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Isotopic Insights into Livestock Production in Roman Italy: Diet, Seasonality, and Mobility on an Imperial Estate

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ABSTRACT

Agriculture is the most important intersection between farming communities and the natural world, with major implications for land exploitation and labour organisation. In Italy, at the heart of the Roman Empire, understanding of agriculture remains heavily dependent on ancient sources, which are unable to provide a regional or diachronic view of practices across the socio-economic spectrum. In order to gain insight into agricultural economies in Roman Italy and their social and environmental implications, this article reconstructs agro-pastoral strategies at an imperial estate in southern Italy through a multi-isotope investigation of livestock bone collagen and tooth enamel. Analysis of carbon, nitrogen, oxygen and strontium isotopes ($\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$, $^{87}Sr/^{86}Sr$) are combined to evaluate animal management and mobility at Vagnari vicus and the villa of San Felice in the Basentello Valley. Results reveal taxon-specific herding strategies with the potential for significant inputs from legume forage/fodder and/or natural environments. Caprine herding did not appear to include long-distance transhumance. This analysis moves past previous text-based generalisations to provide a new and nuanced perspective on animal production in rural southern Italy and its economic and environmental implications.

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Roman economy; imperial estates; animal husbandry; transhumance; agriculture; Puglia

Introduction

For agrarian empires like Rome, agriculture was the most important intersection between people and the natural world. It formed the foundation of complex food production systems, fuelled urban and military supply, and shaped the organisation, timing, and intensity of rural labour. The socio-economic and environmental consequences of changes to farming systems, widely recognised in relation to prehistoric agriculture (e.g. Bogaard, Fochesato, and Bowles 2019; Styring et al. 2018), are beginning to receive greater recognition in the Roman period (e.g. Lepetz and Zech-Matterne 2018; Lodwick 2023). However, in Italy, at the core of the Roman empire, research into ancient farming is dominated by discussion of villas, settlement dynamics, oil/wine production, and particularly by ancient texts (Marzano 2020; Witcher 2016). Interest in the production of staple resources – cereals and livestock – and the environmental archaeology needed to understand them, has lagged behind, particularly when viewed in relation to advancements in agricultural research elsewhere in the Roman world (e.g. the north-west provinces: Aguilera et al. 2018; Allen and Lodwick 2017; Lepetz and Zech-Matterne 2018; Lodwick 2023; Lodwick et al. 2020).

From the writings of ancient authors like Cato, Varro, and Columella, to the many political dramas interwoven with agriculture and pastoralism, Roman history presents a detailed litany of practices undertaken at particular moments (e.g. Bowman and Wilson 2013; Roselaar 2010; White 1970); however, the geographic and chronological applicability of these accounts, as well as their relevance to different levels of society, remain open questions. Agronomic texts are increasingly recognised as reflections of their cultural and political context rather than simply farming manuals (Hollander 2019, 1–10). Their treatment of farming is also not exhaustive, with a focus on villa agriculture and on-farm animal management that does not engage as expansively with extensive forms of herding. Large-scale ranching and pastoralism –

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important means of creating surplus animals and secondary products – are in fact classified by Varro as a separate enterprise to farming, and excluded from his discussion of animal husbandry (*Rust.* 1.1.11; 1.2.11–22; 2.praef.4–5).

Over the last twenty years, zooarchaeological studies have supplied new data on animal management in Roman Italy, with increasing numbers of synthetic works in recent years (e.g. Albarella, De Grossi Mazzorin, and Minniti 2019; De Grossi Mazzorin and Minniti 2017; MacKinnon 2004; Minniti and Abatino 2022; Trentacoste et al. 2021). These analyses have been crucial to defining animal management strategies at different scales, and they have raised questions about the localisation of livestock production, exchange and seasonal movement of animals, and feeding strategies. Bioarchaeological analyses, which provide direct evidence for animal diet and mobility, are able to address these questions, and isotopic studies are now providing insight into livestock management in broader Roman contexts. For the provinces, strontium isotope analyses have supplied evidence for dynamic cattle supply networks, in which animals were moved over long distances (Groot and Albarella 2022; Madgwick et al. 2019; Minniti et al. 2014; Nieto-Espinet et al. 2020). In contrast, isotopic analysis of animals from Roman Italy has only been conducted as a support for human-centred studies (e.g. De Angelis et al. 2020; Emery et al. 2018; Killgrove and Tykot 2013; O'Connell et al. 2019; Soncin et al. 2021). The modest number of animals sampled, as well as the focus of many of these studies on the city of Rome and its immediate environs, which drew resources from great distances, makes it difficult to draw broader conclusions on the organisation of Italian agriculture. Consequently, we have little idea of where animals in Roman Italy were managed and how they were fed, and therefore of the landscapes and varying degrees of human labour involved in their production.

Aims

Here we undertake the first livestock-focused, multi-isotope analysis of pastoral practices in Roman Italy, to investigate animal management and mobile herding strategies at the Roman imperial estate in the Basentello Valley in Puglia (Figure 1). The estate's location places it close to the Via Appia, a major artery joining central and southern Italy, as well as transhumance routes linking upland Lucania with the Basentello Valley and Murge plateau. The estate thus lay at an important waypoint connecting upland summer pastures with winter grazing in the plains, as well as routes joining productive inland areas with coastal centres like Taranto and Metaponto to the south. This location along a network of drove roads suggests the estate was involved in transhumant sheep husbandry (Small, Volterra, and Hancock 2003). To investigate this hypothesis and other aspects of livestock management, we use carbon (δ^{13}C) and nitrogen (δ^{15}N) isotopes from bone collagen to compare livestock diets, and carbon (δ^{13}C), oxygen (δ^{18}O), and strontium (^{87}Sr/^{86}Sr) isotopes from caprine tooth enamel carbonates to determine seasonal changes in sheep/goat diet and mobility patterns. These analyses provide new evidence for agricultural strategies, mobile pastoralism, and environmental exploitation in southern Italy, and consequently for the organisation of a major sector of the Roman rural economy in the region.

Models of Animal Production in Roman Italy

Current models of livestock production in Roman Italy range from highly intensive to highly extensive. One end of the spectrum is represented by enclosed, on-farm, and feed-dependant management, exemplified by the 27-room courtyard pigsty at the villa of Settefinestre (Ricci 1985); conversely, animals could be raised entirely off-site in natural pastures, or herded at great distance following seasonal forage (Gabba and Pasquinucci 1979; Pasquinucci 2021). At least for pigs, strategies along this spectrum were likely practiced in parallel, and zooarchaeologists have highlighted the importance of extensive, free-ranging production systems based on woodland resources, alongside production of stall-fed animals (MacKinnon 2001; Trentacoste et al. 2021). Despite arguments for transhumance as a particular socio-ecological adaptation dependant on a range of factors, including political integration and economic specialisation (Carrer and Migliavacca 2019; Cleary and Smith 1990; Corbier 1991), it remains cited as the primary production strategy for sheep in Roman southern Italy, even if the distances involved (long/short) are debated for different historic periods or left obscure (Gabba and Pasquinucci 1979; Pasquinucci 2021).

Understanding of the level of integration between livestock and arable farming also varies. Convertible husbandry and ley farming – long rotations in which fields vary between pasture, fodder crops, and cereals – have been emphasised, but with a focus on different aspects: some authors have highlighted the importance of long periods of pasture and its management (Bowes et al. 2017), while others stress heavy application of manure and crop rotations (Kron 2000; 2004). Isotopic analysis of Roman cereals is still in its infancy, but recent work in Britain points to extensive cultivation practices, at least for sampled assemblages in this province; livestock were likely integrated to maintain soil fertility, although manuring was not to a level that would register strong isotopic evidence (Lodwick 2023; Lodwick et al. 2020). Stable isotope analysis of crops from pre-Roman Gabii in central Italy points in a similar direction,

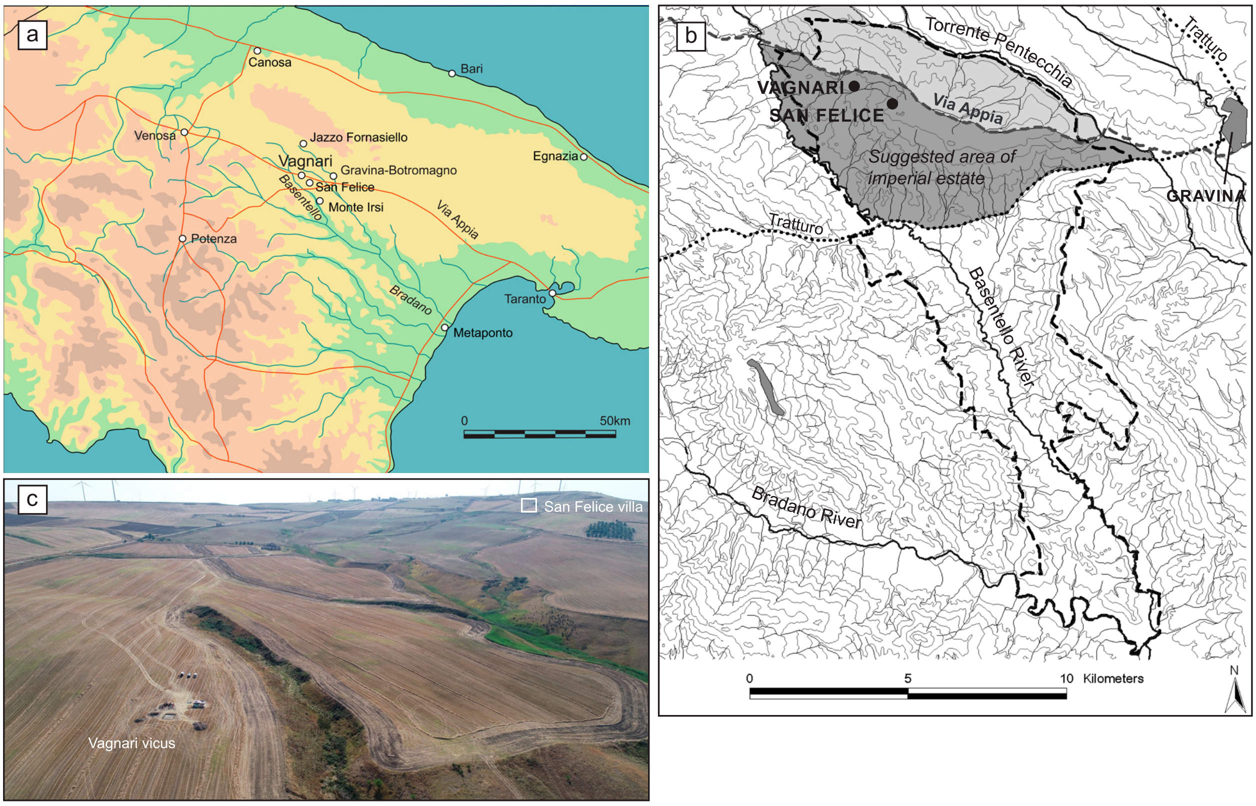

Figure 1. Study area: (a) map of southern Italy with location of study sites and other major settlements (after Carroll 2022b), (b) hypothesised area of the imperial estate (base map by C. Small); and (c) drone view of the modern landscape (Photo by V. Ferrari and G. Ceraudo, Laboratorio di Topografia antica e Fotogrammetria dell'Università del Salento).

since low crop nitrogen isotope values suggest that crops were not heavily manured (Gavériaux et al. 2022). Archaeobotanical remains of livestock fodder, both in Italy and in the provinces, demonstrate a well-developed infrastructure for the production and transport of animal feed, extending from the rural landscape into settlements and cities (Kron 2004).

The Basentello Valley Estate

The productive settlement of Vagnari vicus and adjacent villa of San Felice (approximately 1.5 km southeast) are located in the Basentello River Valley in Puglia (Figure 1). They are thought to form part of a large productive estate owned by the Imperial family (Carroll 2022a; Small and Small 2005; Small, Volterra, and Hancock 2003). The strategic position of the estate near traditional drove-ways and on the Via Appia, with links to the west and east coast of Italy, was clearly advantageous for the hub of an imperial possession. Zooarchaeologial studies at Vagnari documented a prevalence of sheep/goat remains during the main life of the vicus (c. 40–50%, first to fourth centuries AD) (MacKinnon 2011; Trentacoste 2022). Trends at San Felice villa were similar, with evidence for a mixed agro-pastoral scheme (MacKinnon pers. comm.). At both sites, there was a predominance of sheep/goat belonging to a mix of ages, followed by pigs and cattle. A slight, but not significant, elevated proportion of pigs and younger taxa at San Felice may point to greater dietary wealth at the villa.

Vagnari Vicus

The vast agricultural and pastoral territory around the settlement (vicus) at Vagnari was occupied in the Roman imperial period, from the first to fourth centuries AD (Carroll 2022b). The retrieval here of ceramic roof tiles stamped with the names of imperial slaves indicates that this territory was the property of the owner of those slaves – the Roman emperor himself. Archaeological fieldwork indicates that the emperor was not the first Roman landowner in the region. A study of the excavated material culture and structures confirm that occupation of the site at Vagnari goes back to the second century BC, possibly the result of the seizure of land by powerful senatorial families from Rome who grew rich by colonising areas following the Roman conquest. This private landholding then entered imperial possession, perhaps through inheritance, in the early first century AD. Archaeological evidence points to the period between the late first and the end of the third century AD as the most active and productive phase of occupation in the vicus at Vagnari. A period of building activity and expansion during the second century appears to coincide with the destruction of the villa at San Felice, suggesting that these events may be linked. The fourth century AD witnessed the decline and abandonment of many of the buildings in the vicus.

The archaeological investigations at Vagnari have revealed a variety of human activities that involved the exploitation of the landscape and its resources. This imperial settlement had a diverse economy, ranging from cereal cultivation and animal husbandry, to metal-working, the tile and pottery industry, and the production of wine and oil (Carroll 2022a). To the south of the vicus, a Roman cemetery was laid out that was in use in the second and third century AD (Brent and Prowse 2014; Small et al. 2007). Previous isotopic investigation of humans from this cemetery provided comparative information for the current study (Emery et al. 2018; Semchuk 2016).

San Felice

The Roman site at San Felice is a courtyard villa, constructed in the second half of the first century BC and eventually abandoned in the first half of the second century AD (McCallum et al. 2011). It was probably the administrative centre of the imperial estate, located near the main habitation and production centre at Vagnari. The villa was initially built as a private structure, possibly by someone associated with the gens Pompeia (McCallum and VanderLeest 2014; Small and Small 2022). As with Vagnari vicus, it became an imperial possession by the early first century AD. Evidence for this ownership comes from tiles stamped GRATI.CAESARIS (belonging to Gratus, slave of Caesar), examples of which were recovered during both surface survey and excavation (McCallum and VanderLeest 2014).

From the beginning, the villa had a distinct division between a productive area (*pars rustica*) and a residential area (*pars urbana*). The productive area, which appears to have been expanded once the structure became an imperial estate, included a wine production area, of which a series of settling basins and a dolium yard have been excavated. The villa's residential area included *opus signinum* flooring (waterproof concrete) and frescoes in both the first and second Pompeian styles. A large dump within the structure's peristyle included what might be termed luxurious objects, such as a silver mirror, a bronze lamp, and an intaglio gemstone, among other finds dating to the first century AD.

Abandonment of the structure as a residential unit took place at some point in the early second century AD, possibly after a disastrous landslide, which may have been associated with an earthquake (McCallum et al. 2011; McCallum and VanderLeest 2014). In the aftermath, the area of the villa continued to be used as an industrial area, with the insertion of a limekiln, a pit kiln, and an updraught pottery kiln (Munro 2012; Munro 2020). This activity may have continued at the site until the third century AD, after which it was completely abandoned.

Isotope Analysis

Carbon (δ^{13}C) and Nitrogen (δ^{15}N) Isotopes in Bone Collagen

Analysis of carbon and nitrogen stable isotopes can be used to investigate forage and fodder provisioning, as well as pasture exploitation, through the study of animal diets. In bone collagen, δ^{13}C and δ^{15}N values primarily reflect dietary protein, and represent a long-term average of dietary intake (Ambrose and Norr 1993; Sponheimer et al. 2003). In sheep, goats, and cattle, it would be expected that isotopic values in skeletal tissues reflect consumed plants, although herbivores with nutritional deficiencies may also eat dead animals and bones (Provenza, Meuret, and Gregorini 2015). The omnivorous diets of pigs can contain a wide range of food sources, including plants, human food waste, fungi, invertebrates, carrion, eggs, amphibians, and small mammals (Greenfield 1988; Schley and Roper 2003). Isotope values differ between diet and consumer due to fractionation, with differences of approximately 5‰ in δ^{13}C and 3–5‰ in δ^{15}N (Deniro and Epstein 1981; Fernandes, Nadeau, and Grootes 2012; Hedges and Reynard 2007; Minagawa and Wada 1984).

Carbon isotope values in plants vary with photosynthetic pathway (C_3 and C_4) and provide information on growing conditions, particularly water availability (Farquhar, Ehleringer, and Hubick 1989; Körner, Farquhar, and Wong 1991; Wallace et al. 2013). Temperature, altitude, and forest cover also influence carbon stable isotopes in plants (Heaton 1999; Körner, Farquhar, and Wong 1991; Moreno-Gutiérrez et al. 2012; Tieszen 1991). In terms of livestock, this variation has been useful for identifying animals raised in closed-canopy forests, which have lower δ^{13}C values compared to those in open landscapes (Bonafini et al. 2013).

Nitrogen isotope values in plants provide information on ^{15}N enrichment in soils, which can vary with a range of natural and anthropogenic practices (Szpak 2014). Aridity, salinity, burning, waterlogging, and denitrification can all impact nitrogen isotope values in soil (Guiry, Noël, and Fowler 2021; Hartman and Danin 2010; Sponheimer et al. 2003). Manuring enriches ^{15}N in soils and consequently plants grown in them, whether manure is applied consciously to increase the fertility of arable agricultural fields, or unintentionally as a result of repeated pasture use and stocking density (Bogaard et al. 2007; Makarewicz

2014; Szpak et al. 2012; Treasure, Church, and Gröcke 2016). Manuring has a different impact on legumes compared to cereals and grasses, as a result of legumes' ability to fix atmospheric nitrogen. Particular manures or intensive application is needed to significantly raise nitrogen isotope values in both soils and legumes growing in them (Fraser et al. 2011; Szpak 2014; Szpak et al. 2014; Treasure, Church, and Gröcke 2016). Finally, the part of the plant consumed is also important for interpreting isotope values from herbivore bone collagen. Compared to grains, cereal stems, leaves, and chaff are enriched in ^{15}N by c. 1–4‰ and ^{13}C by c. 2‰ (Szpak 2014; Wallace et al. 2013).

Oxygen (δ^{18}O), Carbon (δ^{13}C), and Strontium (^{87}Sr/^{86}Sr) Isotopes in Tooth Enamel

Sequential sampling of caprine tooth enamel captures high-resolution changes in isotopic values, which can be used to investigate livestock seasonality and mobility (Balasse 2002; Makarewicz and Sealy 2015). Isotopic values measured in sheep tooth enamel represent an average signal over approximately six months of enamel maturation (Balasse, Obein, et al. 2012b; Zazzo et al. 2010). Oxygen isotope values in herbivore enamel reflect that of consumed water sources, including drinking water, leaf water, and plant dry matter (Balasse 2002; Fricke and O'Neil 1996; Kohn, Schoeninger, and Valley 1996; Levin et al. 2006). These water sources vary significantly in their oxygen isotope composition, which may also vary seasonally based on evaporation and transpiration.

In Italy, oxygen isotope values in precipitation vary seasonally, with low values recorded during winter months and high values during summer (Figure 2) (Giustini, Brilli, and Patera 2016; Longinelli and Selmo 2003). However, deviations from the sinusoidal pattern can be produced by amount effects, with lower meteoric δ^{18}O values during high volumes of precipitation. Altitude also has an impact, and lower meteoric δ^{18}O values are documented at higher elevation. This patterning in the oxygen isotope composition of precipitation is visible in the study region, with the lowest meteoric δ^{18}O values recorded at the most elevated weather station (Piloni, 1274 m.a.s.l) and higher values on the coast.

Seasonal changes in precipitation and temperature levels can lead to variation in the stable carbon isotope values of plants, creating seasonal patterning in sheep and goat diets. Enrichment in dietary ^{13}C can reflect changes in plant growing conditions as well as seasonal differences in grassland plant communities (Lowdon and Dyck 1974; Ode, Tieszen, and Lerman 1980; Smedley et al. 1991; Tieszen et al. 1997). Further seasonal complexity may be introduced through foddering, a practice widely attested by Roman textual sources and archaeobotanical evidence (Kron 2004; Lepetz and Zech-Matterne 2018). The impact of winter foddering, for example, will depend on the carbon isotope composition of the plant supplied: tree-leaf fodder could lead to seasonal ^{13}C depletion in enamel, while summer cut grasses would produce a relative ^{13}C enrichment, especially if C_4 plants formed part of the fodder (Balasse, Boury, et al. 2012; Makarewicz and Pederzani 2017). Considering the strong seasonality in temperature and precipitation on the Basentello estate, which has twice as much rainfall in the winter (c. 160 mm) compared to the summer (c. 80 mm) (WorldClim 2017), seasonal patterning would be expected in δ^{13}C values in tooth enamel from local sheep and goats.

Strontium isotope ratios (^{87}Sr/^{86}Sr) in animal tissues reflect bioavailable strontium inputs incorporated into the body through diet, which pass without fractionation through the food chain (Bentley 2006; Blum et al. 2000; Flockhart et al. 2015). Compared to bone, tooth enamel has been demonstrated to be comparatively resistant to diagenetic alternation, preserving the biogenic ^{87}Sr/^{86}Sr signature, although minor alternations (<0.0005) may occur (Madgwick, Mulville, and Evans 2012). Geology has the largest impact on bioavailable strontium values, with strontium isotope ratios in bedrock determined by the age and rubidium-to-strontium ratio of the formation (Bentley 2006; Faure and Mensing 2005). Modern agricultural practices and precipitation can, however, have a significant impact (Evans et al. 2010; Maurer et al. 2012; Techer et al. 2017; Thomsen and Andreasen 2019).

Results from a study by Emery et al. (2018) of human mobility at the Vagnari cemetery offer evidence for expected ^{87}Sr/^{86}Sr values in 'local' animals raised within the same resource catchment as humans buried at the vicus (even if the exact distance this represents is undefined). Emery et al. (2018) analysed: humans from the Vagnari cemetery ($n = 43$, mean 0.70862, 1sd = ±0.00055); sediments ($n = 5$, 0.7087–0.70886); fauna from the cemetery (unidentified ungulate teeth, $n = 3$, 0.70802–0.70874); and fauna from the nearby sites of Botromagno and Parco San Stefano (10 km east) (ungulate teeth, $n = 5$, 0.70851–0.70877). Land snails were also sampled but are not considered here, because their strontium isotope values do not necessarily provide an accurate estimate of bioavailable ^{87}Sr/^{86}Sr ratios (Britton et al. 2020; Evans et al. 2010; Maurer et al. 2012).

Materials and Methods

Isotopic Analysis

Samples were taken from 73 animal bones and 15 sheep/goat teeth. Samples from San Felice were

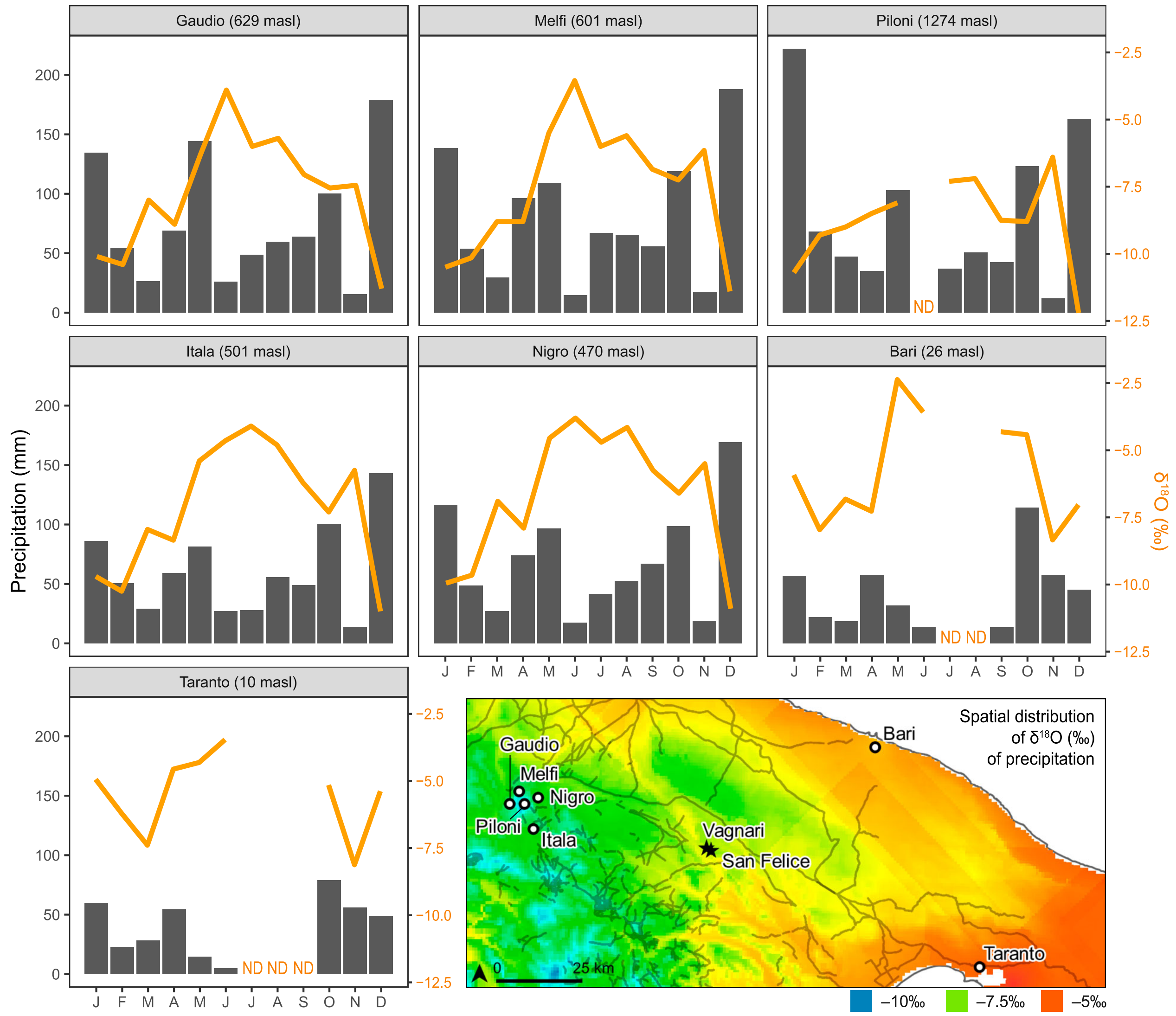

Figure 2. Monthly amount and δ^{18}O composition of modern precipitation from southern Italian weather stations. Map shows the location of weather stations and δ^{18}O distribution of modern rainfall. Data from IAEA/WMO (2019) and Giustini, Brilli, and Patera (2016). Study site elevations: Vagnari 326 masl, San Felice 455 masl.

dated to the first and second centuries AD based on stratigraphy and associated materials. Materials from Vagnari vicus derived from contexts dated to the late second and third centuries AD, with the exception of two samples from the second to first century BC: bone VV25 and tooth VV12, the later of which was radiocarbon dated to 2118–1999 cal BP (2100 ± 19 ^{14}C years BP, 95.4%, OxCal).

Isotopic Analysis of Bone Collagen

Details on measurement and quality control methods of stable isotope values from bone collagen are presented in Supplement 1. Collagen was extracted from crushed bone following the method described in Richards and Hedges (1999). Stable carbon and nitrogen isotope values were measured at the Research Laboratory for Archaeology and the History of Art (RLAHA), University of Oxford, using a SerCon 20/22 continuous flow mass spectrometer coupled to a Callisto elemental analyzer. δ^{13}C and δ^{15}N values were calibrated relative to VPDB and AIR, respectively, using laboratory working standards (alanine: δ^{13}C = −27.11 ± 0.1, δ^{15}N = −1.56 ± 0.18; seal bone collagen: δ^{13}C = 12.54 ± 0.1 δ^{15}N = 16.14 ± 0.18). Uncertainty for δ^{13}C and δ^{15}N was estimated as ±0.2‰ based on repeated measurements of calibration and check standards (precision) and the difference between the observed and known δ values of the check standards and their standard deviations (accuracy) (Szpak, Metcalfe, and Macdonald 2017). Collagen yields, C:N ratios, and %C and %N fell within accepted ranges (Ambrose 1990; Guiry and Szpak 2021; van Klinken 1999). No correlations were observed between C:N and δ^{13}C or δ^{15}N values as might indicate humic acid contamination (Guiry and Szpak 2021). Results that appeared as visual outliers were re-run for confirmation, and acceptable values averaged. The full original dataset (including %C, %N and collagen yields), associated analysis script with quality control checks, and the cleaned dataset with bone sample descriptions, contextual details, and averaged stable isotope values has been deposited in an open science repository (Trentacoste 2023).

Results from animal bone collagen were plotted alongside stable isotope data from a separate study of humans from the contemporary Vagnari necropolis (Semchuk 2016) and fauna from other Italian sites: Pompeii and Herculaneum (Soncin et al. 2021), Velia (Craig et al. 2009), Portus (O'Connell et al. 2019), Isola Sacra (Prowse 2001), and the Etruscan sites of Murlo and Orvieto in central Italy (Trentacoste et al. 2020).

Isotopic Analysis of Tooth Enamel

Sheep and goat mandibular third molars (M3) and maxillary second (M2) and third (M3) molars were selected for analysis of oxygen, carbon, and strontium isotopes from tooth enamel carbonates. Enamel samples were prepared at RLAHA, University of Oxford. For San Felice, stable isotope samples were removed from the tooth hypocone at c. 2 mm parallel increments. Teeth from Vagnari vicus were bulk sampled. Enamel preservation was checked using attenuated total reflectance Fourier transform infrared spectroscopy (ATR-FTIR) (Supplement 1; further data online in Trentacoste (2023)), and all teeth produced peak height ratios (C/P, IRSF, C/C, BPI, API) within the ranges of well-preserved bioapatite proposed by France, Sugiyama, and Aguayo (2020). Oxygen isotope enamel samples were not chemically pretreated, due to the potential for these procedures to alter isotopic composition (Pellegrini and Snoeck 2016). Samples were analysed for $\delta^{13}C$ and $\delta^{18}O$ at the Department of Earth Sciences, University of Oxford, using a Thermo Delta V Advantage gas source mass spectrometer, fitted with a Gas Bench II peripheral. The resulting $\delta^{13}C$ and $\delta^{18}O$ ratios were calibrated against internal laboratory enamel standards (mammoth: $\delta^{13}C = -12.6 \pm 0.12$; $\delta^{18}O = -6.72 \pm 0.26$; wildebeest: $\delta^{13}C = 0.56 \pm 0.12$; $\delta^{18}O = 1.84 \pm 0.19$ enamel) and are reported relative to VPDB. External analytical precision based on repeat measurement of in-house standard NOCZ is 0.06‰ for $\delta^{13}C$ and 0.09 for $\delta^{18}O$ (1σ, $n = 120$).

Strontium isotope analysis was performed on transverse slices of approximately 2 mm cut from the top, middle, and bottom of the tooth protocone. The processing of samples for Sr isotope analysis followed the routine method employed in previous studies (e.g. Trentacoste et al. 2020; Ventresca Miller et al. 2021) (Supplement 1). Repeat analyses of an in-house carbonate reference material processed and measured with the samples from this study ($^{87}Sr/^{86}Sr$ 0.708929; 2σ 0.000030; $n = 5$) are in agreement with long-term results in this facility ($^{87}Sr/^{86}Sr$ 0.708911; 2σ 0.000040; $n = 414$). The analysis of tooth enamel carbonates is also available open access online (see 'Data analysis and visualisation' below).

ZooMS

Morphological species identifications of the sheep/goat teeth were confirmed using Zooarchaeology by Mass Spectrometry (ZooMS) preformed on dentine collected from the anterior pillar of the tooth, collected during the preparation of enamel samples (Supplement 1). Resultant mass spectra were compared with those that represent sheep (*Ovis aries*) and goat (*Capra hircus*) published previously (e.g. Buckley and Kansa 2011). All 15 teeth were assigned to species level.

Data Analysis and Visualisation

Data analysis was performed in R software (R Core Team 2020) using rstatix, tidyverse, ggpubr, and car packages (Fox and Weisberg 2019; Kassambara 2021; Wickham et al. 2021). Original data, cleaned and averaged collagen isotope results, and analysis/visualisation scripts are deposited in an open repository (Trentacoste 2023).

Collagen isotope results were assessed for normality using a Shapiro–Wilk test and for homogeneity using Levene's test. On the basis of these assessments, ANOVA and Kruskal–Wallis multivariate analyses were applied as appropriate. Differences between groups were tested using a Mann–Whitney U test. Intra-estate differences for particular taxa were assessed using a Student's *t*-test. Isotopic niche space and overlap were estimated using the kernel utilisation density method in the rKIN package at 50%, 75% and 95% contours (Eckrich et al. 2020).

Sequences of oxygen isotope values from tooth enamel carbonates ($\delta^{18}O_{carb}$) were used to estimate birth seasonality at San Felice based on the cosine model and non-parametric splitting–coalescence–estimation method (SCEM) presented in Chazin et al. (2019), using the R script provided in the publication. These methods estimate birth seasonality using the position of the maximum $\delta^{18}O_{carb}$ value scaled relative to the length of the tooth (Balasse, Obein, et al. 2012b).

Results

Carbon and Nitrogen Isotopes from Bone Collagen

Summary statistics, results of statistical tests, and isotopic niche estimates are included in Supplement 1. Raw and cleaned stable isotope values from bone collagen are available in Trentacoste (2023). Carbon isotope values from all taxa demonstrated a diet based on C_3 plants, with no evidence for significant C_4 plant consumption (Figure 3). Compared to humans from Vagnari, herbivores have $\delta^{13}C$ and $\delta^{15}N$ values

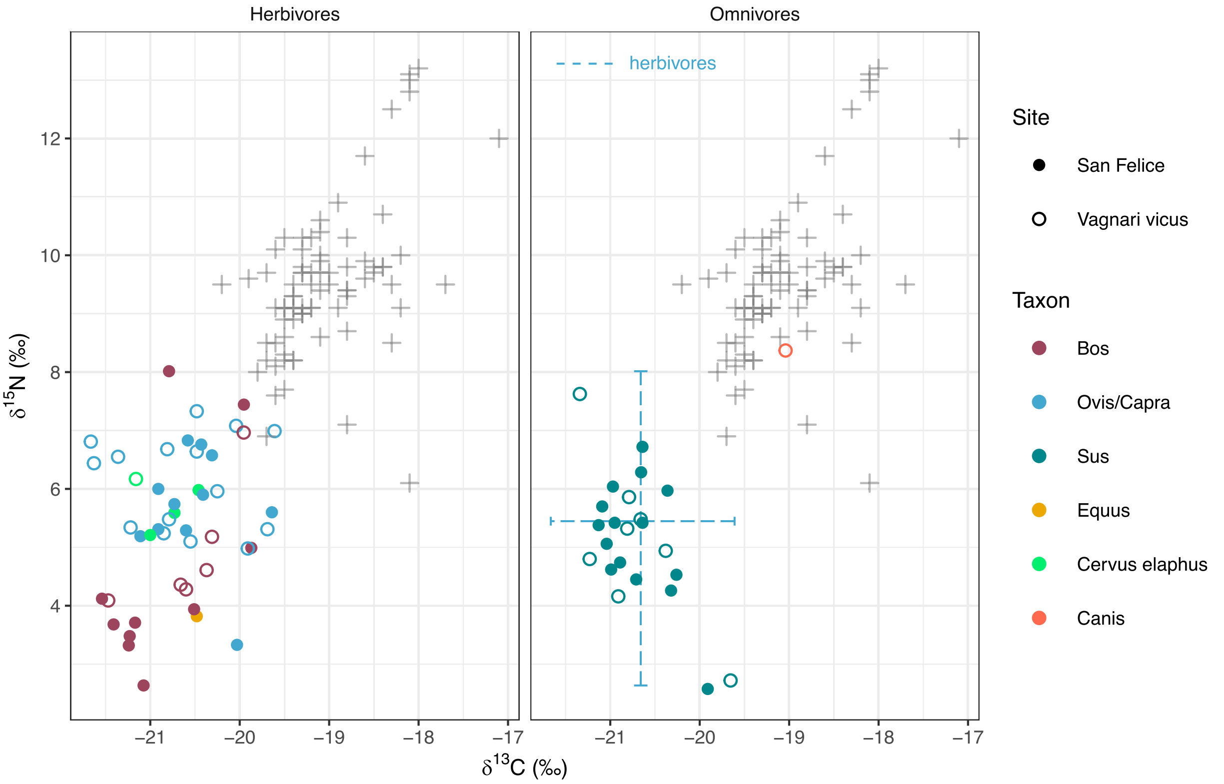

Figure 3. δ^{13}C and δ^{15}N values from animal bone collagen compared to values from humans from the Vagnari cemetery (grey crosses). Human data from Semchuk (2016).

consistent with their lower trophic level. The single dog sample produced results comparable with human isotope values and consistent with an omnivorous diet. Carbon and nitrogen isotope values from pigs overlap with those from herbivores and are clearly separated from humans as well as the dog, indicating a largely herbivorous diet rather than one based on human food waste. The isotopic composition of collagen from taxon was similar at both locations, with no statistical evidence for intra-estate differences in livestock diets at Vagnari vicus versus San Felice villa (Supplement 1).

Within the main domestic taxa (cattle, sheep/goat, pig), variation was greater in nitrogen isotopes than in carbon isotopes (Figure 4). Cattle and pigs produced the widest range of δ^{15}N values (cattle 5.4‰, pigs 5.1‰); sheep/goat δ^{15}N values varied by 4.0‰. There was strong evidence for differences in δ^{15}N values from cattle, sheep/goat, and pig based on a Kruskal–Wallis test ($H(2, 65) = 13.3$, $p = 0.001$, large effect size = 0.182; see Supplement 1). Mann–Whitney U tests showed strong evidence for differences in δ^{15}N values between cattle and caprines ($U = 89$, $p = 0.002$, moderate effect size $r = 0.48$), as well as pigs and caprines ($U = 430$, $p = 0.009$, moderate effect size $r = 0.38$), but not for cattle and pigs ($U = 117$, $p = 0.058$). Variation in faunal δ^{13}C values was comparatively small, c. 2.0‰ or less, with no evidence for differences between the main domestic taxa based on an ANOVA test ($F(2, 62) = 0.738$, $p = 0.482$).

In comparisons of isotopic niche space, cattle produced the largest area in each estimation (Figure 5, Supplement 1), indicative of a more diverse diet and

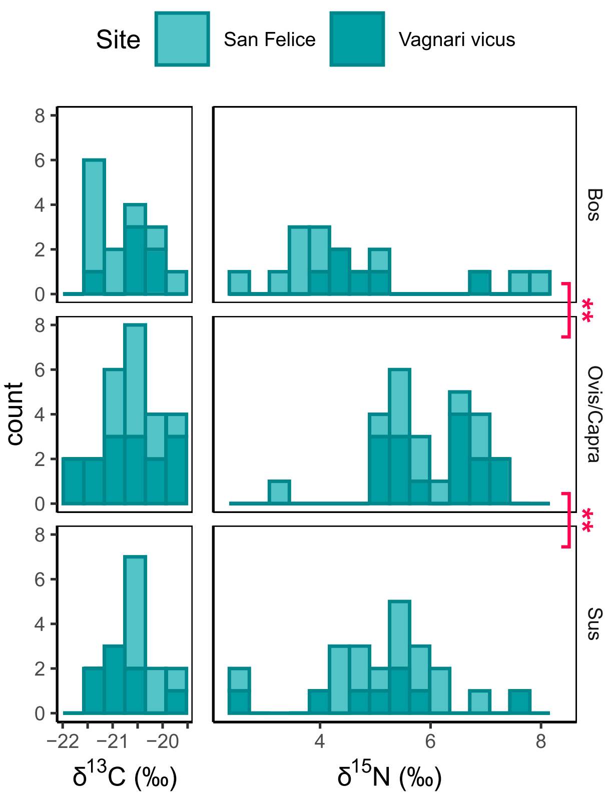

Figure 4. Distribution of isotope values from animal bone collagen. Stars indicate results of statistical tests (see text for details).

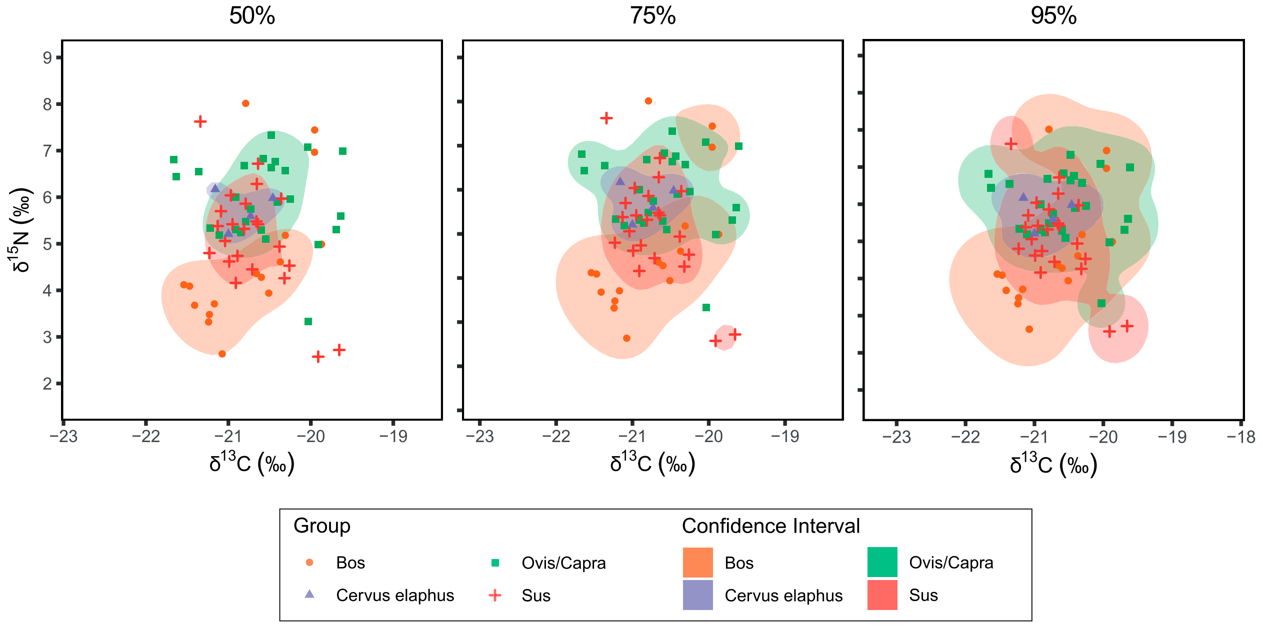

Figure 5. Niche size and overlap estimated using kernel utilisation density (KUD) at different contour intervals (50%, 75%, and 95%). Red deer (*Cervus elaphus*) included for visual comparison; the small sample (<10) may not accurately reflect the niche space of the population.

resource base compared to sheep/goat or pigs. Low isotopic values in cattle, which fell outside the isotopic space of other domesticates (in the lower left of the plot) were notable at all contour levels. Following cattle, caprines occupied the second-greatest isotopic area in all estimates. Results from pigs almost entirely overlapped with values from herbivores, especially sheep/goat (c. 68–75% overlap).

Comparison of collagen isotope values from the Basentello estate with other studies of Etruscan and Roman fauna demonstrated a high degree of dietary diversity, both within and between different sites (Figure 6). This was especially notable in nitrogen isotope values for individual taxa.

Oxygen and Carbon Isotopes from Tooth Enamel Carbonates

Contextual details and descriptions for individual enamel samples are included in Supplement 1; stable carbon ($\delta^{13}C_{carb}$) and oxygen ($\delta^{18}O_{carb}$) isotope values from tooth enamel are presented in Trentacoste (2023). Summary statistics for intra-tooth samples from San Felice are also presented in Supplement 1. All teeth from San Felice produced a complete $\delta^{18}O_{carb}$ min–max cycle. $\delta^{18}O_{carb}$ values from San Felice ranged between −6.8‰ and 1.0‰; $\delta^{13}C_{carb}$ values ranged between −14.1‰ and −9.9‰. The amplitude of variation in intra-tooth isotope values at San Felice was 2.7‰ or less for $\delta^{13}C_{carb}$ values, while change in $\delta^{18}O_{carb}$ values ranged between 1.8‰ and 6.6‰. Stable isotope values from bulk samples from Vagnari vicus fell within the range of incremental samples from San Felice (Figure 7).

Intra-tooth stable isotope results from San Felice followed sinusoidal patterns reflective of season variations (Figure 8(a)). Most teeth (SF01, SF04, SF05, SF06, SF08) demonstrated a parallel relationship between $\delta^{18}O_{carb}$ and $\delta^{13}C_{carb}$ sequences, with minimum and maximum values for each isotope relatively aligned. Amongst these individuals, the $\delta^{18}O_{carb}$ and $\delta^{13}C_{carb}$ sequences from sheep SF01 and goats SF03 and SF05 are closely aligned in their sinusoidal tendencies, while in sheep SF04, SF06, and SF08 the $\delta^{18}O_{carb}$ curves appear compressed compared to $\delta^{13}C_{carb}$ sequences, with low maximum $\delta^{18}O_{carb}$ values. In goat SF07, $\delta^{18}O_{carb}$ and $\delta^{13}C_{carb}$ sequences are closely aligned at the beginning of the sequence, and then diverge closer to the enamel–root junction.

Results for birth seasonality at San Felice based on variation in the scaled position of the maximum $\delta^{18}O_{carb}$ value (x_0/X) are included in Supplement 1. Cosine models closely fit $\delta^{18}O_{carb}$ values (Pearson's correlation coefficient 0.96–0.99) for four of the seven teeth, but fits were poorer for individuals SF01, SF03, and SF08 (0.83–0.88) due to the presence of high/low values at the ends of their $\delta^{18}O_{carb}$ curves. While a slightly better fit could be achieved for these teeth through the use of Balasse, Obein, et al. (2012b)'s eight-parameter equation, the resulting models were not realistic. Except for tooth SF03, differences between the x_0/X seasonality estimates generated by the two models were 0.09 or less, which correlates to a little over a month in calendar terms (Balasse et al. 2020). To compare upper and lower teeth, seasonality

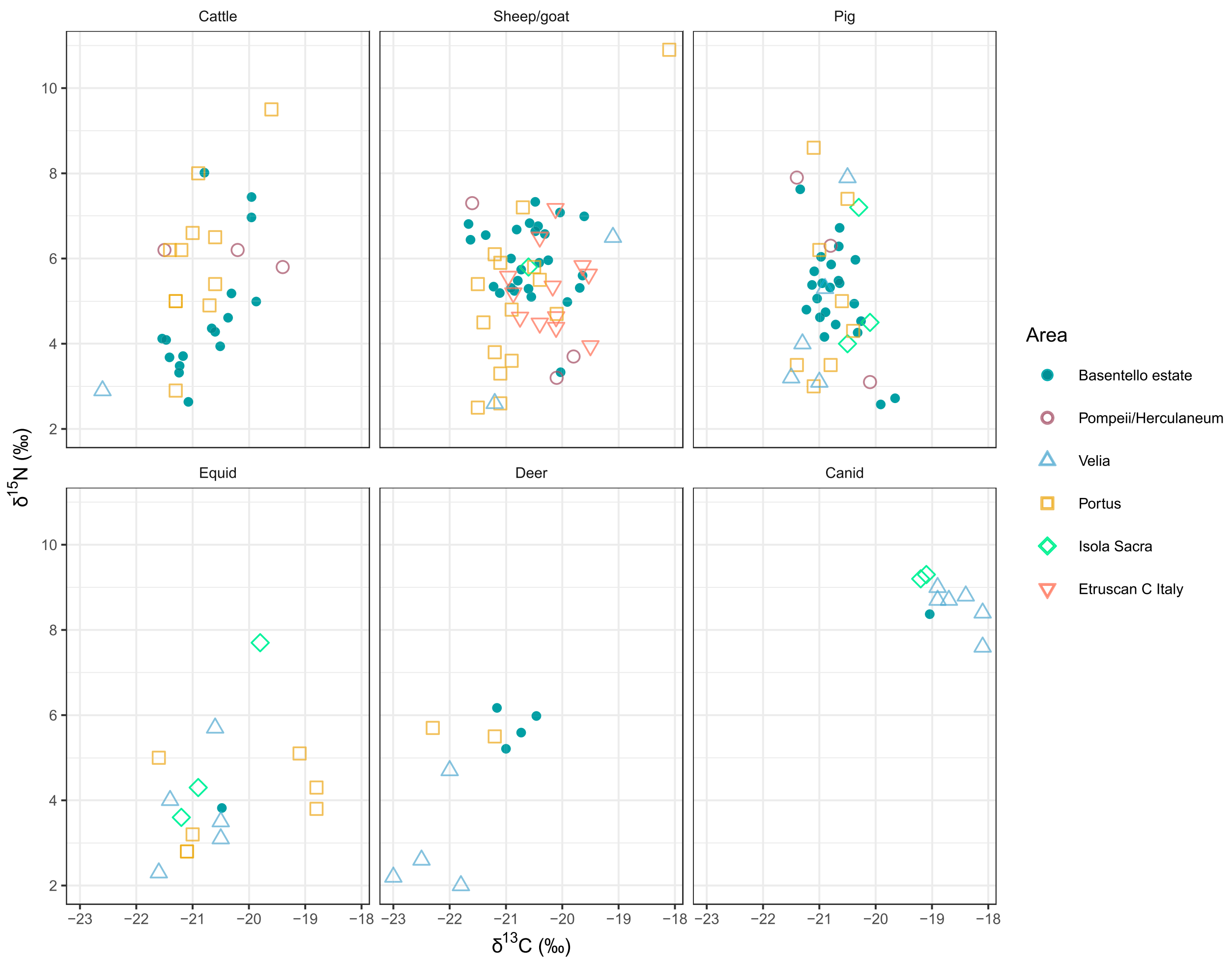

Figure 6. Isotope values from animal bone collagen compared to other Roman and Etruscan sites. Data from Pompeii and Herculaneum (Soncin et al. 2021), Velia (Craig et al. 2009), Portus (O'Connell et al. 2019), Isola Sacra (Prowse 2001), and Etruscan central Italy (Trentacoste et al. 2020).

estimates from maxillary M3s were adjusted by subtracting the average offset from lower M3s (0.073) found in a recent study of modern sheep teeth (Balasse et al. 2020). Both models registered births at different periods across at least two seasons, including when teeth with poor cosine fits were excluded (Figure 8 (b)). Both sheep and goat births were spaced across the year. Comparison with modern reference sets for sheep birth season (Balasse et al. 2023), places caprine births across the year in late winter/spring (sheep SF04, goat SF07) and late summer/autumn (sheep SF08, goat SF05).

Strontium Isotope Results

Supplement 4 presents sample details and $^{87}Sr/^{86}Sr$ isotope ratios obtained from sheep and goat tooth enamel are available in Trentacoste (2023). Nearly all results fell within a narrow range between 0.7084 and 0.7087, within 1.5x the interquartile range (IQR; Lightfoot and O'Connell 2016) of other fauna and humans from the Basentello estate (Figure 9). The range of intra-tooth values from individual teeth was generally small, 0.0003 or less. Based on the IQR, sheep VV12 produced outlying $^{87}Sr/^{86}Sr$ values (0.7091–0.7096), although these were still within the range of values measured in humans. This tooth also produced a slightly larger range of intra-tooth $^{87}Sr/^{86}Sr$ values (0.0005).

Discussion

Livestock Pasturage and Foddering Practices

Multi-isotope analysis of diet and mobility at the Basentello estate demonstrates complex and varied pastoral and animal farming practices. Similarity in carbon isotope values across bone collagen from livestock and red deer illustrates that these animals ingested plants growing in similar sorts of environments, and that this diet was based on C_3 plants, with no evidence for significant consumption of water-stressed vegetation or of C_4 plants like millet. All collagen $\delta^{13}C$ values were above −22.5‰, indicative of herding in relatively open environments, rather than dense forests (Berthon et al. 2018). This does not imply a treeless landscape, only that grazing and fodder cutting were not frequently undertaken in closed-canopy woodland. This

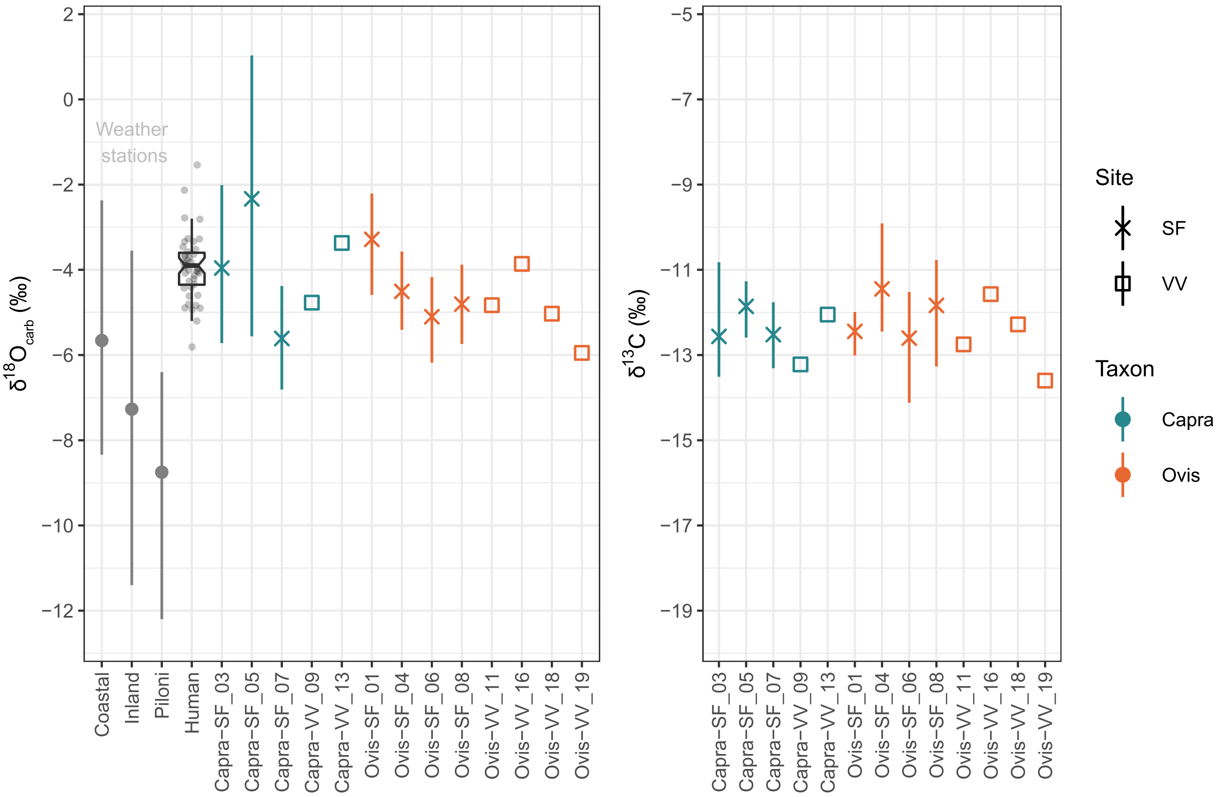

Figure 7. $\delta^{18}O_{carb}$ **(a)** and $\delta^{13}C_{carb}$ **(b)** values from San Felice (incremental enamel samples: range and mean) and Vagnari vicus (bulk enamel samples: single value). Data from Vagnari humans and weather stations (coastal: Bari and Taranto 10–24 masl; inland: Gaudio, Melfi, Itala, Nigro, 470–601 masl; Piloni, 1274 masl) provided for comparison.

is consistent with botanical evidence for cereal cultivation and the presence of savannah-like vegetation, in particular macchia, around the Basentello estate (McCallum et al. 2011; Stirn and Sgouros 2022). However, compared to the current landscape, in Roman times the area would have encompassed significantly more Mediterranean oak forest and shrubby pasture, the remnants of which survive in the near-by Bosca Difesa Grande. The inhabitants of the estate exploited these types of environments for fuel and materials, and such areas were likely also used for pasture and fodder (Fiorentino et al. 2011).

Nitrogen isotope values from bone collagen and niche space estimates point to a high degree of dietary diversity between individual animals. This diversity was especially visible in cattle, which produced the greatest range of $\delta^{15}N$ values as well as the largest isotopic niche area. The notable variety in $\delta^{15}N$ values within and between species suggests that they were grazed on and/or foddered with plants from different environments and subject to different levels of nitrogen inputs: crop fields, meadows, pastures, open forest, river valleys, waste land, abandoned paddocks, etc. This diversity aligns with historical accounts, which recommend different feeding regimes depending on species, working/reproductive status, and season (MacKinnon 2004). Data on the isotopic composition of cultivated versus uncultivated plants are needed to distinguish crop-fed livestock from those raised in extensive silvo-pastoral systems, and there are not yet isotopic studies of Roman plants from the region.[1] Nevertheless, by integrating the data in hand with the broader archaeological and documentary evidence, we can begin to reconstruct possible production scenarios.

Nitrogen isotope values provide evidence for organised and taxon-specific herding strategies. Pigs have $\delta^{15}N$ values comparable with herbivores, and in fact lower than many of the sheep/goats. Pigs were thus largely herbivorous, with diets well distinguished from humans and dogs. Such herbivority in pigs suggests extensive management rather than stall-feeding on human table scraps. While it is possible that sty-raised pigs were fed exclusively plants, metric data does not show notable size or morphometric variation that might imply the presence of large and fat, porker-type pigs associated with stall-feeding in Roman sources (cf. MacKinnon 2011; Trentacoste 2022). For cattle, two dietary groups are visible: a larger group with low $\delta^{15}N$ values between 2.6–5.2‰, with values below 4‰ falling outside the isotopic niche space of other livestock, and a small group with high $\delta^{15}N$ values around 7–8‰. The separation between these groups reflects two different feeding and management strategies. Zooarchaeological analysis of cattle from Vagnari identified a wide range of sizes, suggesting the presence of cows, bulls, and oxen, and/or different cattle ‘breeds’ or types

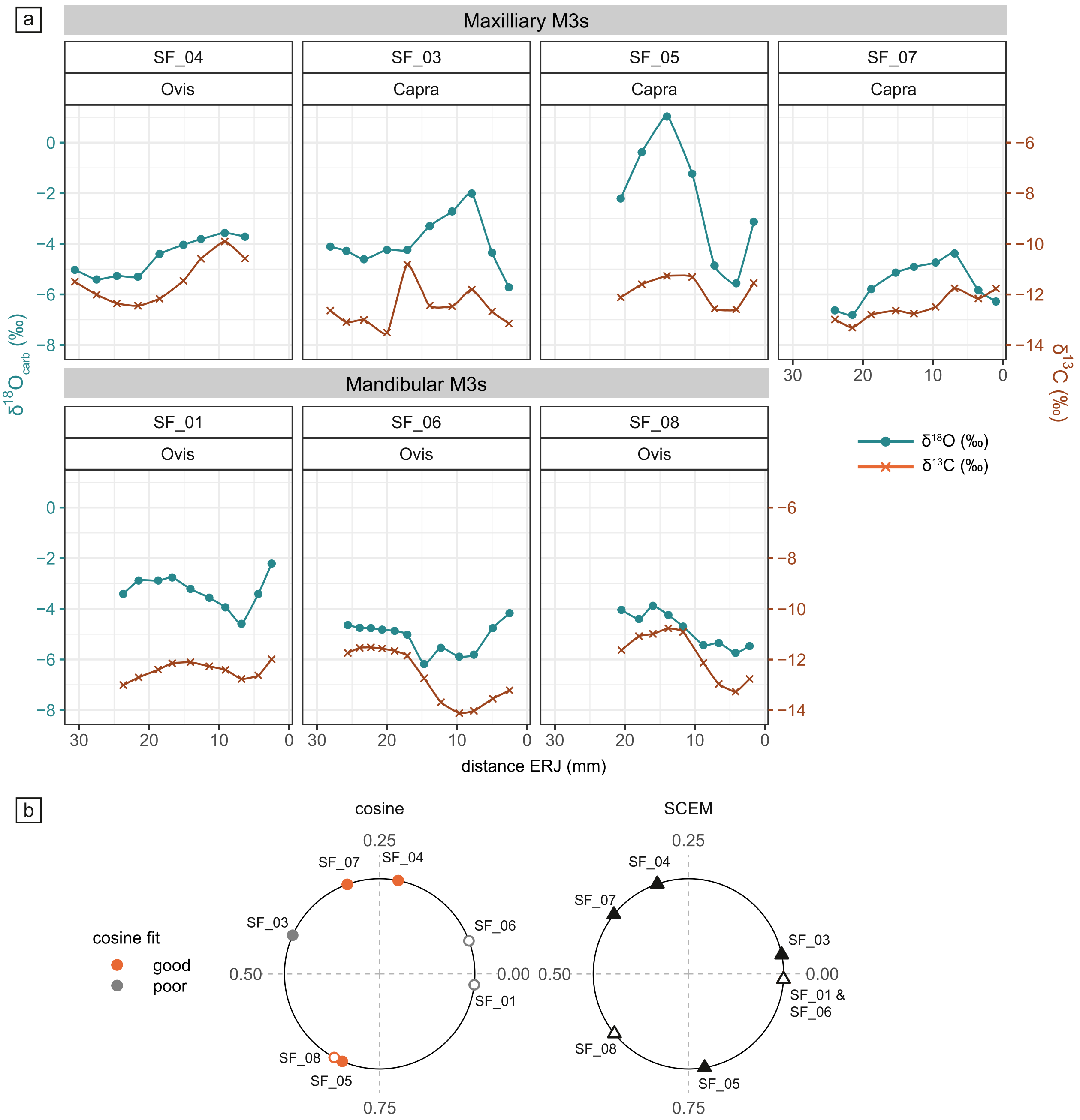

Figure 8. Results of stable carbon and oxygen isotope analysis of third molars (M3s) from San Felice: **(a)** sequential stable isotope values from individual teeth, and **(b)** birth seasonality estimates from cosine and SCEM models (Chazin et al. 2019), with adjusted values for maxillary M3s (open symbols).

(MacKinnon 2011, 130; Trentacoste 2022, 178–179). Different groups cattle may have been raised in different management systems, linked to the animals' function (e.g. working, breeding, milking, or meat production) and environmental tolerances, similarly to what has been suggested for the management of different types of pig (MacKinnon 2001). Nitrogen isotope values from sheep/goats generally fell between the two cattle groups. The relatively low overlap of sheep/goat onto cattle isotopic niche space (c. 5% at 50%, to 50% at 95%) suggests that a large proportion of cattle were herded separately to sheep/goats. This division is most notable for San Felice, which produced the majority of low cattle $\delta^{15}N$ values.

In terms of human practice, reliance on supplemental food resources likely contributed to differences between caprine and cattle diets, with cattle having more varied diets due to a combination of their higher feed requirements, management location (near versus far from site), and the availability of food sources (chaff, hay, leaves, etc.), as well as a higher cultural and economic value. Cattle required a far greater economic outlay to acquire, and, in the case of oxen, would be expected to have working lives of over a decade. A different feeding strategy compared to sheep and goats – 'the petty cash' of livestock capital' (King 1983) – would therefore be expected, with cattle offered the first bites of what

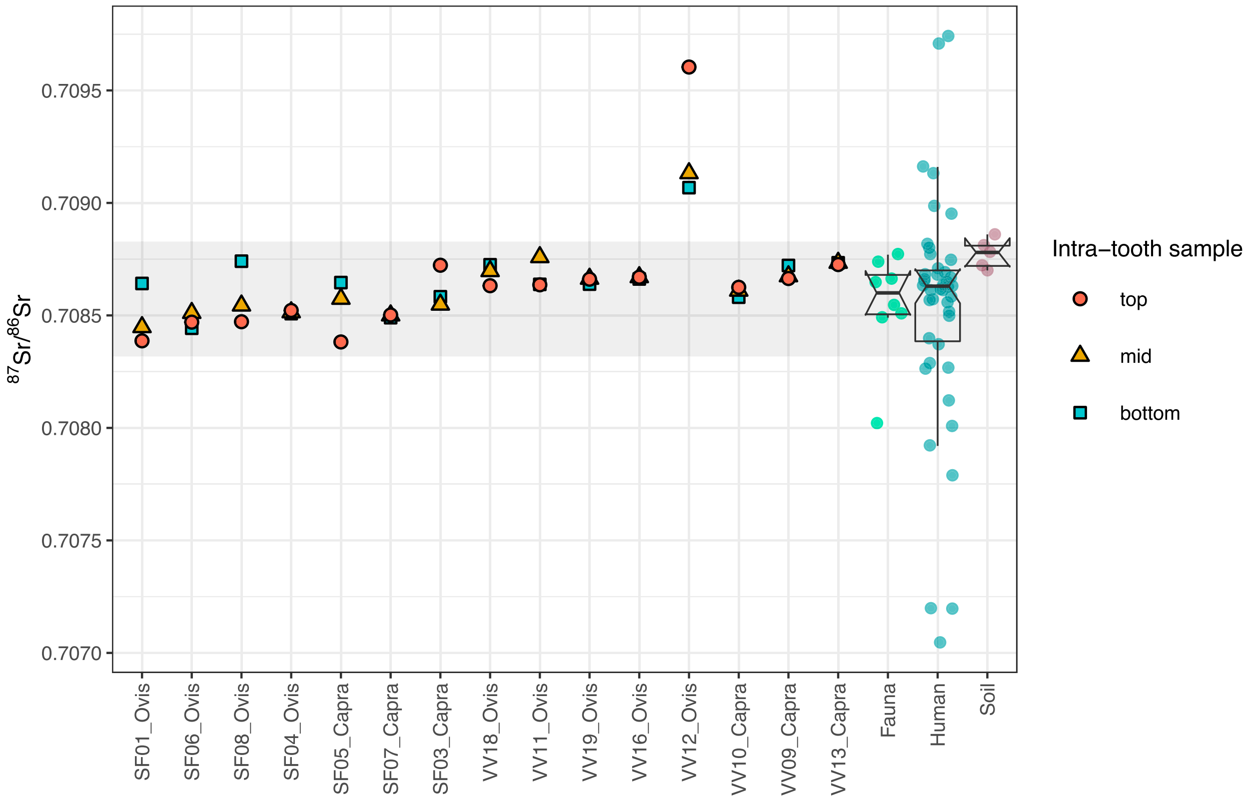

Figure 9. Intra-tooth samples from sheep and goats from San Felice and Vagnari vicus compared to results from fauna, humans and soil from Emery et al.'s (2018) study of the Vagnari cemetery. Shading indicates 1.5IQR of $^{87}Sr/^{86}Sr$ values from humans and comparative fauna.

was available (which might be from a diverse ecological and environmental pool of fodder), especially in moments of shortage. In traditional herding systems in Basilicata, fodder crops were cultivated for cattle, while sheep were fed from opportunely cut plants (Boag 1997). This approach had an impact on the size of sheep flocks, which were constrained by the annual low in pasture carrying capacity. Supplemental feed only provided during lambing and in extreme weather, or where rents for pasture were cost prohibitive. This is a different approach compared to many modern production systems, where herd size is associated with maximum annual carrying capacity, and stock maintained by supplemental feeding through leaner months, often at significant financial cost to the farmer.

If isotopic evidence points to different herding and feeding strategies, what did these entail in terms of practice and location? Without plant isotope data we cannot confidently separate farm-fed and extensively managed animals, but we can construct two potential scenarios based on which taxon we believe consumed the most uncultivated plants:

1. If we assume red deer ate predominantly wild plants, the nitrogen isotope composition of the four red deer bones can be used to infer $\delta^{15}N$ values of un-manured wild vegetation (Styring et al. 2017). Based on a c. 4‰ enrichment of bone collagen over diet, this suggests that wild plants grazed by red deer had nitrogen isotope composition around 1.7‰. Considering the nitrogen isotope composition of cattle collagen, most cattle would be expected to have consumed plants with $\delta^{15}N$ values between c. −1.4‰ and 1.2‰, below the estimated nitrogen isotope values of plants consumed by of red deer. Although the red deer sample size is only four individuals, the overlap in isotopic niche space was lowest when compared with cattle, c. 12% or less, suggesting cattle and red deer fed on different food sources. To produce such low $\delta^{15}N$ values in this scenario, cattle must have consumed a diet rich in legumes. Nitrogen isotope values from most sheep/goats, which are comparable with those of red deer, would then be interpreted as resulting from plants subject to little or no ^{15}N enrichment above the estimated values for wild vegetation, e.g. unmanured fields or lightly stocked pastures. These results align well with crop isotope data from pre-Roman Gabii, where the majority of wheat and barley crops had low $\delta^{15}N$ values (<3‰) suggestive of low/no manuring. They also align with reconstruction of the broader landscape of the imperial estate, which indicated large areas given over to grazing land (Small and Small 2022).

The $\delta^{15}N$ values measured in pig collagen, which are lower than those from sheep/goat, would be consistent with pasture-raised animals, e.g. feeding in the area's native oak woodlands – an environment well appreciated by ancient authors precisely for mast production and well represented on the imperial property (MacKinnon 2001; Small and Small 2022; Trentacoste 2016). However, in order to produce comparatively low δ^{15}N values, some pigs must also have fed on legumes, either as beans or leafy fodder/forage, e.g. clovers or lucerne. This is consistent with Varro's description of a diet based primarily on mast, followed by beans, barely, other grains (*Rust.* 2.4.6; 2.4.15), as well as the general emphasis on legumes as a livestock food source. Such incorporation of cultivated crops into pig diets would imply a closer style of management and level of integration with on-farm activities, at least for some pigs. Carbon isotope values from pig collagen may also point in this direction: δ^{13}C values were comparable to those from cattle and sheep/goats, suggesting pigs did not consume considerable quantities of fungi and plant roots, which are comparatively enriched in ^{13}C (Hamilton, Hedges, and Robinson 2009). Forest resources may therefore have been complimentary to cultivated foods or seasonally exploited.

In all livestock, high δ^{15}N values (above c. 6–7‰) would indicate diets with a high proportion of ^{15}N-enriched foods: crops or meadows subject to manuring, pastures with higher stocking densities or managed by burning, and/or ^{15}N-enriched areas within or immediately around the vicus, such as waste ground, verges, and plots previously occupied by gardens, animal pens, or middens (Kriszan et al. 2014). It could also reflect greater consumption of grain, which is enriched c. 1–4‰ compared to leaves and steams (Fraser et al. 2011; Szpak 2014); however, based on the greater caloric needs of cattle, it seems unlikely that sheep/goat would have been fed a more-grain rich diet.

2. In a second scenario, we assume red deer fed regularly on ^{15}N-enriched plants in pastures, crop fields, and gardens, and are therefore unreliable for estimating the isotopic composition of wild plants. Although much of the estate was occupied by forest and pasture, field survey indicates that agricultural activities dominated at least a 500 ha area around the study sites (Small and Small 2022, 223; Wigand 2022). In such a landscape, red deer bones recovered from a productive agricultural vicus are as likely to represent animals killed opportunistically to protect crops as they are of sport hunting in distant, unmanaged areas. Nitrogen isotopes values from red deer at the estate are amongst the highest measured in Roman Italy, even if the sample size is small (see Figure 5). Considering that the pigs were largely herbivorous, we assume that they were predominantly pasture-raised in the area's abundant mixed-oak woodland, as frequently described in the ancient sources, and therefore are a more accurate indicator of uncultivated environments. Pigs did not consume considerable amounts of fungi, perhaps because these were not hugely abundant in a managed silvo-pastoral Mediterranean landscape (as compared to a temperature primordial forest). Since pigs are omnivorous, we would expect them to have slightly higher δ^{15}N values than cattle raised extensively in similar environments, with this trend visible in the results. While Roman working oxen were stalled and fed on the farm, forage was preferred when cattle were not working (Cato *Agr.* 54.1), and other cattle are described as pasturing in woodland and moving to more remote areas (Varro, *Rust.* 2.5.11; Columella, *Rust.* 6.22, 6.23.2–4). Forest vegetation and leaf/branch fodder, which have low δ^{15}N values (Domínguez et al. 2012; Ogaya and Peñuelas 2008), are also frequently described in the ancient sources as an important food source for cattle (MacKinnon 2004, 90). Higher δ^{15}N values found in sheep/goat would therefore result from the consumption of ^{15}N enriched plants – cultivated, manged, or spontaneous – in fields and pastures.

These dietary reconstructions have different implications for arable activity and farm labour requirements. In the first scenario, cattle production is dependent on the production of legumes and largely farm-based; sheep/goats are herded on areas subject to little, if any, ^{15}N enrichment (compared to the estimated isotopic composition of wild plants), implying low stocking densities and minimal manuring of any arable fields that were integrated with caprine farming. In the second scenario, cattle production is predominantly extensive and off-site, with far fewer labour and cost inputs; sheep/goat herding occurs at higher densities or integrated with manured arable fields. Both scenarios are consistent with the ancient sources, depending on if we view the majority of sampled cattle as near-site working animals or as silvo-pastured herds. The archaeozoological and archaeobotanical evidence from the estate is similarly ambivalent on this point. Faunal analysis found a majority of adult cattle in a wide range of sizes, alongside juveniles (MacKinnon 2011; Trentacoste 2022). The lack of a clear bimodal distribution cattle biometry on the estate – potentially influenced by the presence of difference varieties of cattle – prevents confident reconstruction of sex ratios, so it is unclear if the majority of animals were cows or oxen.

If legumes were indeed consumed in significant quantities, available archaeobotanical data suggests that they were cut as hay or grazed, rather than fed as beans. Beans and small field legumes were present in low densities throughout the Vagnari and San Felice archaeobotanical assemblages (Stirn and Sgouros 2022; Taylor 2012), but their low frequencies compared to wheats and barley indicate that beans were not stored or processed to the same extent (at least in the same areas of the villa and vicus) as cereals. Leafy legumes, whether sown or spontaneous, are a major component of traditional farming in southern Italy and a fundamental part of fallow in traditional dryland agriculture in the region (Boag 1997). Their value as forage, fodder, and rotational crops was widely recognised in Roman Italy, and they constituted a major element in hay found at Oplontis, carbonised during the eruption of Vesuvius (Kron 2004).

Mobility and Seasonal Herding Practices

Strontium isotope values from all caprines except sheep VV12 were consistent with herding within the same isozone as the majority of humans and comparative fauna, or mobility to areas with similar bioavailable Sr isotope ratios (Figure 10). Beyond this, interpretation of strontium isotope results in terms of geographic location, must be made with caution due to the low resolution of strontium isomapping in the region. However, it appears that long periods of grazing did not occur within the Murge plateau or in the Lucanian Apennines, which would be expected to produce lower (<0.7082) values, although short excursions into these areas or their fringes may be obscured by the band sampling method and/or the location of sample on the tooth lobe. The near lack of variation in the Sr isotope results from some teeth suggests stationary management and perhaps enclosure. The slightly higher intra-tooth variation in $^{87}Sr/^{86}Sr$ values visible in sheep SF01 and SF08, and in goats SF03 and SF05, points to some sub-annual change in animal location, which is not documented in all caprines. This could represent movement to areas of a similar $^{87}Sr/^{86}Sr$ baseline, such as around Metaponto or the area between Foggia and Sulmona; however $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ curves indicate that any seasonal mobility was to a similar eco-zone, which excludes climatically distinct pastures of the high Apennines (see below).

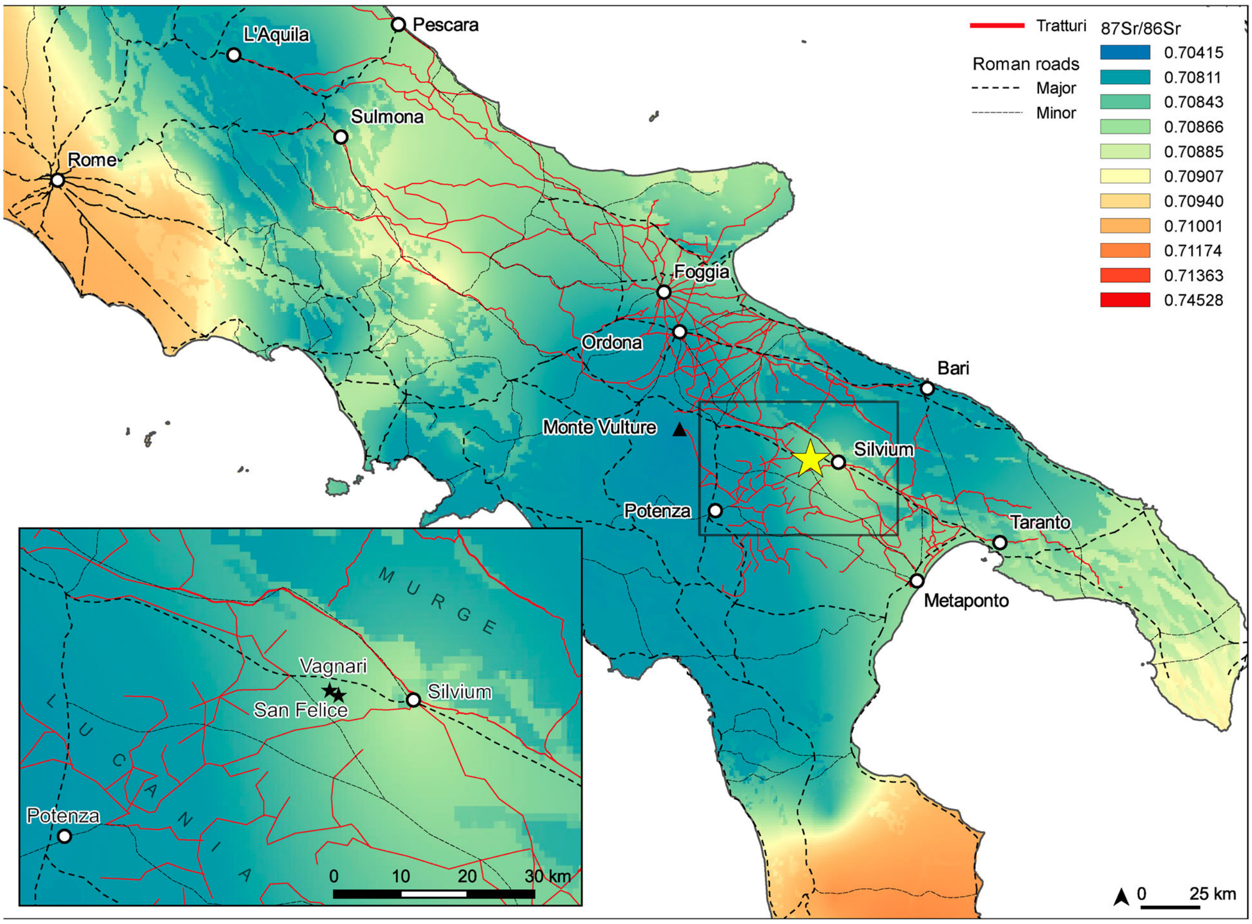

Figure 10. 'Bioavailable' strontium variation in southern Italy in relation to Roman roads and historic drove roads (tratturi). Data from Lugli et al. (2022); La Carta Generale dei Tratturi, Tratturelli, Bracci e Riposi. Scala 1:500,000 (1959); and regional authorities: Beni culturali – archeologici – Tratturi art. 10 del D.Lgs. 42/2004 (Regione Basilicata 2020); Testimonianze della Stratificazione Insediativa: aree appartenenti alla rete dei tratturi (Regione Puglia 2022).

High $^{87}Sr/^{86}Sr$ ratios recorded in sheep VV12 point to long-distance import. Based on the current isoscape, to account for the maximum Sr isotope value measured in this sheep (0.7096), the animal would need to have originated in Calabria, central or northern Italy, or an overseas location.[2] Interpretation is however limited by the resolution of current strontium isoscaping. Other than samples used in studies of Vagnari, regional mapping is based on a few water samples (Lugli et al. 2022), which may not accurately capture Sr isotope ratios in grasses growing on the *terra rossa* soils that overlay much of the karst plateau of the Alta Murgia.

$\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ curves from sheep/goat from San Felice were generally synchronous: the carbon isotope composition caprine diets varied as expected with seasonal cycles temperature and dryness. This association indicated that animals were not moved to different eco-zones in the summer (Tornero et al. 2018), as is done in long-distance transhumance to high Apennine pasture – a confirmation of strontium isotope data, which indicates that sheep grazed on similar substrates during both the summer and winter seasons. There was no clear relationship between $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ results and $^{87}Sr/^{86}Sr$ ratios as might suggest altitudinal mobility patterns or sourcing of animals from other locations, as has been observed in sheep in central Italy (Trentacoste et al. 2020).

The multi-season distribution of births for sheep and goats also suggests that caprines were present on the estate throughout the year, at least at San Felice. If caprine breeding was similarly staggered at Vagnari, peaks in the culling of sheep/goat at particular ages, as documented in zooarchaeological study (MacKinnon 2011), may represent a selection strategy aimed at animals of a particular age/size, rather removal of sheep/goats to distant locations.

Variation in the min/max values and amplitude of $\delta^{18}O_{carb}$ curves suggests that caprines varied significantly in their drinking behaviours and water intake sources while raised on an area (or areas) with similar $^{87}Sr/^{86}Sr$ ratios. The high amplitude variation in $\delta^{18}O_{carb}$ values recorded for goat SF05 points to ingestion of $\delta^{18}O$-enriched leaf water; the flatter intra-tooth $\delta^{18}O$ curves of other caprines, which are lower in amplitude than isotopic variation in modern rainfall, point to greater reliance on summer grazing in more humid environments or to drinking from ground water sources. Springs in southern Italy fed by groundwater with long residence times display a time-averaged signal with little seasonal variation in $\delta^{18}O$ values (Cotecchia 2014; Parisi et al. 2011). As an area at the edge of the karstic plateau of the Murge, groundwater flows in the direction of the estate, emerging from numerous springs that would have provided water sources (Wigand 2022; Wigand and McCallum 2017). Considering this complex regional hydrogeology, the amplitude and absolute values of oxygen isotope results probably reflect inter-individual differences in drinking behaviour and consumption of leaf, open and ground water sources. Different management patterns, linked to reproductive status or production aims, would be expected even for caprines raised within in a similar catchment. Further work comparing oxygen isotope values from obligate drinkers like cattle to those documented in caprines would help untangle the isotopic signatures of different water sources.

Overall, these results may recall herding practices in the area during the mid-twentieth century, with animals typically moving within a sub-30 km range (Boag 1997; Sprengel 1971, 133–140). Multi-stop herding patterns were also common for large holdings, with sheep herded across cereal fields, the near-by hills of Lucania, and natural pasture on the Murge. Longer-distance journeys were undertaken only in times of scarcity. Exploitation of a mosaic of grazing resources (arable, fallow, unploughed pasture and light woods) distributed across moderate vertical gradients and different facing slopes, alongside vegetation management through controlled burning, could have supported year-round grazing on the estate or its near environs.

Conclusions

This multi-isotope study has provided new insight into livestock farming practices in Roman Puglia, and is the first bioarchaeological analysis dedicated to animal management in Roman Italy. It has revealed an agro-ecosystem in which cattle, caprines and pigs had different niches and roles. Dietary isotope values and inter-species differences suggest different forms of integration with arable agriculture and modes of exploiting un-cultivated landscapes. In particular, results suggest the possibility that sown legumes may have had major role in cattle and possibly pig diets, although further work is needed to untangle this from more extensive systems. Caprines were herded within the same resource catchment that fed the majority of people living in the vicus – supplemented by the import of at least one individual from across a significant distance. If caprine mobility was indeed regularly practiced, this was on a local or sub-regional scale rather than to the ecologically distinct high Apennines.

These results are not necessarily inconsistent with the pastoral economy that is repeatedly stressed in discussion of Roman southern Italy; they do however encourage a reframing and greater level of nuance in conceptualisation of animal management in the region beyond generic transhumance to distant uplands. Epigraphic evidence clearly shows Roman Puglia as a centre for herding and wool production (Gabba and

Pasquinucci 1979; Grelle and Silvestrini 2001; Small, Volterra, and Hancock 2003), but our study highlights the potential for more locally focused herding rhythms. The lack of isotopic evidence for widespread long-distance caprine transhumance implies a degree of integration into arable cultivation regimes. Closer management of caprine herds would help maintain fertility on Puglia's calcareous soils, as well as to promote the productivity of spontaneous growth on bare fallow by selectively distributing the seeds of preferred forage plants (Boag 1997; Halstead 2014, 212–230).

Of course, our results only provide evidence on the animals that died and were deposited at Vagnari and San Felice. These are animals consumed by the residents of these rural locations, raised to meet the needs of estate's inhabitants for meat, milk, and wool, and to preform essential agricultural tasks: ploughing, weeding, fertilising, soil compacting/loosening, etc. It is possible – if not plausible – that the Basentello estate was indeed involved in larger-scale and longer- distance herding, but that these animals were not consumed on site. Animals belonging to the imperial fiscus enjoyed special privileges (Corbier 1983), and were likely herded distinctly from livestock owned by the estate's comparatively humble inhabitants. In traditional southern Italian pastoral systems larger herds (>400–500 sheep) were likely to be moved longer distances, with smaller flocks kept locally (Barker et al. 1991; Boag 1997). With sufficiently large samples, biometric work could shed light on this topic: caprine size ranges are wide, and potentially indicative of different varieties of sheep and goat. This complexity reinforces a need to shift away from monolithic, simplistic reconstructions of rural activity, especially if gleaned exclusively form biased textual sources. Further interdisciplinary research could shed new light on how the animal economies of imperial estates intersected with the smaller-scale activities undertaken by those who lived, worked, and died on these properties.

Lastly, the multi-isotope approach applied here demonstrates the need for a multi-proxy perspective to untangle ancient herding systems in Roman Italy, and it also has implications for the study of human mobility in the region. Firstly, our expansion of strontium isotope analysis from the eight teeth originally sampled by Emery et al. (2018) revealed one of the herbivores used to construct the local strontium isotope baseline (FS186) as an outlier compared to other livestock. The 'local range' as defined by this previous study could potentially be reduced, leading to identification of more individuals as migrants. Secondly, our results reinforce the likelihood off-site management in swine production. The most likely environment for this style of management is mast forest, which is often located in different topographic areas and geologic substrates than agricultural field. Pigs may therefore be a poor representation of what are relevant 'local' strontium isotope ratios for humans.

Even with new data in hand, we are unable to close open questions on the broader nature of Roman agriculture in the region and its reliance on intensive versus extensive strategies. Results are ambiguous on this point and can be read in different ways. This is an area that would benefit immensely from future work. More data, particularly from plants, are needed to define arable regimes and improve reconstruction of pastoral strategies. Further baseline work on flora and fauna is crucial, for example to map strontium variation in the biosphere relevant to grazing animals. Analysis of tooth enamel from cattle, which have different drinking requirements than caprines, would help resolve mobility and watering patterns (Makarewicz and Pederzani 2017), while compound-specific analysis of amino acids, which can directly demonstrate woody plant consumption, is needed to confirm leafy hay foddering (Kendall et al. 2019). These future directions offer promising opportunities for interdisciplinary research and discussion across archaeology, archaeological science and ancient history, with the potential to address long-term questions of land use, rural economy, and the development of human-environment interactions in this Mediterranean landscape.

Notes

1. O'Conncell et al.'s (2019) notable research at Portus is of limited utility in this case, due to the high potential for imported grain and unreliable measurement of δ^{15}N values in individually sampled grains.
2. Unfortunately VV12 could not be sampled for O isotopes due to damage during radiocarbon dating.

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