: the pollen record points to a markedly open and deforested landscape, a condition that persisted thereafter. Pollen from cultivated, ruderal, and pastoral plants is abundant, indicating strong anthropogenic impact, plausibly linked to the proximity of the settlement. As the authors observe, "*differently from other Mediterranean sites where arboreal vegetation recovered after the drought of 4000 cal. BP, in the Tavoliere Plain the landscape remained substantially open, probably because of intense local human activity in a semi-arid area*".

During excavation, particular attention has consistently been paid to the collection of archaeobotanical data: each excavated layer is sampled at a rate varying between 5% and 100%, depending on the context. This strategy provides a broad and detailed record for both the different phases of occupation and various contexts within each phase.

The evidence derived from anthracological remains at the site is influenced by the selective practices adopted by the community of Coppa Nevigata in procuring timber. Wood was probably chiefly obtained from forests on the nearby slopes of the Gargano promontory, as well as from riparian environments near the site (Fiorentino-D'Oronzo 2012; Primavera *et al.* 2015). For the 16th century BCE, the dominant arboreal taxa derive from mesophilous woodland environments, such as *Fagus* and deciduous oaks, indicating temperate-humid conditions. Species characteristic of Mediterranean maquis display a locally xerophilous tendency. Riparian taxa such as *Populus/Salix* are also attested, along with *Vitis*, probably in its wild form[5]. Data from core C5 indicate the presence of nearby Mediterranean maquis and taxa reflecting increased anthropogenic impact, such as Prunoideae. From a climatic perspective, a more pronounced xerophilous tendency appears to emerge. In the Subapennine period (13th-12th centuries BCE), a decrease in xerophilous taxa and an increase in mixed mesophilous woodland, particularly *Ostrya carpinifolia* would suggest warmer and more humid conditions. However, as noted above, this picture may partly reflect selective strategies in timber procurement. An increase in pine remains points to the probable presence of coastal pinewoods.

The subsistence economy appears to have been strongly based on the cultivation of C_3 cereals, particularly wheat and barley (Fiorentino-D'Oronzo 2012), with a shift from the Late Apennine period onwards towards the cultivation of *Triticum dicoccum*, which is better adapted to warmer and drier climatic conditions.

The earliest sporadic evidence for C_4 plants in the region, most notably broomcorn millet, dates to the phase 1500-1300 BCE coming from limited remains at few sites in central Apulia (Grotta della Tartaruga and Monopoli Piazza Palmieri; Primavera *et al.* 2015). Millet continues to be scarcely represented during the Late Bronze Age: at Coppa Nevigata, only a single seed has been identified, while a few finds come from the Taranto area (Taranto San Domenico).

Stable isotope analyses on human remains from Trinitapoli, in the southern coastal Tavoliere, indicate a diet primarily based on C_3 plants, confirming either the absence or the deliberate avoidance of millet, while animal proteins do not appear to constitute a major dietary component (Arena *et al.* 2020; Varalli-Moggi Cecchi-Goude 2022). Organic residue analyses, however, have demonstrated the occurrence of miliacin in two imported Late Bronze Age Aegean vessels from Roca (Arena *et al.* 2024).

7.3 Zooarchaeological data and breeding practices

Explorations at the site have so far yielded over 45,000 taxonomically identified animal remains, in addition to more than 400,000 aquatic mollusc remains. This dataset provides a statistically robust basis for reconstructing the Bronze Age subsistence economy at Coppa Nevigata, from the early Protoapennine to the Late Subapennine periods (18th-12th centuries BCE; Minniti 2012; Siracusano 2012).

Throughout all phases, primary economy was centred on the husbandry of caprines, cattle, and

[5] For the Apennine period (15th-14th centuries BC), results from on-site sampling were previously unavailable and are only now being published within the framework of the PRIN PNRR Shores project.

Site	HERDS ID	PALTO Number	Taxonomic ID
Coppa Nevigata	COP_180	3046	*Ovis aries*
Coppa Nevigata	COP_183	3048	*Capra hircus*
Coppa Nevigata	COP_185	3049	*Ovis aries*
Coppa Nevigata	COP_186	3050	*Ovis aries*
Coppa Nevigata	COP_189	3051	*Ovis aries*
Coppa Nevigata	COP_202	3054	*Capra hircus*
Montarice	MNT_26	3007	*Ovis aries*
Montarice	MNT_27	3008	*Ovis aries*
Montarice	MNT_28	3009	*Ovis aries*
Montarice	MNT_30	3010	*Ovis aries*
Montarice	MNT_31	3011	*Ovis aries*
Montarice	MNT_32	3012	*Ovis aries*
Montarice	MNT_35	3013	*Capra hircus*
Montarice	MNT_36	3014	*Capra hircus*
Solarolo	ORD_18	3003	*Ovis aries*
Solarolo	ORD_25	3004	*Ovis aries*
Solarolo	ORD_37	3005	*Ovis aries*
Solarolo	ORD_178	3006	*Ovis aries*

Tab. 2: ZooMS identification results for the subset of archaeological teeth analysed in this study. The table reports the site of provenance, HERDS ID and unique lab number (PALTO), and the final taxonomic identification.

Risultati dell'identificazione mediante ZooMS per il sottoinsieme di denti archeologici analizzati in questo studio. La tabella riporta il sito di provenienza, l'ID HERDS e il numero di laboratorio univoco (PALTO), nonché l'identificazione tassonomica finale.

pigs. Caprines – mixed sheep and goat herds, with a predominance of sheep – consistently dominate the assemblage, accounting for 48 to 66% of the remains. Cattle range between 20% and 30%, while pigs never exceed 20%.

Caprines were raised for both meat and secondary products, particularly fleece. Caprine milk exploitation, probably increasing in the Late Subapennine, is documented by small percentages of lambs and kids slaughtered within the first six months of life and, more indirectly, by females culled between two and four years of age. Cattle were kept both for ploughing and for direct meat consumption; the notable evidence of calves slaughtered within the first year of life (4 to 20%) likely indicates cow's milk exploitation. Pigs were mainly slaughtered between the first and third years of life, reflecting an optimal meat-oriented strategy, although a significant consumption of piglets – with more tender and higher-quality meat – is also documented.

Wild resources, deriving from hunting (red deer, roe deer, wild boar), fishing, and tortoise gathering, played a secondary but significant role, with an incidence of 5 to 30%. The large quantity of highly fragmented murex shells from the marine environment strongly indicates purple dye production at the site, particularly from the Protoapennine to the Late Apennine periods (Minniti-Recchia 2018).

8. RESULTS

8.1 ZooMS

ZooMS analysis was carried out on a subset of hemimandibles previously identified zooarchaeologically as *Ovis* vel *Capra* on a morphological basis. Peptide mass fingerprinting enabled species-level attribution of these specimens, allowing assignment to either *Ovis aries* or *Capra hir-*

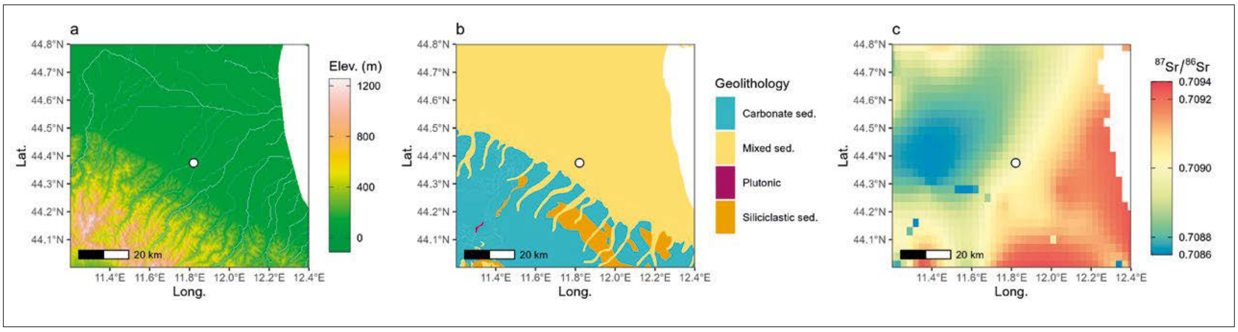

Fig. 6. a) DEM, b) geolithological map, and c) isoscape of bioavailable $^{87}Sr/^{86}Sr$ of Solarolo's territory.
a) DEM, b) mappa geolitologica e c) isoscape del $^{87}Sr/^{86}Sr$ biodisponibile per il territorio di Solarolo.

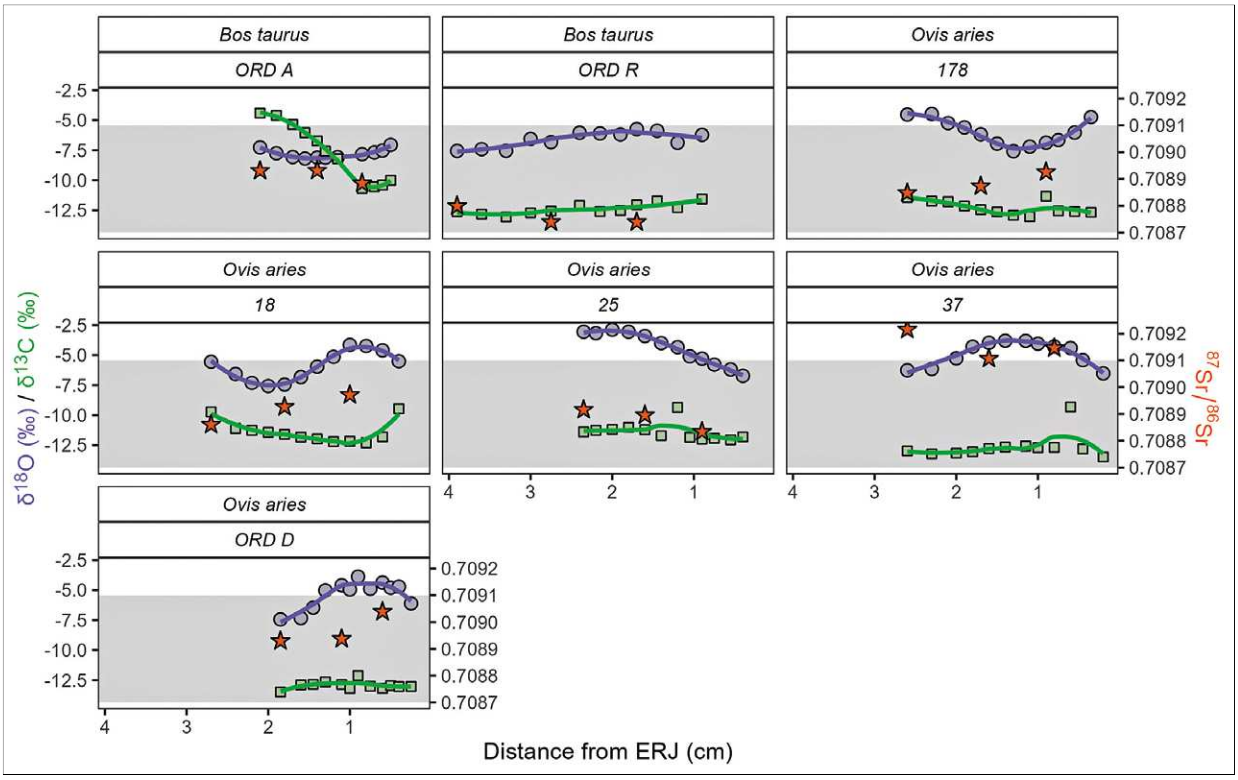

Fig. 7. Intra-tooth $^{87}Sr/^{86}Sr$, $\delta^{18}O$, $\delta^{13}C$ isotope profiles of herbivores at Solarolo.
Profilo isotopico intra-dente di $^{87}Sr/^{86}Sr$, $\delta^{18}O$, $\delta^{13}C$ degli erbivori di Solarolo.

cus across the analysed assemblage from Coppa Nevigata, Montarice, and Solarolo (tab. 2).

8.2 Isotope analysis and data interpretation

8.2.1 *Solarolo, via Ordiere*

ZooMS analyses identified all caprine specimens from Solarolo as sheep.

Four of the five sheep display $^{87}Sr/^{86}Sr$ values compatible with the local environmental baseline (~0.7087-0.7091) (fig. 6). In addition, their $\delta^{18}O$ profiles reflect the sinusoidal fluctuations typical of local annual variation at latitudes characterized by marked seasonal contrasts between warm and cold period (fig. 7). $\delta^{18}O$ values range between −2.9‰ and −9.6‰, an interval broadly consistent, though slightly lower, with present-day precipitation in Romagna. The limited intra tooth variation observed across all $^{87}Sr/^{86}Sr$ triplets suggests non-mobile management practices. One individual, ORD_37, differs from this pattern, exhibiting a slightly more radiogenic strontium isotopic composition. Comparable values are well

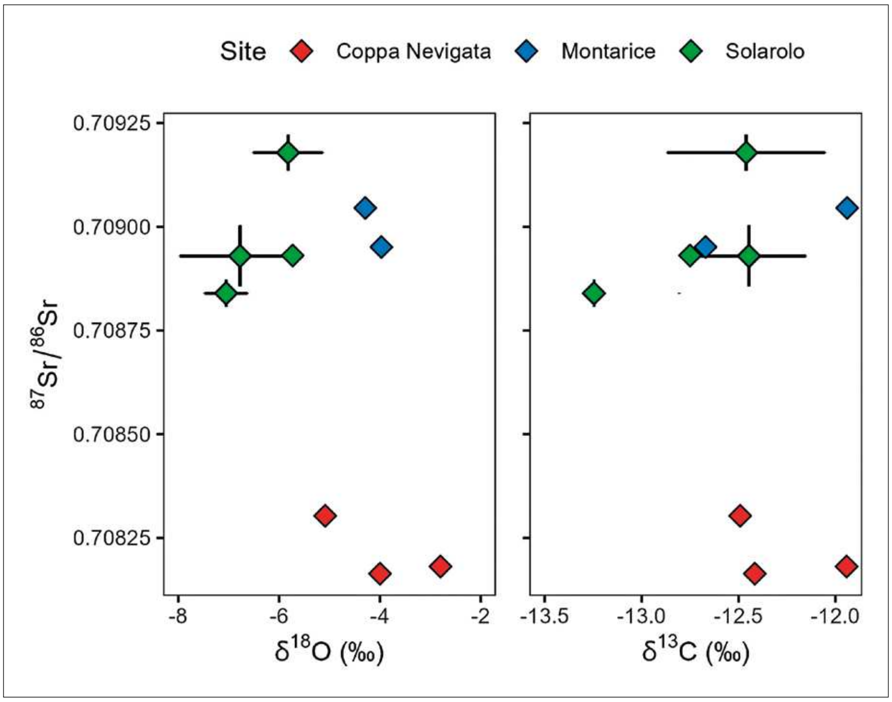

Fig. 8. $^{87}Sr/^{86}Sr$, $\delta^{18}O$, $\delta^{13}C$ values among pigs of all sites. Error bars represent the standard deviation of intra-tooth replicates.

Valori di $^{87}Sr/^{86}Sr$, $\delta^{18}O$, $\delta^{13}C$ fra i vari suini di tutti i siti analizzati. Le barre di errore rappresentano la deviazione standard di campioni replicati.

represented along the Adriatic coastal areas of Romagna, approximately 30 km east of Solarolo; for this reason, this individual is interpreted as non-local, likely originating from the coastal hinterland, although provenance from another area with similar geolithology cannot be excluded.

The two cattle analyzed also show local or slightly less radiogenic Sr isotope signatures, although their $\delta^{18}O$ profiles appear flatter than those of sheep, plausibly reflecting differences in drinking behaviour or water sourcing. Nevertheless, the limited variation in $^{87}Sr/^{86}Sr$ values indicates that these bovines were raised locally.

Of the three pigs, two are clearly compatible with the local $^{87}Sr/^{86}Sr$ baseline, suggesting that they were raised on site (fig. 8). By contrast, ORD_B displays a non-local Sr isotope signature and therefore was probably imported. Notably, its $^{87}Sr/^{86}Sr$ value is similar to that of sheep ORD_37, potentially indicating a comparable provenance. This pattern may reflect regular exchanges of animals between communities settled in central and western Romagna. Alternatively, acts of abduction could also occur with relative frequency.

Carbon isotope values provide particularly informative insights into feeding strategies. Cattle ORD_A shows a substantial increase in carbon isotope values (ranging from −8.2‰ to −4.4‰) during the autumn-winter period, whereas in spring-summer $\delta^{13}C$ values drop to between −10.0‰ and −10.7‰. This pattern suggests that during the colder season the animal's diet was supplemented with a variable proportion of C_4 plants, estimated-using a linear mixing model-at between 9% and 37% of the consumed plant material. The timing of the C_4 plant ingestion would imply a storage of fodder for the cold season.

Similarly, sheep ORD_18, ORD_25, and ORD_37 are characterized by significant $\delta^{13}C$ peaks of up to −9.3‰, all concentrated in the autumn, whereas their regular values range between −11‰ and −13.5‰. These patterns suggest the possible integration of C_4 plants into the diet of most sheep at the end of the warm season. However, linear mixing model estimates suggest that the proportion of C_4 plants does not exceed 1% of total plant intake.

This isotopic evidence – clearer in cattle ORD_A and more limited in the three sheep – can be explained either by the ingestion of spontaneous C_4 plants (less likely for cattle, given the substantial estimated proportion) or by the integration of

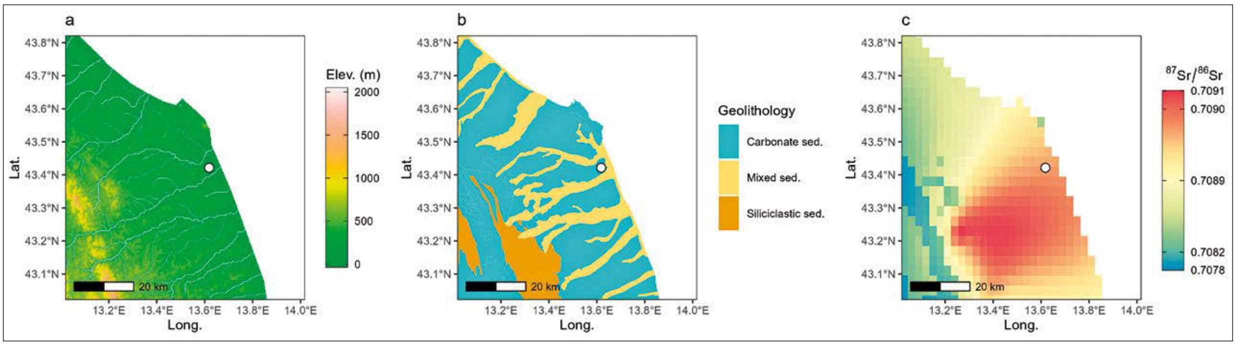

Fig. 9. a) DEM, b) geolithological map, and c) isoscape of bioavailable $^{87}Sr/^{86}Sr$ of Montarice's territory.
a) DEM, b) mappa geolitologica e c) isoscape del $^{87}Sr/^{86}Sr$ biodisponibile per il territorio di Montarice.

cultivated C_4 plants, most plausibly millet. *Panicum miliaceum*, in fact, is particularly abundant in MBA 2 layers at Solarolo, accounting for up to 22% of the cultivated taxa (see above). Moreover, $\delta^{13}C$ peaks are concentrated in the autumn, which coincides with the harvest season of this cereal. As noted above, millet is characterized by a short growing cycle, summer maturation, and high resistance to drought and elevated temperatures (Kirleis *et al.* 2022). The isotopic and archaeobotanical evidence suggests that the use of millet as animal fodder was a planned and practiced strategy, if not systematic, then at least relatively regular, perhaps applied in years characterized by scarce spring and summer rainfall.

In conclusion, the isotopic data delineate a framework fully consistent with the archaeological and archaeobotanical evidence. The territory surrounding the village was sufficiently wide and open to provide adequate fodder for herbivores, which explains the non-mobile management of animals. The long-term occupation of the settlement (c. 300-350 years) appears sustainable only if agricultural practices were organized in a manner that avoided conditions leading to soil overexploitation. This was likely achieved through crop rotation – suggested by the wide spectrum of cultivated cereals – and fallow periods, during which cereal cultivation was replaced by grazing. Overall, the evidence points to an integrated organization of agriculture and residential animal management.

8.2.2 *Montarice*

The picture emerging from isotope analysis appears quite different for Montarice. First, ZooMS analysis indicates that two of eight *Ovis vel Capra* specimens are goats, while the remaining individuals are sheep. Goat MONT_36 appears to be local and non-mobile, as its $^{87}Sr/^{86}Sr$ profile is flat and consistent with the local signatures (0.7088-0.7092)[6] (fig. 9), and $\delta^{18}O$ shows typical seasonal variation (fig. 10). In contrast, goat MONT_35 shows variable $^{87}Sr/^{86}Sr$ values and a flat $\delta^{18}O$ curve, which concurrently suggests that the animal was transhumant, being moved elsewhere during the warmer seasons, perhaps to mountainous areas of the Marche region.

Sheep exhibit even greater variability in mobility patterns. MONT_26, MONT_27, MONT_30, and MONT_32 show $^{87}Sr/^{86}Sr$ triplets in which at least one value falls outside the expected local range. In particular, MONT_26 appears to have grazed elsewhere during the warm season, while MONT_30 and MONT_32 likely did so during colder seasons[7]. For these animals, we can infer seasonal mobility (transhumance) from or towards various places, although data might also indicate the use of different pastures in the hinterland of Montarice at different times of the year. Conversely, $^{87}Sr/^{86}Sr$ triplets of sheep MONT_28 and MONT_31 show low variability and are compatible with local baselines, which suggests a resident management strategy for these domestic herbivores.

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6 Despite the limited availability of $^{87}Sr/^{86}Sr$ baselines for the Marche region, this range is strongly supported by the interval published by Esposito *et al.* (0.7087-0.7092) for the area of Fermo, approximately 30 km south of Montarice (Esposito *et al.* 2023). This interval also clearly reflects the high degree of geolithological and biogeochemical homogeneity across the Marche region.

7 We will not discuss MONT_27 $\delta^{18}O$ values, since they show an atypical, random intra-tooth variation likely derived from analytical issues.

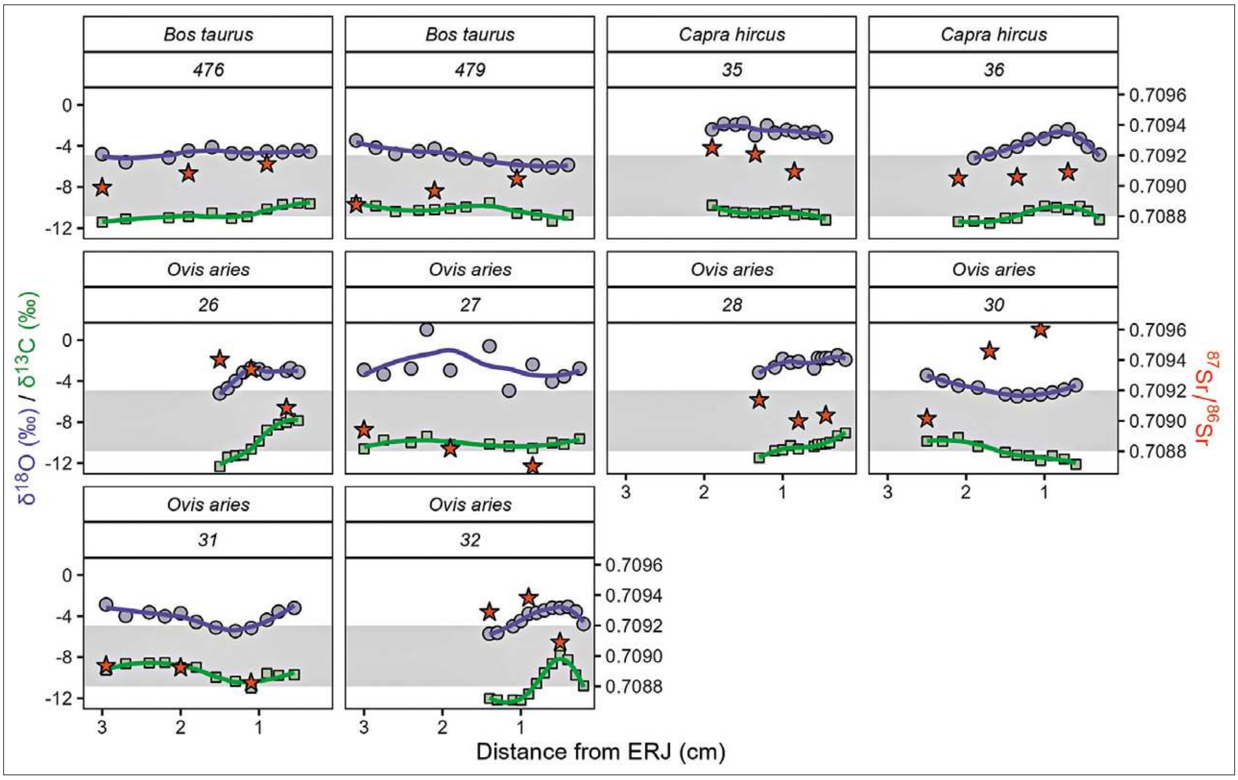

Fig. 10. Intra-tooth $^{87}Sr/^{86}Sr$, $\delta^{18}O$, $\delta^{13}C$ profiles of herbivores from Montarice.
Profilo isotopico intra-dente di $^{87}Sr/^{86}Sr$, $\delta^{18}O$, $\delta^{13}C$ *degli erbivori di Montarice.*

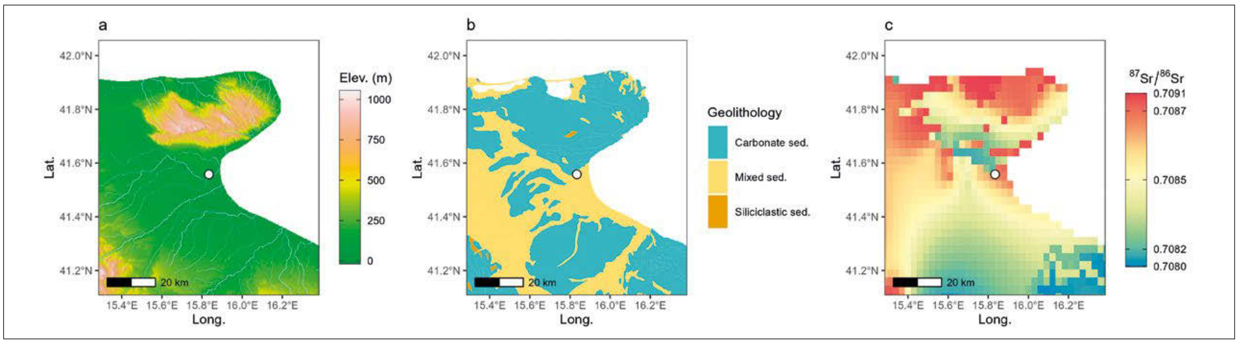

Fig. 11. a) DEM, b) geolithological map, and c) isoscape of bioavailable $^{87}Sr/^{86}Sr$ of Coppa Nevigata's territory.
a) DEM, b) mappa geolitologica e c) isoscape del $^{87}Sr/^{86}Sr$ *biodisponibile per il territorio di Coppa Nevigata.*

Regarding $\delta^{13}C$, MONT_26, MONT_28, MONT_31, and MONT_32 show some high values, which are compatible with the integration of C_4 plants into the diet. Linear mixing models estimate C_4 plant contributions of 13%, 2%, 7%, and 12%, respectively. Although the absence of archaeobotanical data from Montarice limits direct comparison with crop types, the strikingly high $\delta^{13}C$ values, reaching up to −7.6‰, suggest intentional feeding with C_4 plants, presumably millet. Moreover, the fact that all four individuals display $\delta^{13}C$ enrichment during the late summer-autumn seasons reinforces the hypothesis of artificial feeding in specific times of the year.

The two cattle from Montarice, MONT_476 and MONT_479, show $^{87}Sr/^{86}Sr$ values fully compatible with the local signature, low variability in $\delta^{18}O$ values, and low $\delta^{13}C$ values, consistent with a C_3-plant-based diet. For these individuals, we can argue for a residential management strategy.

Similarly, the two pigs, MONT_480 and MONT_481 seem indigenous and show no evidence of C_4-plant intake (fig. 7).

Overall, animal management practices in Montarice are characterized by a high rate of seasonal mobility among caprines. This is likely linked to the high soil erodibility in the Marche region (Grimm *et al.* 2002; van der Knijff-Jones-Montanarella 1999; Zema-Bombino-Zimbone 2023), an issue that will be discussed in greater detail below.

Considering the strong negative impact of large herds on the fragile calcareous vertisols of the Apennine region (cfr. Torresani *et al.* 2019; Arroyo-Pueyo-Barrantes 2024), this strategy could be justified by the need to maintain the productive potential of land in the immediate vicinity of the site for agricultural purposes, while moving animals towards the broader hinterland (short-distance transhumance) or even to more remote regions (long-distance transhumance).

The combination of residential and mobile strategies for Montarice sheep and goats could be explained by the presence of large mobile herds alongside small groups or single animals that were kept within individual households for subsistence purposes.

8.2.3 *Coppa Nevigata*

ZooMS analysis on the caprines from Coppa Nevigata confirmed the presence of two goats and four sheep, previously identified through morphological analysis. Previous studies established that commonly sheep outnumber goats throughout the Bronze Age sites in peninsular and Northern Italy (Cianfoni-De Grossi Mazzorin-Minniti 2024; Minniti 2021). All analysed sheep (COP_180, COP_185, COP_186, COP_189) show limited ^{87}Sr/^{86}Sr variability (0.7081-0.7083), fully compatible with the environmental range of the Tavoliere plain and the Gargano area (0.7080-0.7085)[8] (fig. 11), as well as with recently published human from the settlement itself (0.7081-0.7085; Thompson *et al.* 2025). δ^{18}O profiles range between 0 and −4.5‰, which clearly reflects the low variation in atmospheric temperatures typical of Mediterranean coastal areas. Both isotopic proxies suggest a non-mobile (local) management of these animals (fig. 12).

The two goats exhibit contrasting isotopic patterns. COP_183 shows Sr and O isotope values comparable to those of the sheep. In contrast, COP_202 is characterized by a highly radiogenic ^{87}Sr/^{86}Sr triplet (0.7109, 0.7108, 0.7113) and a δ^{18}O range from −4.4‰ to −8.2‰. These latter are considerably lower than those of all other analysed specimens from Coppa Nevigata and are typical of much colder regions (e.g. the Alpine areas)[9]. We can therefore interpret COP_202 as a goat, imported to Coppa Nevigata likely from the Alpine region during the Subapenninic phase. Between 1 and 2 years of age, when it was still in the place of origin, the animal used to move towards a more radiogenic area during the warm seasons, plausibly for some forms of transhumance.

The two cattle (COP_223 and COP_225) show limited ^{87}Sr/^{86}Sr variability and full compatibility with the environmental range of the Tavoliere and Gargano areas. This suggests a local management strategy for bovines. Bulk analyses of pig specimens (COP_194, COP_198, COP_203) similarly indicate that these animals were likely local or, alternatively, raised within the hinterland of Coppa Nevigata (fig. 7).

Carbon isotope data indicate a predominant C_3-plant-based diet for all animals, as also documented by archaeobotanical record (see above). Nevertheless, some individuals (*Bos* COP_225, *Capra* COP_183, *Ovis* COP_185 and COP_189) display relatively enriched δ^{13}C values, up to −9‰. This may reflect occasional ingestion of C_4 plants or of plant species typical of coastal/lagoon environments, characterized by enriched δ^{13}C values.

[8] Compared to the Italian territory, fewer ^{87}Sr/^{86}Sr data are currently available from the trans-Adriatic regions (e.g. Dudás-Burbank 2023; Gregorčič *et al.* 2021). Nevertheless, the geolithological similarities between the two shores suggest broadly comparable strontium isotope signatures. Consequently, it cannot be excluded that some of the animals identified as 'local' at Coppa Nevigata may in fact have originated from Istria, Dalmatia, or the southern Balkans. However, the high degree of ^{87}Sr/^{86}Sr and δ^{18}O homogeneity among specimens strengthen the local hypothesis.

[9] The Alpine provenance hypothesis is also corroborated by the high ^{87}Sr/^{86}Sr values identified in the area of Trento and Valsugana (Ladegaard-Pedersen *et al.* 2022). Other potential origins, such as the trans-Adriatic regions of the Karst, Dalmatia and the Balkans – proposed on the basis of archaeological evidence indicating contacts with southeastern Italy (Arena 2020; Cazzella-Recchia 2020) – can be excluded. These regions are characterized by significantly lower ^{87}Sr/^{86}Sr and higher δ^{18}O (e.g. Gregorčič *et al.* 2021; Dudás-Burbank 2023; Thompson *et al.* 2025), than those observed in the present dataset.

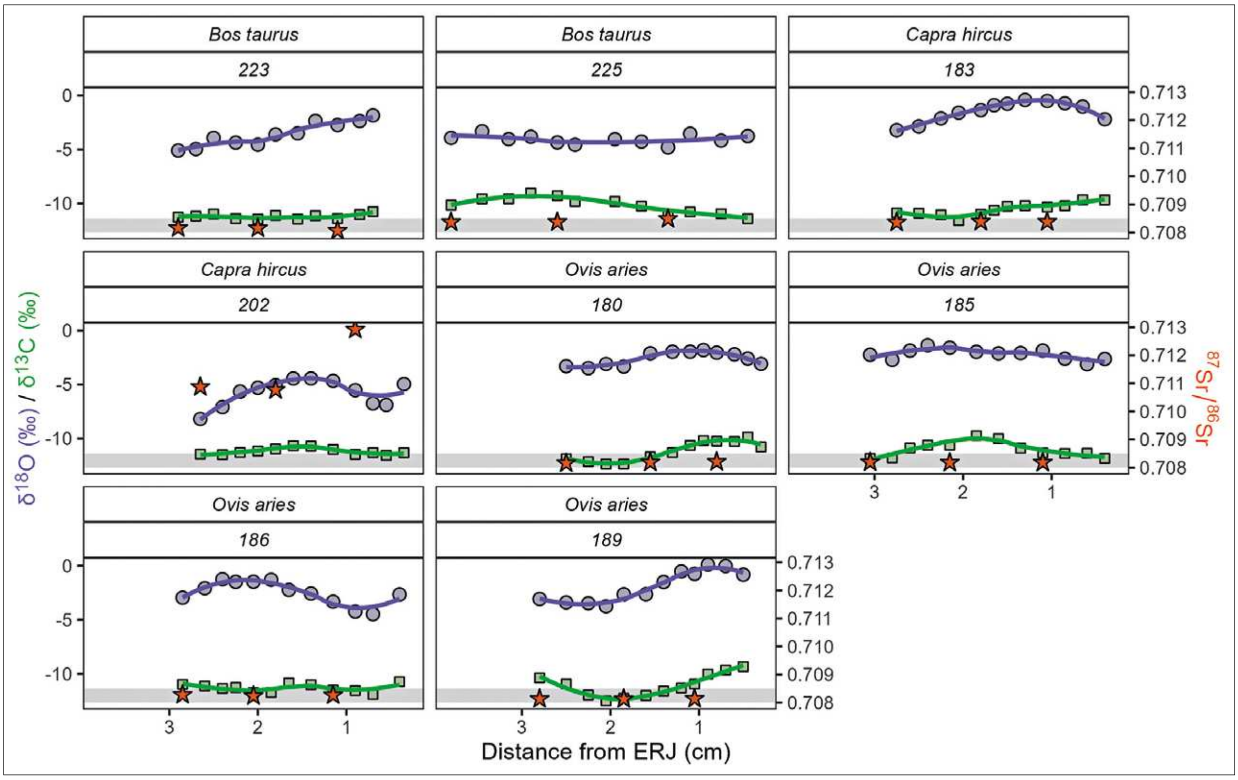

Fig. 12. Intra-tooth $^{87}Sr/^{86}Sr$, $\delta^{18}O$, $\delta^{13}C$ profiles of herbivores from Coppa Nevigata.
Profilo isotopico intra-dente di $^{87}Sr/^{86}Sr$, $\delta^{18}O$, $\delta^{13}C$ degli erbivori di Coppa Nevigata.

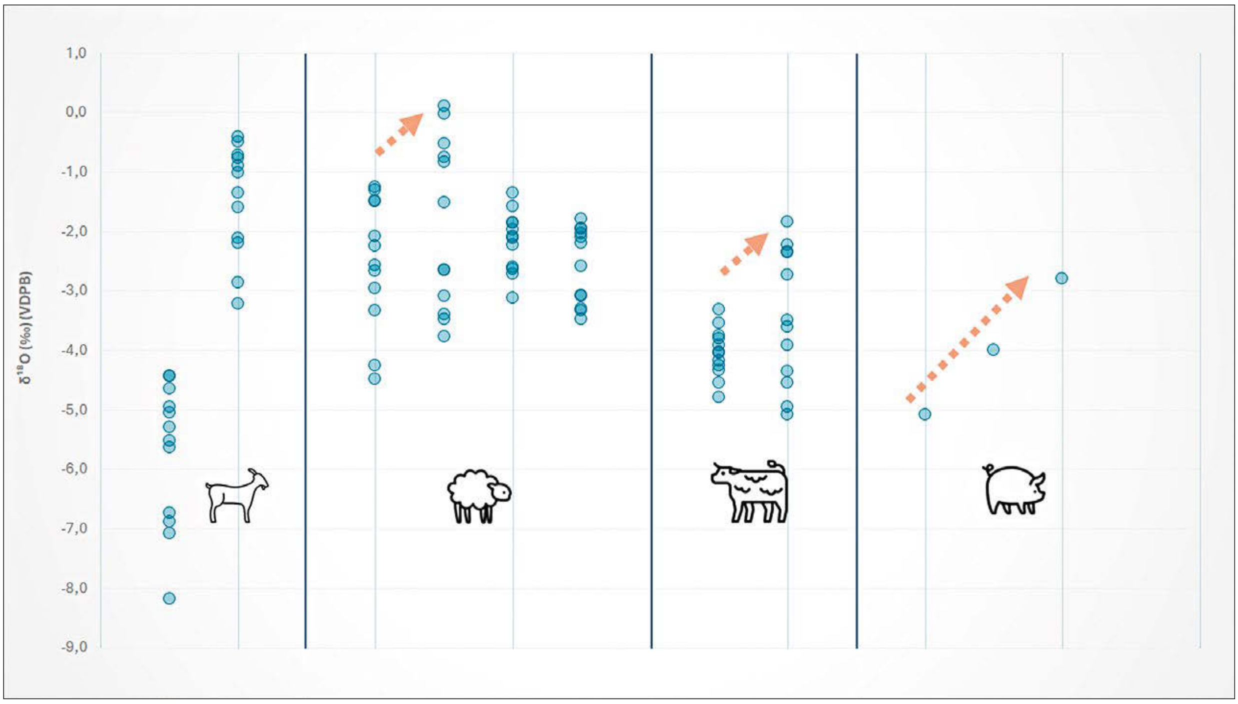

Fig. 13. $\delta^{18}O$ values for each animal analysed from Coppa Nevigata. Red arrows indicate increasing values at the onset of the Subapenninic phase (Recent Bronze Age; 1350-1150 BCE).
Valori di $\delta^{18}O$ per tutti gli animali analizzati da Coppa Nevigata. Le frecce rosse indicano i valori crescenti alla transizione alla fase Siubappenninica (Bronzo recente; 1350-1150 a.C.).

One of the most interesting aspects, which certainly requires further investigation, is the chronological trend observed in $\delta^{18}O$ values. Although the small sample size from Coppa Nevigata precludes broad generalization, there is an overall tendency towards an increase in $\delta^{18}O$ values over time, particularly at the transition to the Subapenninic phases. This pattern is observable among obligate (cattle and pigs) and non/semi-obligate drinkers (sheep; goats are exclusively from the Subapennine phase) and may reflect a possible increase in atmospheric temperatures, leading to higher $\delta^{18}O$ values in groundwaters consumed by the animals, both directly and indirectly through ingested vegetation (fig. 13).

9. DISCUSSION

The results of this study reveal a clearly differentiated pattern of animal management between the Po and Tavoliere plains – represented here by Solarolo and Coppa Nevigata – and the hilly regions of the Middle Adriatic region, represented by Montarice (fig. 14). At Solarolo and Coppa Nevigata, herbivores were kept in the immediate vicinity of the settlements. The exploitation of nearby pastures was likely integrated into an agricultural system based on crop rotation and fallow, with natural manuring as a primary strategy for maintaining soil fertility. As demonstrated by the modelling of territorial exploitation and archaeobotanical data at Solarolo and Coppa Nevigata, the area under the sites' control was sufficiently extended and open to supply all the fodder required for herbivorous livestock. Using rough estimates, an adult cow and an adult sheep require approximately 2 ha and 0.5 ha of grazeland per year, respectively, in temperate climates (Putfarken *et al.* 2008). Based on the estimated MNI of domestic animals coexisting at Solarolo-125 cattle, 208 caprines, and 133 pigs (see above)-the minimum grazeland required is roughly 350 ha. This area is well within the estimated 3,200 ha controlled by the Solarolo settlement. Pollen data indicate that approximately 60% of this territory consisted of open land (cropfields + pastures). Assuming that 30% of this open land was exploited as grazeland (under a rotation/fallow system), about 960 ha would have been available for this purpose, nearly three times the area required to sustain the estimated domestic herbivore population, based on zooarchaeological and stratigraphic data. In addition to major villages such as Solarolo, territorial management could be supported by smaller settlements, which have left fewer and less visible traces in the archaeological record. It can therefore be hypothesized that surplus land was also exploited by 'invisible' settlements or even small farmsteads.

Residential management among Bronze Age communities of the plain areas is also supported by recent studies, which ascertained the presence of structures specifically used as stables within the settlements, starting from the initial phase of the MBA in the Po-Adige plain, such as at Oppeano and La Muraiola (Nicosia *et al.* 2025; Polisca *et al.* 2025).

Within this predominantly residential management system, limited introduction of external livestock is also attested (one sheep and one pig at Solarolo, one goat at Coppa Nevigata). Accordingly, our revision of published strontium isotope data from a large set of caprines from the Terramara of Montale (Sabatini *et al.* 2022) suggests that at least 2 of the 33 analysed specimens (6%) may have been imported at least from the hinterland. Animal exchange was therefore relatively frequent within the hinterland and could be useful to maintain adequate levels of genetic diversity and herd health, although different, less practical reasons (e.g. gifts, dowries, etc.) must be considered[10]. Another possible explanation, which does not exclude the first, is that part of the non-local livestock may have resulted from acts of forced acquisition, such as theft and predatory raids.

The goat found at Coppa Nevigata, however, indicates that some animals could be imported from distant regions, in this case likely from the Alpine area. This evidence well matches a framework of intense terrestrial and maritime exchange between the coastal regions of the Adriatic, and more in general of the Mediterranean that involved primarily finished artefacts and raw materials (Cazzella-Recchia 2020). The supply of metal and Baltic amber from the regions of

[10] Our protocol did not involve sex determination through genetic analysis. Ideally, it would be important to establish which imported animals were males or females. For example, specific males with certain characteristics (e.g. body mass) could be selected for interbreeding.

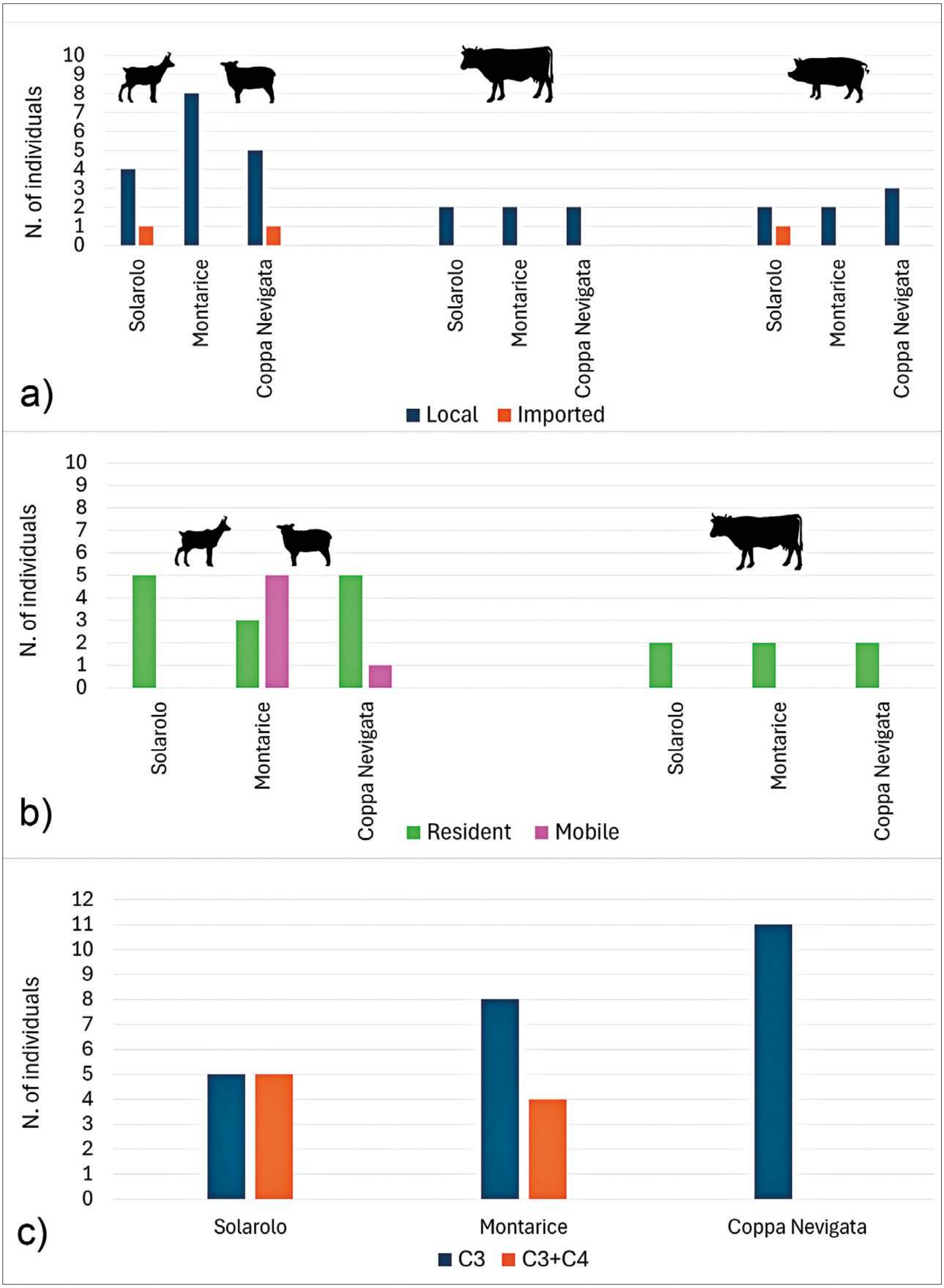

Fig. 14. Data interpretation. a) number of local and imported animals per site; b) number of resident and mobile animals per site; c) number of animals characterized by C_3-plant based diet and by the integration with C_4 plants.

Interpretazione dei dati. a) numero di animali locali e importati per sito; b) numero di animali allevati localmente o mobili stagionalmente per sito; c) numero di animali caratterizzati da dieta a base di piante C_3 o con integrazione di C_4.

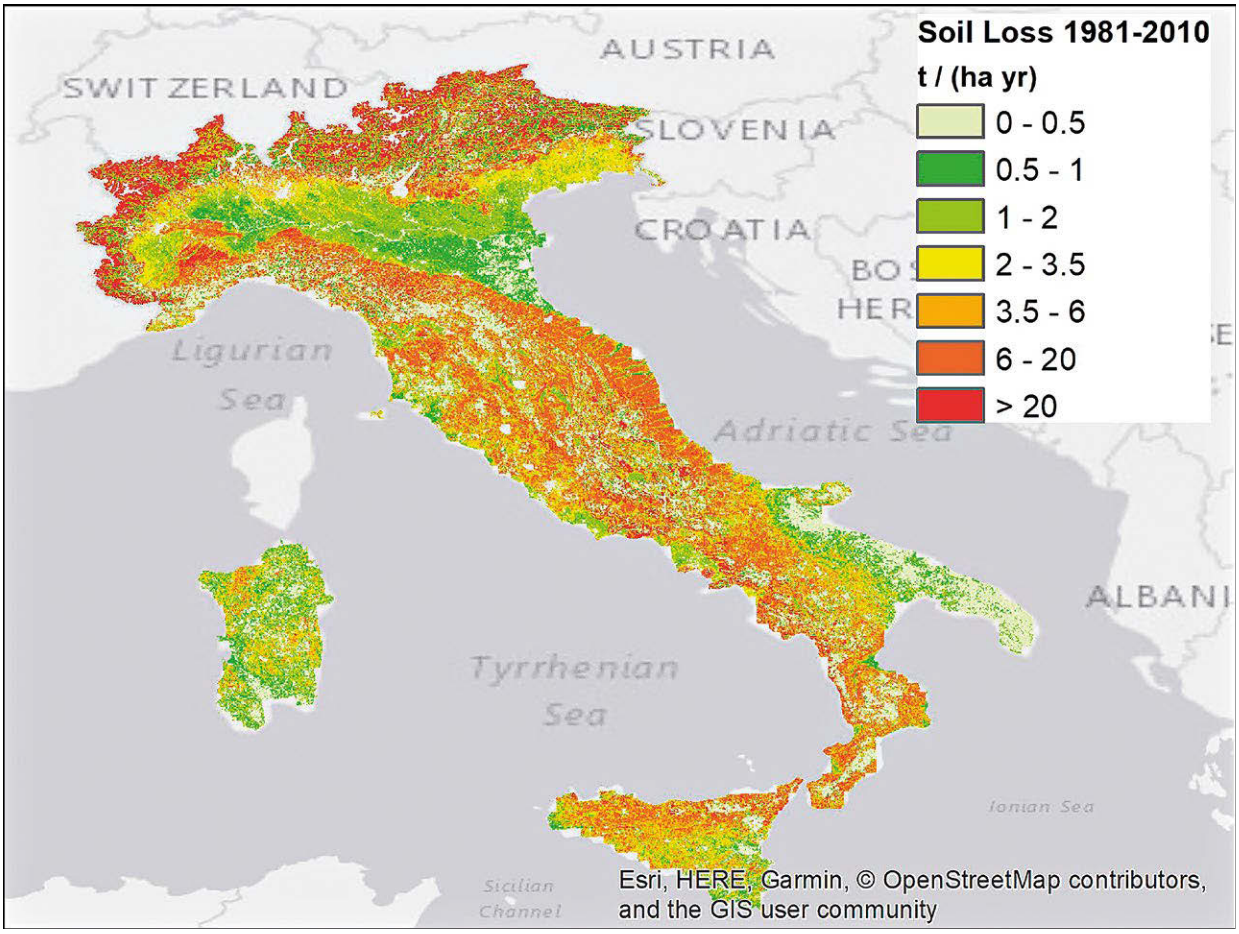

Fig. 15. Map of soil loss in Italy (after https://climate.copernicus.eu/soil-erosion-italy).
Mappa di perdita di suolo in Italia (da https://climate.copernicus.eu/soil-erosion-italy)

Northern Italy, in particular, is well-documented in the sites of Northern Apulia at least from an advanced phase of the MBA (Jung-Mehofer-Pernicka 2011; Jung and Mehofer 2013; Bellintani 2014; Cwaliński 2023).

Alternatively, livestock may have been used to provision ship crews during maritime journeys. The substantial volume and frequency of exchanges support the existence of an intensive maritime network, which would have required advanced seafaring technologies, most notably sewn-plank boats, as exemplified by the Zambratija shipwreck, dated to the 13th-11th centuries BCE (Koncani Uhač-Boetto-Uhač 2017).

At Montarice, caprine management followed a more variable strategy. The majority of the animals were grazed on distant pastures, although the specific locations cannot unambiguously be identified, preventing a clear distinction between short- and long-distance transhumance. Nevertheless, evidence for residential management is also attested at the site. This combination of practices suggests a mixed system, which may be interpreted in several ways. Given that the Montarice assemblage spans a broad chronological range (MBA3 to RBA1), a diachronic shift in herd management at the transition to the RBA cannot be ruled out. However, we propose that the most plausible explanation is the coexistence of different ownership and functional regimes: part of the livestock – probably that primarily devoted to wool production – may have belonged to large, transhumant herds, whether of common or private ownership remains to be determined; another portion was likely owned by individual households and oriented toward subsistence needs.

The significant investment in transhumant pastoralism among Bronze Age communities of the Middle Adriatic region was likely a response to the nature of soils along the Apennine ridge. Pedological studies indicate considerable variation in soil erodibility across the Italian territory, largely due to steep slope gradients and fine calcareous sediments, which are particularly susceptible to rainfall-induced erosion. Erodibility maps show limited soil loss in the Po Plain and the Tavoliere (<1 ton ha^{-1} yr^{-1}), whereas mountain areas of the Alps and Apennines experience much higher rates (>20 tons ha^{-1} yr^{-1}) (fig. 15). For the purposes of this study, the hilly areas of the Marche region exhibit high vulnerability (>6 tons ha^{-1} yr^{-1}) (Grimm *et al.* 2002; van der Knijff *et al.* 1999; Borrelli *et al.* 2016).

Zoogenic erosion further exacerbates soil loss in vulnerable pedozones, particularly under conditions of large herds and overgrazing (Torresani *et al.* 2019; Arroyo *et al.* 2024). Animal trampling causes soil compaction, which reduces water infiltration (Kumbasli *et al.* 2010), and detachment of soil particles during hoof lifting. Overgrazing also leads to a loss of vegetation cover and biodiversity (Ibáñez-Martínez-Schnabel 2007; Oztas-Koc-Comakli 2003; Thornes 2007; Zucca-Canu-Previtali 2010). These ecological constraints, plausibly complemented by increased demographic pressure, food demand, investment in wool production and therefore in large sheep herds, likely acted as push factors, encouraging the exploitation of more distant pastures and the adoption of a more extensive pastoral strategy.

Such dynamics may have been one of the principal factors driving the systematic occupation of mountain areas – closer to high-altitude pastures and along major communication routes – observable. from at least MBA3 throughout the Apennines (Cardarelli 2006; Cavazzuti-Putzolu 2015; Putzolu-Cavazzuti 2019). Supporting evidence comes from a recent study in the Tuscan-Emilian Apennines, which documents that soils above 1,550 m were subjected to extensive deforestation by fire and pedogenetic processes during the Recent Bronze Age, likely linked to the use of highlands as grazing pastures (Vittori Antisari *et al.* 2018). Although derived from a different sector of the Apennines, these data are consistent with the broader patterns inferred here.

Beyond ecological push factors, the seasonal displacement of herds likely entailed a wide range of socio-cultural implications. First, passage through territories controlled by different communities would have required a more profound geographical knowledge, as well as forms of negotiation through alliances and agreements, potentially strengthened by exogamic practices (e.g. Cavazzuti *et al.* 2019) and a certain degree of economic interdependence. Second, communication networks had to be maintained in order to secure and facilitate movement, implying a substantial investment of labour in the maintenance of paths and a dense occupation of upland areas. Further research is needed to assess the extent of mobile pastoralism in central and southern Italy; however, these preliminary results clearly highlight the complexity of the phenomenon.

Another noteworthy aspect is the occasional incorporation of C_4 plants into the animal diet, occurring predominantly during autumn. Approximately half of the herbivores from Solarolo and one third of those from Montarice exhibit $\delta^{13}C$ enrichment consistent with episodic consumption of C_4 plants. The sporadic nature of this signal may reflect responses to specific environmental conditions, such as particularly dry summers that reduced the availability of fresh pasture and necessitated the use of supplementary fodder for herbivores. On the contrary, Coppa Nevigata does not show this kind of evidence, as confirmed by archaeobotanical data.

Although spontaneous plants, such as cockspur grass (*Echinochloa crus-galli*) might be included in the C_4-plant proportion (cfr. Nicosia *et al.* 2025), multiple independent lines of evidence, including archaeobotanical and biomolecular data, seems to indicate broomcorn millet (*Panicum miliaceum*), as the major contributor. Millet is known to have been cultivated by Middle Bronze Age communities in northern Italy, as documented in MBA2 layers at Solarolo (c. 1550-1450 BCE) (Carra 2009, 2012, Carra *et al.* 2023) and Muraiola di Povegliano (Polisca *et al.* 2025), as well as in MBA3 contexts (1450-1400 BCE) at the Lavagnone lake-dwelling site (Filipović *et al.* 2020) and at the votive pool of Noceto (Rottoli-Castiglioni 2009). Isotopic analyses of both collagen and enamel apatite further indicate that human and animal diets in the Po Plain included variable proportions of C_4 plants from at least the Middle Bronze Age onward (Tafuri *et al.* 2018; Cavazzuti *et al.* 2019; Varalli-Moggi-Cecchi-Goude 2022), and in Recent Bronze Age at Punta Zambrone (Rumolo *et al.* 2020). With specific regard to animals, C_4 plant consumption has previously been identified in several bovine and swine specimens from multiple sites, including

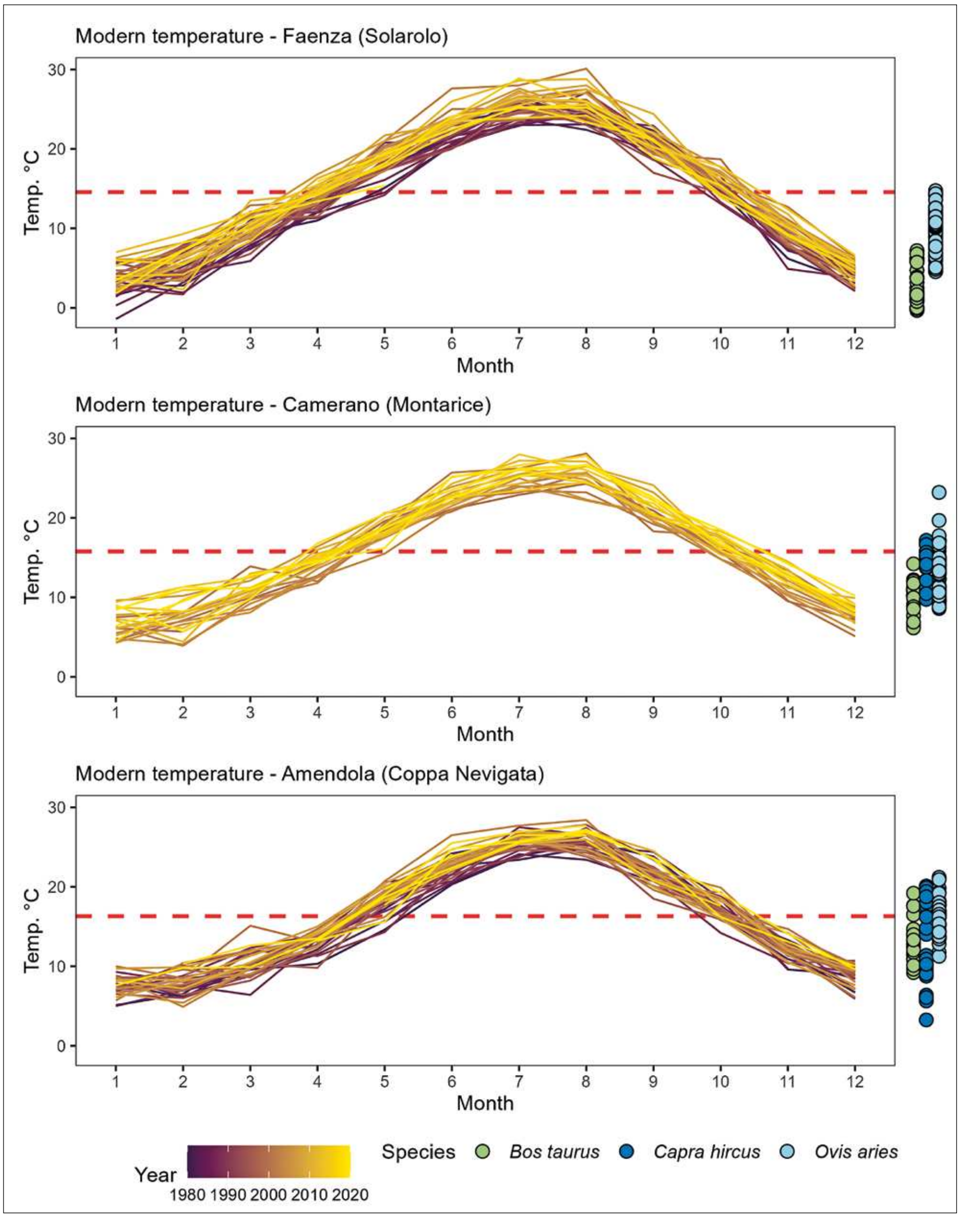

Fig. 16. Atmospheric temperature records from 1980 to 2020 (https://scia.isprambiente.it/) for representative sites in the vicinity of the study areas. Horizontal dashed red lines represent the average annual temperature at each site. Filled circles are temperature estimates based on the $\delta^{18}O$ values of herbivores' enamel. These data consist of direct measurements, not modelled to account for enamel damping, and therefore do not capture the full amplitude of the water isotope signature.

Temperature atmosferiche misurate tra il 1980 e il 2010 (https://scia.isprambiente.it/) in siti prossimi alle zone campione di questo studio. Le linee tratteggiate orizzontali rappresentano la temperatura media al suolo da ogni sito. I cerchi colorati rappresentano le temperature stimate sulla base dei valori di $\delta^{18}O$ sullo smalto degli animali analizzati. Questi dati consistono in misurazioni dirette, non modellate per tenere conto dell'effetto di attenuazione dello smalto, e pertanto non catturano l'intera ampiezza del segnale isotopico dell'acqua.

Mereto, Olmo di Nogara, and Fondo Paviani (Tafuri *et al.* 2018; Cavazzuti *et al.* 2019).

Another interesting aspect derives from the analysis of $\delta^{18}O$ variations among the three different sites. The higher values recorded among local animals in Coppa Nevigata, compared to Montarice and Solarolo reflect the climatic differences between south, central and northern Italy that clearly depend on latitude and distance from the coast (cfr. Giustini-Brilli-Patera 2016).

Higher $\delta^{18}O$ values recorded among local animals in Coppa Nevigata reflect the warmer and more stable climatic conditions of southern Italy, whereas lower values at Montarice and Solarolo correspond to cooler and more continental settings.

Air temperature estimates derived from $\delta^{18}O$ values of herbivore enamel are broadly consistent with modern mean annual temperatures at each site, suggesting comparable climatic conditions (fig. 16). Solarolo, however, represents a notable exception, with reconstructed average temperature lower than present-day values. This discrepancy may reflect local ecological factors affecting the isotopic signal (e.g. consumption of ^{18}O-depleted drinking water), or alternatively, cooler conditions at the time of enamel formation (MBA2), which could be connected to the 3.6 ka event, suggested by the advance of the Tyrolean Alps glaciers (beginning of the Loebben oscillation) (Moran *et al.* 2017).

An interesting diachronic trend in our results is provided by $\delta^{18}O$ from Coppa Nevigata, where we detected an increase of values among sheep, cattle, and pigs at the transition to the *Subapennine* phase, which may reflect a possible increase in atmospheric and ground temperatures around 3.2 ka BP (see for example Molloy 2022 and references therein). This trend, also supported by archaeobotanical data, certainly requires additional isotopic confirmation.

Future studies applying multi-isotopic protocols to larger, well dated faunal assemblages will be essential for validating and refining regional climatic reconstructions in specific areas and for disentangling environmental from management driven isotopic signals.

10. CONCLUSIONS

This study represents a first attempt to reconstruct animal management strategies across different Bronze Age contexts in present-day Italy using an integrated multi-isotopic and zooarchaeological approach. Our results highlight a range of diversified practices, largely shaped by local ecological conditions, particularly pedological characteristics.

In the Po and Tavoliere plains, isotopic evidence points to an integrated system combining residential husbandry and agriculture, oriented toward intensive land use and maximization of food production in the immediate vicinity of settlements, complemented by a relatively frequent import of livestock, either from the hinterland or from distant regions.

In contrast, in the Marche region, communities appear to have adopted a mixed strategy of residential management and transhumance for different kinds of herds (e.g. for subsistence or for wool production), likely in response to the high susceptibility of local soils to erosion in the surrounding hinterland.

We also identified the occasional use of C_4 plants (broomcorn millet) as fodder for domestic animals at Solarolo and Montarice, further indicating a close interdependence between agro-pastoral practices.

Although the sample size remains too limited to support broader generalizations, this study establishes, in our view, a robust methodological framework for investigating animal management, mobility and land use strategies in prehistoric contexts. Future research applying similar integrated approaches to larger datasets will test and refine the patterns we observed here and place them within a broader comparative perspective of the socio-economic organization of Bronze Age communities.

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Data availability

All ZooMS data are available on Zenodo: https://doi.org/10.5281/zenodo.18554110

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