

Systems change: Investigating climatic and environmental impacts on livestock production in lowland Italy between the Bronze Age and Late Antiquity (c. 1700 BC – AD 700)

Angela Trentacoste^{a,b,*}, Ariadna Nieto-Espinet^c, Silvia Guimarães Chiarelli^{d,e},
Silvia Valenzuela-Lamas^d

^a Institute of Pre- and Protohistoric Archaeology, Christian-Albrechts-Universität, Johanna-Mestorf-Straße 2-6, 24118, Kiel, Germany

^b Institute for Archaeology, University of Oxford, 36 Beaumont Street, OX1 2PG, Oxford, United Kingdom

^c Grup d'Investigació Prehistòrica (GIP), Departament d'Història, Universitat de Lleida, Pl. Víctor Siurana 5, 25003, Lleida, Spain

^d Archaeology of Social Dynamics (ASD), Consejo Superior de Investigaciones Científicas Institució Milà i Fontanals (IMF-CSIC), Carrer de les Egipcíacues 15, 08001, Barcelona, Spain

^e CIBIO-InBIO, Centro de Investigação em Biodiversidade e Recursos Genéticos, Universidade do Porto, Campus de Vairão, Rua Padre Armando Quintas 7, 4485-661, Vairão, Portugal

ARTICLE INFO

Keywords:

Zooarchaeology
Roman period
Bronze age
Iron age
Agriculture
Biometry

ABSTRACT

Animal management is shaped by its environmental and landscape context, but these factors are rarely investigated quantitatively in zooarchaeological studies. Here we aim to examine the relationship between trends in zooarchaeological data and environmental and climatic dynamics between the Middle Bronze Age and Late Antiquity in lowland northern Italy (Po–Friulian Plain). This region provides an ideal test case to investigate the impact of landscape variables (precipitation, solar irradiance, elevation, soil characteristics) and climate evolution due to the area's relatively homogenous topography and climatic conditions. This study presents a new elaboration and visualisation of zooarchaeological data from northern Italy, investigates correlations between these data and landscape variables, and contextualises trends in relation to regional environmental and climate proxies at two scales. This analysis reveals a shift towards more heterogeneous livestock on a regional level during the Late Iron Age and Roman period, and strong evidence for a correlation between cattle representation and local soil characteristics at a site-level during the Bronze Age. Consideration of climate data shows little relationship between species representation, livestock body size, and climate proxies, indicating that human social dynamics rather than climate change were the primary driver to changes in animal management on the regional macro-scale.

1. Introduction

Agriculture and livestock production are shaped by climatic and environmental influences. Differences in soil composition, elevation, precipitation, and temperature impact farming regimes, and these variables may preclude or promote particular production strategies. As a crucial intersection between the natural and human worlds, investigation of ancient plant and livestock farming can provide a valuable line of evidence on climatic and environmental change, its impact on human societies, and the causal relationships that mediate these impacts (e.g. Vaiglova et al., 2020). Understanding the dynamics of ancient agriculture is particularly important when attempting to associate climatic and

archaeo-historical events: climate change and extreme weather are destabilising for human societies, precisely because they impact food production and can precipitate crop failure and subsistence crises (e.g. Camenisch et al., 2016).

As one of the most ubiquitous and direct lines of evidence for past agricultural practice, zooarchaeological remains have significant potential to provide new insight into the interplay between the environment and human systems. However, understanding environmental impacts on ancient animal production is far from straightforward. While livestock farming is constrained by certain biological limits necessary for the organism to function (e.g. Belhadj Slimen et al., 2016; Hogan and Phillips, 2016), domestic animals can occupy a huge range of physical

* Corresponding author. Institute of Pre- and Protohistoric Archaeology, Christian-Albrechts-Universität, Johanna-Mestorf-Straße 2-6, 24118, Kiel, Germany.
E-mail address: angela.trentacoste@arch.ox.ac.uk (A. Trentacoste).

environments – depending on the level of human intervention in their management, and the extent to which herders and farmers are willing and able to provide food, shelter, protection, and other forms of care. Decisions about how much material and labour to invest in livestock are socially conditioned and not necessarily optimised to maximise production (e.g. Hutchinson, 1992; Gandini and Villa, 2003; Hunter et al., 2022). This negotiation between environmental and social influences is relevant to understanding livestock management in the past (McInerney, 2010; Russell, 2012), and it is particularly relevant to the evolution of livestock husbandry over later prehistoric and Roman times.

Abundant zooarchaeological evidence documents the significant impact of Iron Age social re-organisation and Roman political integration on livestock production throughout different eco-regions of western Europe and north Africa (King, 1999; MacKinnon, 2010; Valenzuela-Lamas and Albarella, 2017; Duval and Clavel, 2018). Notably, in some regions, Roman economic specialisation and administrative integration seems to have allowed animal production to become relatively disconnected from its natural environment compared to prehistoric times: production/consumption patterns closely align with site characteristics, rather than the environmental context (e.g. Nieto-Espinet et al., 2021), and cultural tastes (e.g. for pork) were catered too even in difficult arid and desert environments (MacKinnon, 2010; Crabtree and Campana, 2016; Çakırlar and Marston, 2017). As scholarship becomes increasingly interested in climatic and environmental impacts in the antiquity, and the Roman world in particular (e.g. Haldon et al., 2018; Erdkamp, 2019; McConnell et al., 2020), more nuanced and quantitative understanding of the interplay between foodways, society and the environment is needed. Zooarchaeology offers large-scale datasets and a measurable, reproducible, and scalable means of exploring these relationships.

Despite the impact of the environment on production regimes, landscape variables (soil, elevation, solar irradiance) are rarely considered quantitatively in zooarchaeological studies of Italian materials, which typically evaluate simple geographic characteristics (e.g. north vs south). Landscape approaches and GIS applications have a long tradition in research on protohistoric and Roman Italy (Barker, 1981; Attema et al., 1998; Smith, 2017), and recent work in this area is increasingly concerned with questions of human–environment interaction (e.g. de Haas, 2017). Yet, despite a mutual interest in land-use and regional quantitative datasets, there has been little interaction between zooarchaeological and landscape studies (for an exception see Veenman, 2002). Previous work in an Italian context has sketched out general

differences between broad areas and environment like mountains and lowlands (Riedel, 1994a; MacKinnon, 2004; Trentacoste, 2016; Gastra and Vander Linden, 2018), but further investigation is needed to untangle environmental impacts on a sub-regional scale and in areas of comparatively homogenous climate.

Building on an approach first applied to north-east Iberia (Nieto-Espinet et al., 2021), this paper integrates zooarchaeological data collected during the ZoomWest ERC project (Trentacoste et al., 2018, 2021) with environmental data and climatic proxies to assess the relationship between trends in animal production and regional environmental dynamics between the Bronze Age and Late Antiquity. The study focuses on the Po-Friulian Plain in Northern Italy (Fig. 1). Limiting the study area to this region allows a better understanding of how the landscape shaped food production and the strategies adopted by lowland areas. The area is well suited to disentangling the influence of landscape and cultural patterns, due to its relatively homogenous topography. The study region encompasses a flat, low-lying area, and study materials derive from a single biogeographical region (continental) with similar solar irradiance (Fig. 1d–f). Today, the area is characterised by a temperate fully humid climate with no dry season and hot (Cfa) or warm (Cfb) summers (Rubel et al., 2017) (Fig. 1a).

This study unifies and re-evaluates zooarchaeological data presented in period-specific studies (Trentacoste et al., 2018, 2021) over a longer diachrony, from the Bronze Age to Late Antiquity. It analyses and visualises species abundance using correspondence and hierarchical clustering analysis (see Nieto-Espinet et al., 2021) and re-assesses livestock biometry based on a new and widely available set of standards in the zoolog R package (the default ‘combi’ reference included in the package; Pozo et al., 2021; Pozo et al. in press) in order to facilitate further inter-regional comparisons. The relationship between zooarchaeological and environmental/climatic data is then considered at two scales. Firstly, site-level NISP data were statistically correlated with landscape variables. Previous investigation of the zooarchaeological data led to the impression that livestock representation varied with soil characteristics, particularly ground infiltration (Trentacoste et al., 2018). Soil permeability is different north and south of the River Po (Fig. 1e); these differences in geomorphology may have impacted livestock management via pasture quality, mobility routes, or arable production strategies. This study aims to interrogate this conjecture and to identify if there are correlations with other landscape variables. Secondly, regional-level NISP and biometric data were qualitatively

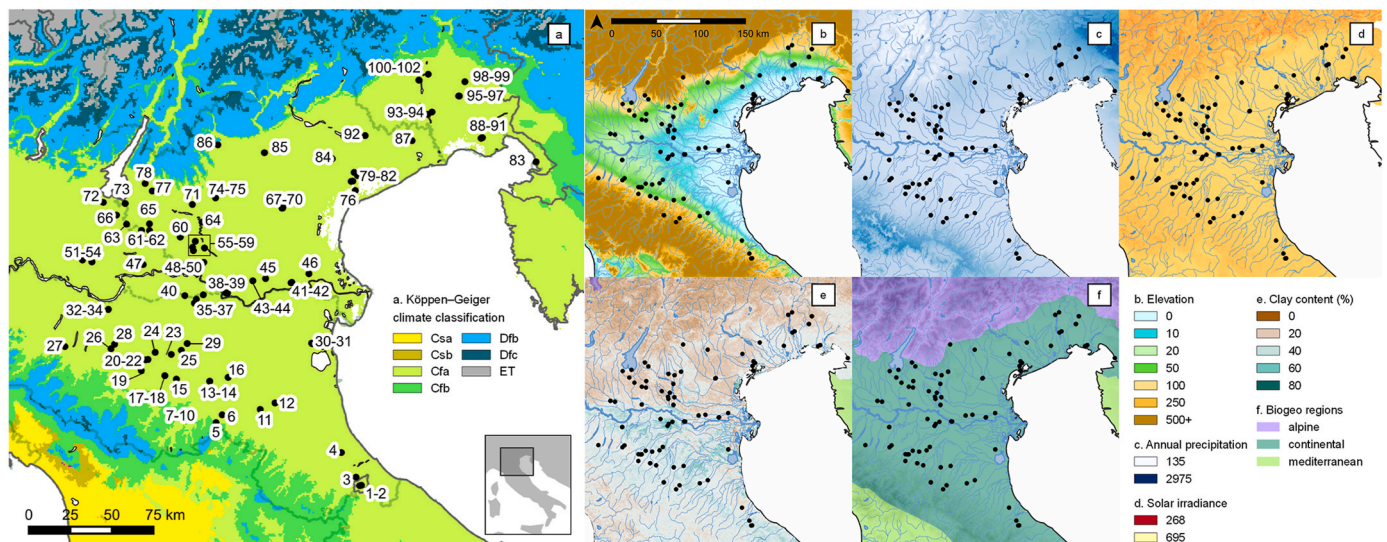


Fig. 1. Study region and landscape variables: a) Köppen–Geiger climate zones, b) elevation (m asl), c) annual precipitation (mm), d) solar irradiance (kWh/m²), e) clay content (%), f) biogeographical regions. See methods section for references and Supplement 1 for site details and numbers.

compared with environmental datasets. This approach allowed us to evaluate the potential interplay between climate/environment, human social organisation, and livestock production.

2. Environmental and archaeological background

The Po Valley is Italy's largest floodplain, and throughout antiquity it has attracted human settlement due to its fertile soils and transport opportunities offered by its fluvial networks. The Po Plain is encompassed by the Alps and Apennines to the north, west and south, and the Adriatic Sea to the east (Fig. 1a). The climate in the plain is shaped by the Po River and interaction with the Alps (Zanchettin et al., 2008; Cassardo et al., 2018). Annual precipitation in the Po Valley is currently c. 640–1000 mm annually, with greater rainfall closer to the mountains (Fig. 1c). Annual precipitation in the Friulian Plain is higher, reaching c. 1500 mm in the east of the region.

Characterisation of the ancient climate is challenging, and regional generalisations are difficult. Northern Italy followed a different climatic trajectory compared to central and southern Italy, particularly for the climatic event at c. 4.2 ka BP (Zanchetta et al., 2016). Unlike in central and southern Italy, where this event was marked by drier conditions, in northern Italy it had less of an impact, or was characterised by a step towards cooler and wetter conditions in the outer Italian Alps (Zanchetta et al., 2016; Furlanetto et al., 2018). Proximity to mountain regions also modifies the study area's climate (Cassardo et al., 2018); proxies may reflect complex local phenomena resulting from orography, cyclones, and local systems, potentially overwriting global climate signals (Scholz et al., 2012). Regional paleoenvironmental records do not always agree. Lake levels from Lake Ledro suggest wetter conditions during the Late Holocene, while isotopic data from Lake Frassino are suggestive of drier climatic conditions than in the mid-Holocene (Baroni et al., 2006; Magny et al., 2012) – discrepancies that may reflect changes in seasonality (Peyron et al., 2011; Magny et al., 2012). Significant anthropogenic impacts on the landscape are documented from the Bronze Age, which complicate the use of vegetation as a climate proxy (Mercuri et al., 2012; Branch and Marini, 2014; Mercuri, 2014).

2.1. Archaeological context and landscape use

The archaeo-historic development of the northern and southern Po Plain followed somewhat different trajectories. During the Middle Bronze Age (1700–1350 BC) the region saw significant growth in settlement numbers south of the River Po (Cardarelli, 2009) and a more complex settlement pattern developed in Friuli (Mihovilić, 2013). At the end of the Recent Bronze Age (c. 1350–1150 BC) the dense settlement network south of the Po was suddenly abandoned, possibly in response to a hydrological crisis (Cremaschi and Pizzi, 2011; Cremaschi et al., 2016). Settlements in Friuli also decreased (Vicenzutto, 2015), but there was great continuity north of the Po River in the Veneto (Cupitò et al., 2012). Following population consolidation at some centres in the Final Bronze Age (c. 1150–950 BC), especially in the Veneto, more distinct regional cultures emerged (Bietti Sestieri, 2010). These periods were important in the emergence of a more visibly hierarchical society, as evidenced by funerary treatment (Bietti Sestieri, 2010; Cavazzuti et al., 2019). Between the 8th and 3rd centuries BC the number of settlements expanded significantly, and centres in the Etruscan southern Po Plain, and subsequently Veneto, developed urban characteristics and settlement hierarchies (Balista et al., 2002; Govi, 2014). The growing presence of La Tène culture in the southern and western Po Plain from the 6th century BC indicates a cultural shift in these areas, which had become largely 'Celtic' in character by the fourth century BC (Frey, 1995; Curina et al., 2015).

Roman annexation of the region over the 3rd and 2nd centuries BC had a significant impact on the organisation of the territory through land reclamation, colonisation, and road building (Matteazzi, 2017; Roncaglia, 2018). However, the broader landscape impact of Roman political

integration was not immediate, and early widespread impacts date predominantly to the 1st centuries BC and AD (Calzolari et al., 2003; De Franceschini, 2003; Matteazzi, 2017). During the late 3rd century and 4th centuries AD, a change in settlement patterns suggests new modes of rural exploitation. A drop in the number of rural sites, and concurrent refurbishment of some rural villas, points to the growth of large estates (De Franceschini, 2003; Sfameni, 2004). Subsequently, plague, war, and climatic deterioration during the 6th century AD had a major impact on the social and environmental landscape of the region (Banaji, 2012; Castrorao Barba, 2014; Forin, 2017).

3. Materials and methods

Analysis was performed using R software (R Core Team, 2020). The data and R script are deposited online (<https://doi.org/10.5281/zenodo.6917159>).

3.1. Zooarchaeological data

NISP (Number of Identified specimens) and biometric data were collected from published literature for assemblages (site phases) dated between the Middle Bronze Age and Late Antiquity, a 2400-year period between approximately 1700 BC to AD 700. The methods underlying the creation of the dataset have been previously published (Trentacoste et al., 2018, 2021). They are presented here in brief. Site details, references, NISP data, raw measurements, and analysis script are available via Zenodo (see link above). NISP data are also available with the paper in Supplement 1. The NISP dataset comprised of 100,729 specimens from 102 site phases. Biometric analysis considered 97 site phases and 5112 measured bones, which were edited for analysis to 4937 specimens with width and/or length measurements. These two forms of zooarchaeological data were selected because they were consistently presented across the dataset. NISP in particular was the only form of zooarchaeological data persistently available in decent sample sizes (>100) at a site level – age information, for example, was typically only available for a small number of individuals and was not consistently presented in a comparable form.

Assemblages were assigned to a chronological period, each covering roughly two to three centuries (Table 1). Those with longer chronologies that could not be assigned to a specific period were attributed to intermediate periods (e.g. Final Bronze Age–Early Iron Age, Mid–Late Roman). Assemblages with longer undifferentiated chronologies that spanned more than two adjacent periods were excluded. The number of sites available and their geographic distribution varied by period (Fig. 2), with notable regional and chronological gaps. Assemblages also differed significantly in size, from one hundred (the lower cut-off for inclusion in the study) to over 18,000 identified livestock specimens. Despite these limitations, the dataset provides adequate spatial and temporal scope to assess broad-scale changes over the longue-durée in the study area.

Table 1
Chronological framework.

Period	Abbreviation	Chronology and details
Middle Bronze Age	BM	c. 1700–1350 BC
Recent Bronze Age (Late Bronze Age)	BR	c. 1350–1150 BC
Final Bronze Age (Late Bronze Age)	BF	c. 1150–950 BC
Early Iron Age	IA0	c. 950–8th century BC
Mid Iron Age	IA1	8th to 6th centuries BC
Late Iron Age	IA2	6th to 2nd centuries BC
Early Roman	Rom.E	Republican and early Imperial: 2nd century BC to 1st century AD, including assemblages dated wholly within the 1st century AD
Mid Roman	Rom.M	Imperial: 1st to 3rd centuries AD
Late Roman	Rom.L	Late Antiquity: 4th to 7th centuries AD

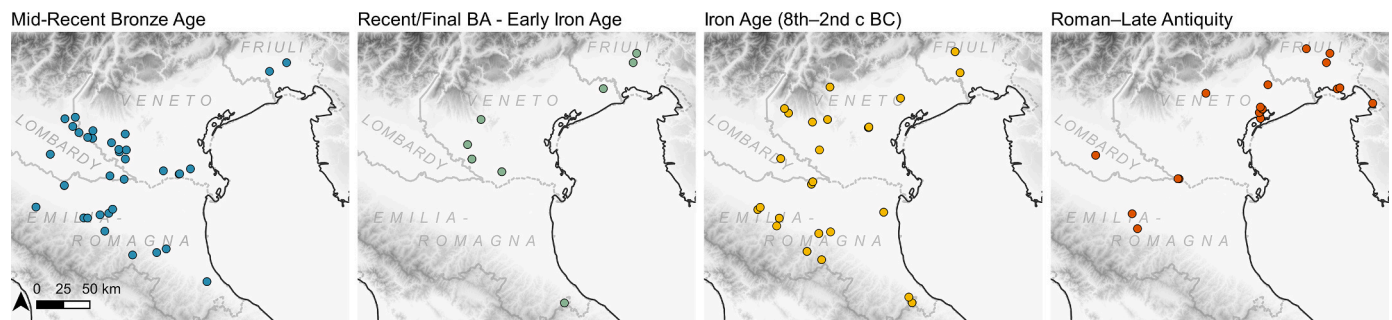


Fig. 2. Site distribution by period for NISP data.

Quantification of livestock abundance was based on NISP. NISP is subject to a series of systematic issues and biases related to recovery and fragmentation (Lyman, 2008); however it is the simplest and most widely used means of aggregating taxonomic data from diverse assemblages. NISP counts were standardised by excluding ribs, vertebra, and fragments not attributed to a specific body part. Quantification of livestock abundance only includes assemblages from habitation contexts with a livestock (cattle, sheep/goat, pig) NISP greater than 100.

Recent zooarchaeological analysis by the ZooMWest project of data from north-east Iberia used Correspondence Analysis (CA) and Hierarchical clustering analysis (HCA) to explore and visualise diachronic changes in NISP profiles (Nieto-Espinet et al., 2021; Huet and Nieto-Espinet, 2022). These techniques proved particularly useful for charting differences in homo-versus heterogeneity in NISP profiles through time, and for visualising diverse datasets; they are increasingly used in zooarchaeological meta-analysis (e.g. Orton et al., 2016; Macheridis and Magnell, 2020; Slim and Çakırlar, 2022). Here CA was used to explore the correlation between NISP, period, and region using the FactoMineR package in R (Lê et al., 2008). Scripts for CA and its visualisation were adapted from the zoomwork package (Huet and Nieto-Espinet, 2022). Hierarchical clustering analysis (HCA) using the native 'hclust' R function was used to group sites with similar NISP profiles, in order to explore differences in the heterogeneity of NISP profiles between periods. HCA was performed on values normalised using the dist() function.

Biometric analysis used Log Standard Index (LSI) values to investigate animal size and shape (Meadow, 1999). LSI values were calculated in R using the zoolog package (Pozo et al., 2021; Pozo et al. in press) using the 'Combi' reference. This computed LSI values using Nieto-Espinet (2018) for cattle, Clutton-Brock et al. (1990) for sheep/goats, and the Basel reference (included in the package) for pigs/wild boar. One length and one width log ratio value from each specimen were included in the analysis, with values selected following the default zoolog 'priority' method and order of selection (length values - GL, GLL, GLM, HTC; width values - Bd, BT, Bp, SD, Bfd, Bfp). In order to control for the presence of wild boar, only LSI values less than 0 were included in the analysis of pigs; the cut off between pigs and wild boar was established based on visual inspection of data distribution (see Trentacoste et al., 2021 and supplementary script on Zenodo). Differences in biometric results were investigated using Mann–Whitney U tests in the rstatix package (Kassambara, 2021).

3.2. Landscape data

Exploratory statistics were used to look for evidence of relationships between NISP and landscape data. Location information and landscape data are provided in Supplement 1. Site locations were compiled in QGIS as a point layer, using location information from excavation reports and regional archaeological maps and databases. Zonal statistics for each variable were calculated from raster data at a 5 km radius around each site. This distance was selected to provide an average picture of the

situation in the immediate vicinity of each site, at a resolution appropriate for macro-scale analysis. This simple approach was used rather than a spatial analysis (e.g. Orton, 2004), because the availability and distribution of zooarchaeological data is highly dependent on research focus and excavation history: clusters and gaps reflect the nature of archaeological investigation rather than differences in past animal management.

As in previous investigations comparing environmental and zooarchaeological data (Conolly et al., 2012; Manning et al., 2013; Ivanova et al., 2018), modern records were used. High-resolution maps and models were not available for the ancient Po–Friulian Plain. Modern data were considered a proxy for landscape and environment structure, and not intended as an exact measure of ancient conditions. Since the study aimed to understand how NISP profiles vary with environmental variables spatially and temporally, rather than reconstruct predictive relationships, the relative rather than absolute value of landscape variables was thus of relevance here. Following Brandolini and Carrer (2020), the geomorphological context of the study area was assumed to have the same primary characteristics over the Late Holocene. Similar assumptions were made for the relative relationships of other environmental variables; however, considering the complex climate situation in the circum-Alpine region and the potential for intra-regional differences in the past (Roberts et al., 2011; Scholz et al., 2012; Cassardo et al., 2018), precipitation and solar irradiance data were more cautiously applied.

Elevation information was taken from Shuttle Radar Topography Mission (SRTM) terrain data from the U.S. Geological Survey (90m resolution; Jarvis et al., 2008). Precipitation data were from World Clim 2.1 (average monthly climate data for 1970–2000, 30 arc-sec; Fick and Hijmans, 2017), and solar irradiance data were from Global Solar Atlas 2.0 (9 arc-sec; developed and operated by Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP); <https://globalsolaratlas.info>). Soil characteristics were derived from LUCAS topsoil data (500m; Ballabio et al., 2016): clay, silt, sand, and coarse fragments content (%), bulk density, and Available Water Capacity (AWC) for the topsoil fine earth fraction. Spearman's rank correlation was computed using the cor.test() function to assess the relationship between NISP profiles and landscape variables.

3.3. Climatic and environmental proxies

Northern Italy has a different climatic trajectory compared to the rest of the peninsula (Zanchetta et al., 2016), so climate proxies were chosen from within or immediately adjacent to the study area. Considered data sources included Frassino and Ledro Lakes (Baroni et al., 2006; Magny et al., 2012), speleotherms from Ernesto and Savi caves (Frisia et al., 2005; Scholz et al., 2012), geoarchaeological and geomorphological evidence for flooding events in the Venetian–Friulian Plain (Fontana et al., 2020; Zanchetta et al., 2021), river bed aggregation/fluvial instability in Emilia (Cremonini et al., 2013), and pollen data from Lake

Lucone (Valsecchi et al., 2006), Lake Mincio (Ravazzi et al., 2013), and Muzzano and Origlio Lakes (Tinner et al., 2003). Lastly, evidence for glacial advances of the Great Altesch Glacier (Holzhauser et al., 2005) and in the Orco Valley (Giraudi, 2009) were included.

Importantly, these sources do not provide a simple or consistent view of a northern Italian climate (Fig. 4d 1–11). For example, pollen records document differing patterns of clearance and forest regrowth in different areas of northern Italy, related to both anthropic impacts and climatic influences. The nature of the Po Valley likely would have varied significantly across its expanse, in terms of settlement distribution and density, vegetation cover and type, and fluvial networks. While a simple picture of climate or environment does not emerge from this integration, the sources represent an important body of evidence to compare to zooarchaeological data and the timing of trends in this dataset, particularly in relation to evidence for warming/cooling, which can impact animal body size (Bergmann, 1847; Weaver and Ingram, 1969; Davis, 1981; Ashton et al., 2000). Information from environmental proxies was compared to zooarchaeological data, but here correlations were not statistically interrogated due to significant differences in the chronological resolution of the different datasets.

4. Results

4.1. Zooarchaeological results

Correspondence Analysis (CA) demonstrated that the majority of the variation in the dataset (dimension 1, 64%) was explained by the abundance of cattle versus smaller livestock (Fig. 3). Assemblages from the South study region generally correlated with sheep/goats or pigs, while assemblages from the North study area tended to correlate with sheep/goats and cattle. Assemblages from Friuli and the Veneto were more diverse in their orientations. Roman assemblages were more likely to have a pronounced emphasis on a particular taxon. HCA showed changes in the diversity of NISP profiles through time (Fig. 4b). The

taller height of the dendrogram's branches in the Roman period and Late Iron Age demonstrate that inter-site differences in NISP profiles were greater in these periods compared to earlier prehistory. This greater diversity was also visible in the outlying points in the CA, and especially when proportions of cattle versus small livestock (sheep/goat/pigs) were compared (Fig. 4a). Roman site type did not appear to have a major impact on similarity in NISP profiles, since site types were distributed across the various clusters.

As in previous studies, LSI values recorded diachronic changes in the size of cattle and sheep/goats compared to relative stability and diminution in pig LSI values (Fig. 4c). Summary statistics for LSI values by period are included in Supplement 2. Mean values from bovids increased through time, and Mann-U tests (Supplement 3) revealed very strong evidence for increases in both length and width values at period transitions (Late Bronze Age to Early Iron Age, and Late Iron Age to Early Roman period, $p < 0.001$). There was also strong evidence for a decrease in width values from bovids during Late Antiquity ($p = 0.001$). However, it is important to note that this grouping of the data on a macro-regional scale conceals subregional trends and introduces variation due to the regional distribution of the data. For example, the decrease in sheep/goat LSI values between the Mid and Late Iron Age reflects a shift in the geographic area represented by the sample, from the Veneto (where sheep/goat were relatively large in IA1) to the North and South regions (where sheep/goats were relatively smaller), rather than a change in the overall trend (see Trentacoste et al., 2018). Previous sub-regional analysis suggested a more gradual evolution of bovid size over later prehistory in all sub-regions, albeit with different regional rhythms (Trentacoste et al., 2018).

Similarly, the previous sub-regional investigation documented a diminution in pig body size over prehistory, with strong evidence for decreases in width values in the southern Po Plain and Veneto when Middle-Late Bronze Age and Mid Iron Age values were compared (Trentacoste et al., 2018). In the grouped dataset presented here this diminution was only visible over a longer durée, between the Middle

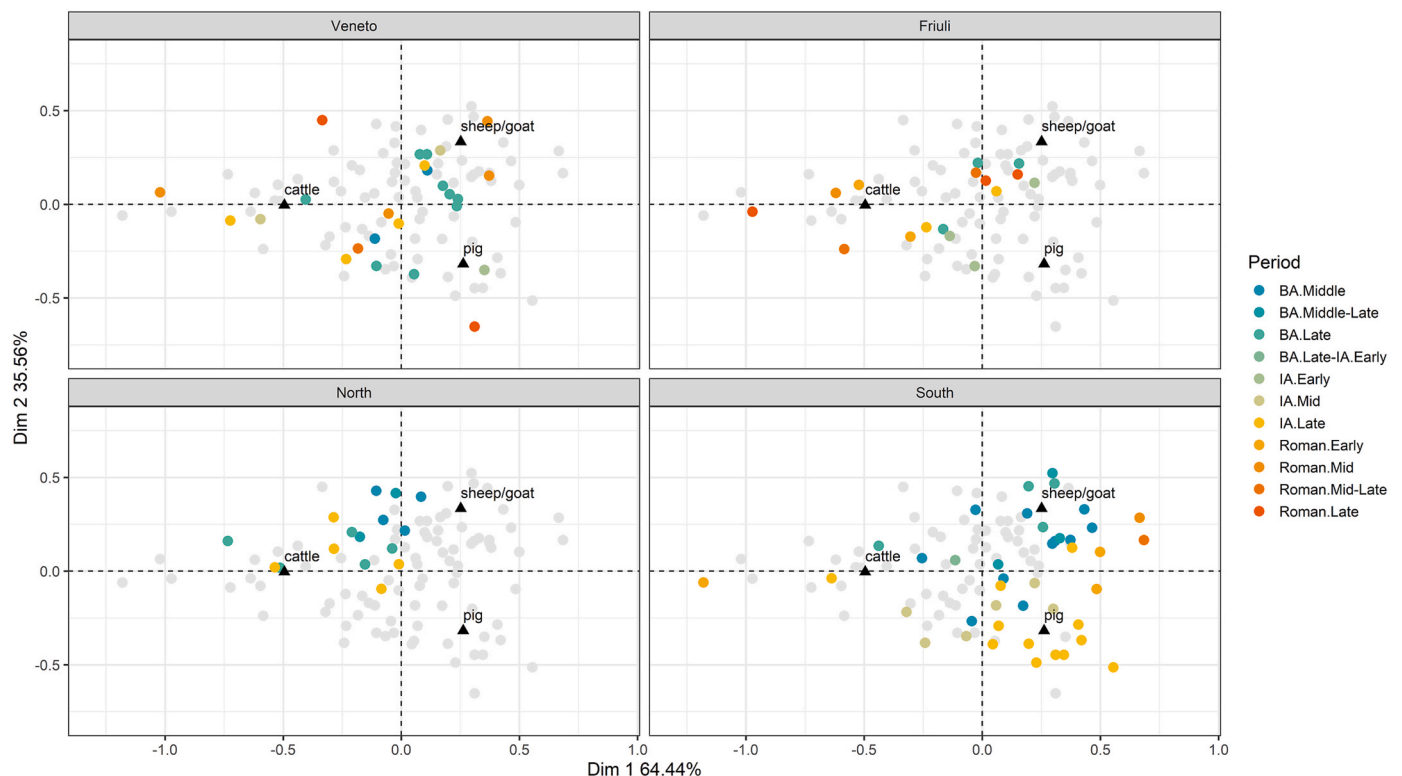


Fig. 3. Correspondence Analysis (CA) of NISP counts (cattle, pig and sheep/goat).

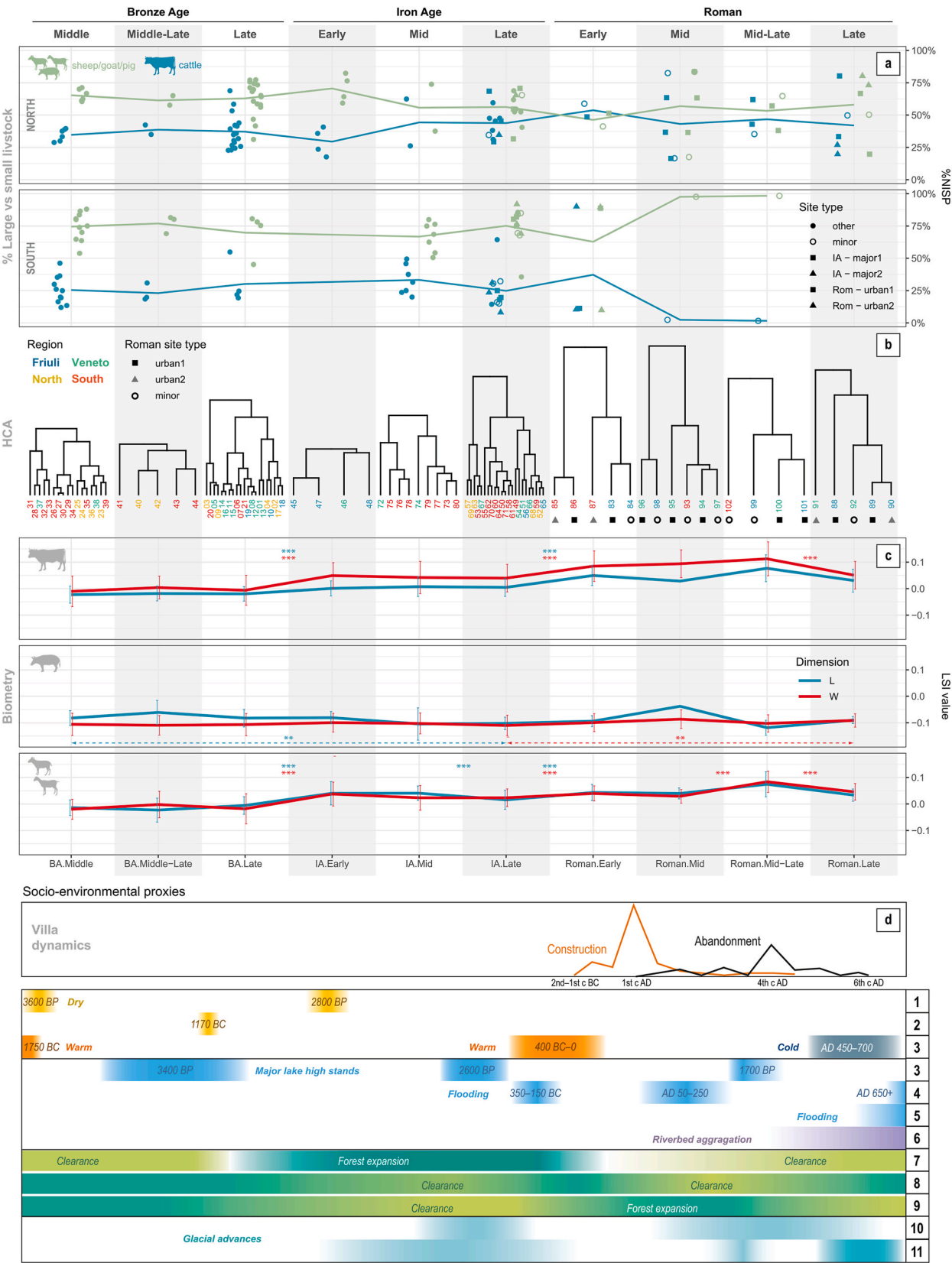


Fig. 4. Changes in zooarchaeological, settlement, and landscape data compared. a) Relative proportions of small livestock (sheep/goat/pigs) versus cattle. Line indicates the mean of the proportions. b) Hierarchical clustering analysis (HCA; see Supplement 1 for HCA numbers). c) Mean LSI values. d) Villa dynamics (De Franceschini, 2003). Local environmental proxies: 1. Frassino Lake (Baroni et al., 2006), 2. Terramara of Poviglio hydrological crisis (Cremaschi et al., 2006), 3. Ernesto and Savi caves (Frisia et al., 2005; Scholz et al., 2012), 4. Ledro Lakes (Magny et al., 2012), 5. Flooding in the Venetian-Friulian Plain (Fontana et al., 2020; Zanchetta et al., 2021), 6. Riverbed aggregation/fluviial instability in Emilia (Cremonini et al., 2013), 7. Lake Lucone (Valsecchi et al., 2006), 8. Lake Mincio (Ravazzi et al., 2013), 9. Muzzano and Origlio Lakes (Tinner et al., 2003), 10. Orco Valley Glacier (Giraudi, 2009), 11. Great Altesch Glacier (Holzhauser et al., 2005).

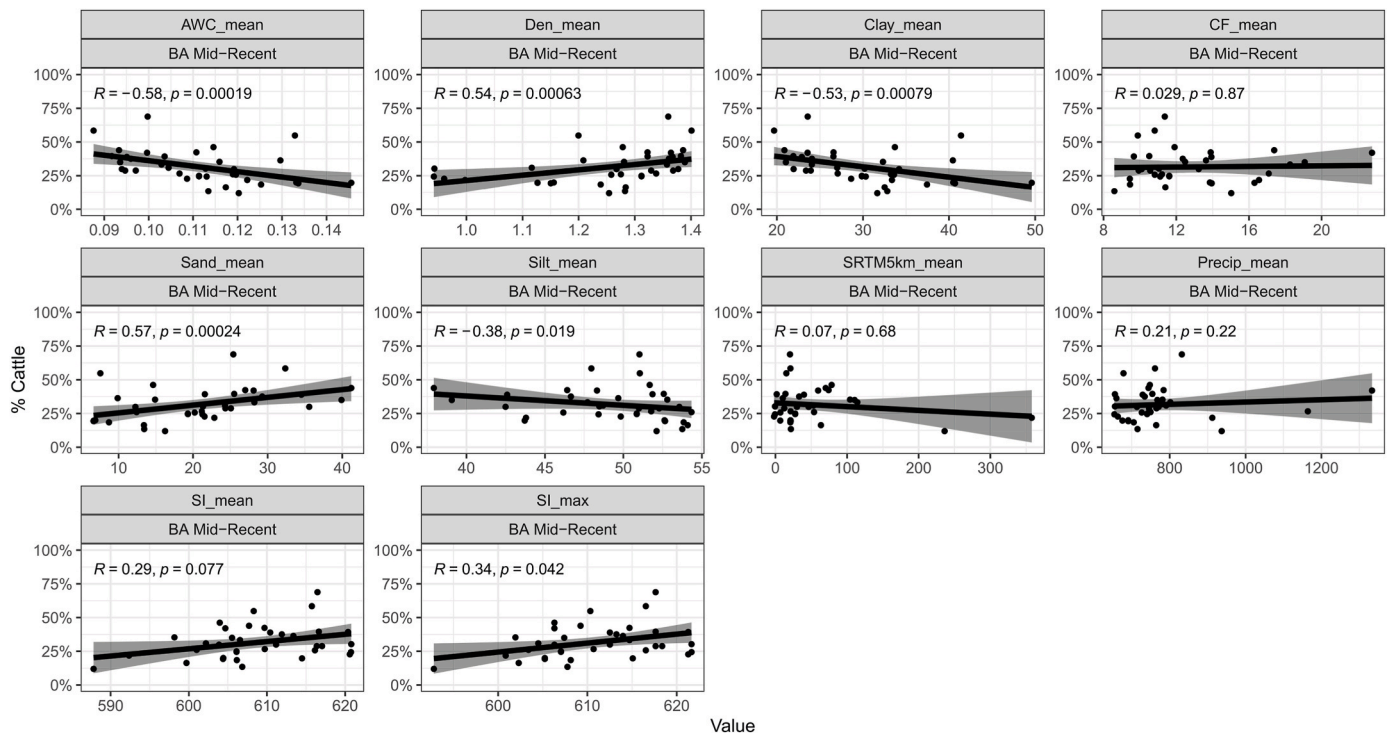


Fig. 5. Relative percentages of cattle from Bronze Age sites compared to landscape variables. Landscape values are an average of values within a 5 km diameter from the sites: mean topsoil clay, silt, sand, and coarse fragments content (%) (Ballabio et al., 2016); topsoil bulk density and Available Water Capacity (Ballabio et al., 2016); mean elevation (m asl) (SRTM data from the U.S.G.S.; Jarvis et al., 2008); mean annual precipitation (mm) (Fick and Hijmans, 2017); mean solar irradiance, and mean of maximum solar irradiance values (kWh/m²) (Fick and Hijmans, 2017). See Supplement 1 for data.

Bronze Age and Late Iron Age. Compared to bovids, the general trend was for relative stability, with an indication of a gradual decrease in height over later prehistory, and perhaps an increase in robustness in Late Antiquity.

4.2. Landscape variables

Since the majority of variation in NISP frequencies was accounted for by the proportion of small versus large livestock, cattle percentages were compared to landscape variables. The majority of comparisons produced little or no evidence for an association with cattle frequencies (see in Supplement 4 for correlation results). The Iron Age and Roman periods produced several pairings with moderate evidence for associations with cattle frequencies (IA1-2 and AWC, $r_s(31) = -0.36$, $p = 0.041$; Rom.M-L silt content, $r_s(13) = 0.53$, $p = 0.042$; Rom.M-L 5 km elevation mean, $r_s(13) = -0.53$, $p = 0.042$). However, comparisons with Bronze Age sites revealed very strong evidence for correlations between available water capacity (AWC), density, clay content, and sand content ($df = 35$, $p < 0.001$, $r_s = \pm 0.53$ – 0.58), with the proportion of cattle negatively associated with clayey soils (Fig. 5). For these pairings, Spearman's correlation coefficient shows a relationship of moderate strength between cattle percentages and soil features. There was also moderate evidence for relationships between Bronze Age cattle frequencies and maximum annual solar irradiance ($r_s(35) = 0.34$, $p = 0.042$) and silt content ($r_s(35) = -0.38$, $p = 0.019$), but Spearman's correlation coefficient shows that these were relatively weak associations.

5. Discussion

This re-evaluation and visualisation of the zooarchaeological dataset unites this information from the Middle Bronze Age to Late Antiquity in Northern Italy for the first time. Previously documented trends (see Trentacoste et al., 2018; Trentacoste et al., 2021) towards higher

percentage of pigs in the Etruscan southern Po Plain (IA1 and IA2) and high proportions of cattle North of the River Po were visible in results. However, HCA and CA added further nuance to the dynamics of NISP profiles. The main variation in NISP was between the proportion of cattle versus smaller livestock, and NISP profiles became notably more diverse in the Late Iron Age and Roman times (Fig. 4 a and b). The particular pig-focused strategy of the Etruscan southern plain, widely discussed in previous work (Farello, 1995; Trentacoste et al., 2018, 2021), was discernible in each of the NISP visualisations included here, and in the HCA most Etruscan sites form their own branch of the Late Iron Age dendrogram (red numbers between 55 and 61). Interestingly, variation in the Roman period does not appear to have a strong relationship with site type. This may result from the small number of assemblages available for Roman times, which were dispersed throughout the whole study region, consequently complicating recognition of sub-regional trends. Equally, such diversity may also be influenced by site formation processes, excavation decisions, and the nature of uncovered areas within sites. As animal processing activities become more specialised and spatially articulated within Roman and later settlements, livestock consumption and disposal activities will differ between more productive/industrial areas and more domestic settings. Indeed, the assemblages with the most pronounced focus on cattle remains have been linked to large scale animal processing – Calvatone/Bedriacum (HCA no. 87, Map no. 52) (Wilkens, 1997), and Aquileia (HCA nos 83, 88, 101; Map nos 89–91) (Riedel, 1994b; Petrucci, 2007). As a result of this greater variation in later periods, traditional approaches to diachronic NISP comparisons (line or bar graphs) were not included here, because they fail to capture the diversity which defines Roman times (e.g. compare mean lines and points in Fig. 4a).

Biometric results largely confirmed previously documented trends: cattle and sheep/goat increased in size, while the size of pigs was more stable. However, this grouping of the data at the macro-regional level obscures the different sub-regional trajectories of livestock size

evolution and impacts mean LSI values due to inter-period differences in the regional origin of the dataset. Analysis at the subregional level, particularly in the Veneto, suggested a more gradual process of size increase in bovids over prehistory (Trentacoste et al., 2018), rather than a single moment of increase followed by relative stability across the Iron Age (as implied in the figure herein). Compared to changes between the Bronze and Iron Age, the subsequent increase in bovid size in the Early Roman period was more pronounced, particularly in cattle (Trentacoste et al., 2021).

Comparisons with landscape variables did not produce good evidence for relationships between NISP and elevation, precipitation, solar irradiance or soil characteristics, except during the Bronze Age. Very strong evidence was found for a negative association between cattle and clay content and AWC, and for a positive association between cattle and soil density and sand content. Correlation does not imply causation, and the modern data interrogated here was intended as a proxy for landscape structure rather than an exact measure of prehistoric geopedology. Nevertheless, this evidence for correlations is interesting for several reasons. Firstly, it confirms the hypothesis proposed in Trentacoste et al. (2018) based on comparison on NISP profiles and soil infiltration mapping, that a relation between species abundance and soil characteristics does exist, at least for the Bronze Age. Secondly, this association is predominantly limited to the Bronze Age. Several strong relationships between NISP values and soil characteristics were documented for this period, but similarly strong evidence was not found in other periods, including when the number of assemblages was robust. Finally, as an animal better adapted than sheep to damper areas, one might expect higher cattle frequencies on clayey soils in the Po Valley, rather than the trend seen here towards fewer cattle in areas subject to greater waterlogging.

Any potential causality behind this association remains unclear, and there are a range of possibilities. Fine-grained sediments typically reflect floodplain features (backswamps, abandoned channels) subject to waterlogging (Fryirs et al., 2012), suggesting that flood risk or damp environments were a factor. Relationships between cattle frequencies and soil qualities may reflect livestock preferences driven by the landscape's influence on cereal production strategies, for instance the importance of animal versus human labour or cultivation regimes. Clay-rich 'heavy' soils are harder to work than lighter soils (Halstead, 2014; Andersen et al., 2016). In areas with heavy soils, smaller fields or less frequent ploughing during the Bronze Age may have disincentivised keeping dedicated teams of working oxen. In later periods, increases in field size and/or more frequent ploughing may have made cattle traction more necessary and attractive. Such concern with cattle-power is likely also reflected in the increase in cattle body size. Alternatively, correlations may be an artefact of the location of different Bronze Age cultural groups. Terramare sites tend to have a particular emphasis on sheep/goat (De Grossi Mazzorin, 2013), a trend which has been linked both to subsistence strategies, as well as the economic importance of wool production (Sabatini, 2020). Terramare sites are distributed across the southern Po Plain, a region characterised by finer sediments and a wetter landscape (Marchetti, 2002).

The relative homogeneity of Bronze Age NISP profiles, and their strong association with landscape variables (not similarly present in later periods), suggests a particular and more locally oriented livestock production/consumption strategy. This system became more detached from the landscape and more diverse in later periods. This is in accordance with quantitative meta-analyses of Neolithic zooarchaeological data, which also highlight the importance the environment in shaping species abundance, especially during the early Neolithic (Conolly et al., 2012; Manning et al., 2013; Ivanova et al., 2018). Large-scale studies of Neolithic Europe and the southwest Asia found c. 20–30% of variance in species frequencies to be accounted for by environmental variables (Conolly et al., 2012; Manning et al., 2013). In later periods socio-economic integration had a greater influence. Analysis of northeast Iberia between late prehistory and Late Antiquity demonstrated that

periods with a lesser degree of economic connectivity displayed husbandry strategies more closely related to the ecological conditions of each area (Nieto-Espinet et al., 2021). Interestingly, in northeastern Iberia the heterogeneity of NISP profile peaks in Roman Republican times, unlike in northern Italy where marked diverse NISP profiles continue through the Roman period.

Comparison of zooarchaeological and environmental trends (Fig. 4d1-11) is challenging due to the diverse nature of past climate proxies. Additionally, northern Italy has a particularly complex situation, due to its changeable fluvial network (Cremaschi et al., 2016) and the interactions between hydrologic budget components in the mountains versus plain, which can have different local patterns of climate change (Cassardo et al., 2018). However, one of the most interesting outcomes of the comparison here is the continued development of regional bovid size over a long-durée characterised by different climatic situations. There were opposite developments in pig biometry on a regional scale over the same period. Most notably, the significant increase in bovid size between the end of the Bronze Age and Iron Age (here IA0–1, 10th–6th centuries BC) corresponds with cold and humid climatic phase marked by Alpine glacial advances (Tinner et al., 2003; Holzhauser et al., 2005). This is then followed by further size increases under a different and warmer climatic regime in Northern Italy from the mid-first millennium BC (Frisia et al., 2005). At the end of the period considered here, in Late Antiquity (Late Roman), there is evidence for a decrease in the size of cattle and sheep/goat, roughly corresponding with a period climatic deterioration from the 6th century AD, seen in a number of proxies (Fig. 4d 3,4,5,6,11). At this same moment, there is indication of an increase in pig size.

These developments suggest that climate was not the driving factor in livestock body size change for the majority of the diachrony considered here. Bovids and pigs follow different pathways, and increases in bovid size in the Roman period contradict Bergmann's rule that animal body size decreases in warmer climates (Bergmann, 1847; Ashton et al., 2000; Meiri, 2011). While body size increases in the Early Iron Age are roughly coincident with evidence for climatic cooling, an increase in length measurements contradict Allen's Rule, which states that animals in colder climates have proportionally shorter extremities than those in warm climates (Weaver and Ingram, 1969). The only period when biometric changes may align with these biological principles is during Late Antiquity (here the Late Roman period), the 5th–6th AD century and later; however the many invasions, plagues and political changes that also define this period also impacted rural production and the broader organisation of society generally (Marazzi, 1997; Christie, 2006; Roncaglia, 2018). Separating climate-mediated impacts on livestock management from social impacts on the same activities is extremely difficult and will require further zooarchaeological datasets in order to more confidently control for age and sex-related variation. Overall, these trends indicate that regional-scale changes in NISP and biometric data, at least during the Iron Age and Roman period, primarily reflect human decision-making and socio-political factors, rather than being determined by environmental factors. However, within this conclusion the precise factor driving body-size change remains open to discussion. Changes in mobility, feeding and breeding regimes, trait selection or other factors – conscious or unconscious – likely had a role (Zohary et al., 1988; Sullivan et al., 2017; Valenzuela-Lamas, 2020).

Results presented here also demonstrate the need to visualise NISP data in ways other than pooled in bar graphs and line plots. Techniques developed for Iberian data over a similar diachrony (Nieto Espinet et al., 2021) have also proved extremely useful in interrogating the Italian data, and at representing new dimensions in NISP fluctuations through time. Although widely used, pooling information in bar or line is not suitable for heterogeneous datasets like those documented in northern Italy during the Roman period. HCA and CA allow this diversity to be better appreciated and also quantified. Our results also demonstrate the ability to identify strong relationships between zooarchaeological and environmental data on a regional scale, in an area of relative

environmental homogeneity. This is an important complement to continental and large-scale approaches where ecological and environmental differences are more pronounced. Greater relative variation in environmental variables over the macro-scale can lead to findings of greater environmental influence in quantitative analyses (see Manning et al., 2013:1055); these relationships do not necessarily hold at regional scales (Gaastra and Vander Linden, 2018). Our work shows the potential for down-scaling these methods in order to understand sub-regional climate and environmental impacts and their varying influence over different periods of human history – an approach essential to moving away from broad-brush and deterministic associations between climatic and archaeo-historical events, and more towards causal and multi-faceted relationships.

6. Conclusion

Zooarchaeological remains offer a ubiquitous source of quantitative data on human–environment relationships. As scholarship becomes increasingly interested in the association of climatic and archaeo-historical events, these zooarchaeological data have the potential to shed new light on the interconnections between human societies, productive strategies, and their environments. Farming plants and animals was the most important nexus of humans and their natural world, and the area of activity where climatic or environmental disruption could prove catastrophic and lead to major social upheaval. This study has sought to take a first step towards a better understanding of the relationship between zooarchaeological and environmental evidence in northern Italy through quantitative and qualitative comparisons. Based on comparison with local climatic datasets, which present a complex and sometimes contradicting picture, regional trends in livestock body size appear human-driven. Correlation of landscape variables and zooarchaeological data produced strong evidence for correlations between soil type and cattle abundance, but only in the Bronze Age. These results confirm previous observations on the relationship between geomorphology and livestock profiles during prehistory. In conjunction with higher homogeneity in NISP profiles, this close correlation with the local landscape suggests Bronze Age management strategies were more closely related to – although not necessarily directly determined by – local ecological conditions than in later periods. In this context, animals and animal remains provide an important means of tracking human responses to a changing socio-economic and socio-ecological context. While these data are not able to function at the exceptionally high-resolution scale of some climate proxies (e.g. McConnell et al., 2020), as a ubiquitous source of evidence, animal remains can be aligned with longer-term environmental changes to chart human adaptations on the broad scale. Here, Iron Age cooling had little demonstrable long-term impact on animal management at a regional scale, which opens new questions about the organisation and resilience of ancient agricultural systems. Zooarchaeology has the potential to be further applied to questions in this sphere, and with new tools (like zoolog) that remove barriers to inter-regional comparisons, there is great potential to shed new light on these themes in Italy and the Mediterranean more broadly.

Author contributions

Angela Trentacoste: Conceptualization, Methodology, Formal analysis, Data Curation, Writing - Original Draft, Visualisation, Funding acquisition. **Ariadna Nieto-Espinete:** Conceptualization, Methodology, Writing - Review & Editing. **Silvia Guimarães Chiarelli:** Conceptualization, Methodology, Writing - Review & Editing. **Silvia Valenzuela-Lamas:** Conceptualization, Methodology, Writing - Review & Editing, Funding acquisition, Supervision.

Data availability

Raw data, references, and R script for the analyses and visualisations

are available on Zenodo (<https://doi.org/10.5281/zenodo.6917159>). Basic data and results of statistical tests are also included in the paper's Supplementary data.

Declaration of competing interest

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

Acknowledgements

This work was financially supported by the ERC-Starting Grant ZooMWest – Zooarchaeology and Mobility in the Western Mediterranean: Husbandry production from the Late Bronze Age to the Late Antiquity (award number 716298), funded by the European Research Council Agency (ERCEA) under the direction of Silvia Valenzuela-Lamas, and by a Gerda Henkel Stifling Scholarship (AZ44/F/20) awarded to Angela Trentacoste. We are grateful to Thomas Huet for support with data analysis in R.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.quaint.2022.11.005>.

References

- Andersen, T.B., Jensen, P.S., Skovsgaard, C.V., 2016. The heavy plow and the agricultural revolution in Medieval Europe. *J. Dev. Econ.* 118, 133–149. <https://doi.org/10.1016/j.jdevco.2015.08.006>.
- Ashton, K.G., Tracy, M.C., Queiroz, A.d., 2000. Is Bergmann's rule valid for mammals? *Am. Nat.* 156, 390–415. <https://doi.org/10.1086/303400>.
- Attema, P.A.J., Burgers, G.J., Kleibrink, M., Yntema, D.G., 1998. Case studies in indigenous developments in early Italian centralization and urbanization: a Dutch perspective. *Eur. J. Archaeol.* 1, 326–381. <https://doi.org/10.1179/eja.1998.1.3.326>.
- Balista, C., Gambacurta, G., Ruta Serafini, A., 2002. *Sviluppi di urbanistica atestina*. In: Ruta Serafini, A. (Ed.), *Este preromana: una città e i suoi santuari*. Canova, Treviso, pp. 105–121.
- Ballabio, C., Panagos, P., Monatanarella, L., 2016. Mapping topsoil physical properties at European scale using the LUCAS database. *Geoderma* 261, 110–123. <https://doi.org/10.1016/j.geoderma.2015.07.006>.
- Banaji, J., 2012. Economic trajectories. In: Fitzgerald Johnson, S. (Ed.), *The Oxford Handbook of Late Antiquity*. Oxford University Press, Oxford, pp. 597–624. <https://doi.org/10.1093/oxfordhb/9780195336931.9780195336013.9780195330018>.
- Barker, G., 1981. *Landscape and Society: Prehistoric Central Italy*. Academic Press, New York.
- Baroni, C., Zanchetta, G., Fallick, A.E., Longinelli, A., 2006. Mollusca stable isotope record of a core from Lake Frassino, northern Italy: hydrological and climatic changes during the last 14 ka. *Holocene* 16, 827–837.
- Belhadj Slimen, I., Najar, T., Ghram, A., Abdrrabba, M., 2016. Heat stress effects on livestock: molecular, cellular and metabolic aspects, a review. *J. Anim. Physiol. Anim. Nutr.* 100, 401–412. <https://doi.org/10.1111/jpn.12379>.
- Bergmann, C., 1847. *Über die Verhältnisse der Wärmeökonomie der Thiere zu ihrer Grösse*. Göttinger Studien 3, 595–708.
- Bietti Sestieri, A.M., 2010. *L'Italia nell'età del bronzo e del ferro. Dalle palafitte a Romolo (2200-700 a.C.)*. Carocci editore, Roma.
- Branch, N.P., Marini, N.A.F., 2014. Mid-Late Holocene environmental change and human activities in the northern Apennines, Italy. *Quat. Int.* 353, 34–51. <https://doi.org/10.1016/j.quaint.2013.07.053>.
- Brandolini, F., Carrer, F., 2020. Terra, Silva et Paludes. Assessing the Role of Alluvial Geomorphology for Late-Holocene Settlement Strategies (Po Plain – N Italy) Through Point Pattern Analysis. *Environ. Archaeol.* 26 (5), 511–525. <https://doi.org/10.1080/14614103.2020.1740866>.
- Çakırlar, C., Marston, J.M., 2017. Rural agricultural economies and military provisioning at Roman Gordion (Central Turkey). *Environ. Archaeol.* 1–15. <https://doi.org/10.1080/14614103.2017.1385890>.
- Calzolari, M., Corti, C., Gianferrari, A., Giordani, N., 2003. *L'età romana nella Pianura modenese, Atlante dei Beni Archeologici della Provincia di Modena, I Pianura*. All'Insegna del Giglio, Florence, pp. 39–51.
- Camenisch, C., Keller, K.M., Salvisberg, M., Amann, B., Bauch, M., Blumer, S., Brázdil, R., Brönnimann, S., Büntgen, U., Campbell, B.M.S., Fernández-Donado, L., Fleitmann, D., Glaser, R., González-Rouco, F., Grosjean, M., Hoffmann, R.C., Huhtamaa, H., Joos, F., Kiss, A., Kotyza, O., Lehner, F., Luterbacher, J., Maughan, N., Neukom, R., Novy, T., Pribyl, K., Raible, C.C., Riemann, D., Schuh, M., Slavin, P., Werner, J.P., Wetter, O., 2016. The 1430s: a cold period of extraordinary internal

- climate variability during the early Spörer Minimum with social and economic impacts in north-western and central Europe. *Clim. Past* 12, 2107–2126. <https://doi.org/10.5194/cp-12-2107-2016>.
- Cardarelli, A., 2009. The collapse of the Terramare culture and growth of new economic and social system during the late Bronze Age in Italy. *Scienze dell'antichità* 15, 449–520.
- Cassardo, C., Park, S.K., Galli, M., O, S., 2018. Climate change over the high-mountain versus plain areas: effects on the land surface hydrologic budget in the Alpine area and northern Italy. *Hydrol. Earth Syst. Sci.* 22, 3331–3350. <https://doi.org/10.5194/hess-22-3331-2018>.
- Castoraro Barba, A., 2014. Continuità topografica in discontinuità funzionale: trasformazioni e riusi delle ville romane in Italia tra III e VIII secolo. *Post-Classical Archaeologies* 4, 259–296.
- Cavazzuti, C., Cardarelli, A., Quondam, F., Salzani, L., Ferrante, M., Nisi, S., Millard, A. R., Skeates, R., 2019. Mobile elites at Frattesina: flows of people in a Late Bronze Age 'port of trade' in northern Italy. *Antiquity* 93, 624–644. <https://doi.org/10.15184/ajq.2019.59>.
- Christie, N., 2006. From Constantine to Charlemagne: an Archaeology of Italy AD 300–800. Ashgate, Aldershot.
- Clutton-Brock, J., Dennis-Bryan, K., Armitage, P.L., Jewell, P.A., 1990. Osteology of the soay sheep. *Bull. Br. Mus. Nat. Hist. Zool.* 56.
- Conolly, J., Manning, K., Colledge, S., Dobney, K., Shennan, S., 2012. Species distribution modelling of ancient cattle from early Neolithic sites in SW Asia and Europe. *Holocene* 22, 997–1010. <https://doi.org/10.1177/0959683612437871>.
- Crabtree, P., Campana, D., 2016. Class and "romanization" in late roman Egypt: issues of identity and faunal remains from the site of amheida in the dakleh oasis, western Egypt. In: Marom, N., Weissbrod, L., Yeshurun, R., Bar-Oz, G. (Eds.), *Bones and Identity: Zooarchaeological Approaches to Reconstructing Social and Cultural Landscapes in Southwest Asia*. Oxbow Books, Oxford, pp. 293–302.
- Cremaschi, M., Mercuri, A.M., Torri, P., Florenzano, A., Pizzi, C., Marchesini, M., Zerboni, A., 2016. Climate change versus land management in the Po plain (northern Italy) during the Bronze age: new insights from the VP/VG sequence of the terramara santa rosa di Poviglio. *Quat. Sci. Rev.* 136, 153–172. <https://doi.org/10.1016/j.quascirev.2015.08.011>.
- Cremaschi, M., Pizzi, C., 2011. Water resources in the Bronze Age villages (terramare) of the north Italian Po plain: recent investigation at Terramara Santa Rosa di Poviglio. *Antiquity Project Gallery* 85. <https://www.antiquity.ac.uk/projgall/cremaschi327>.
- Cremaschi, M., Pizzi, C., Valsecchi, V., 2006. Water management and land use in the terramare and a possible climatic co-factor in their abandonment: the case study of the terramara di Poviglio Santa Rosa (northern Italy). *Quat. Int.* 151, 87–98. <https://doi.org/10.1016/j.quaint.2006.01.020>.
- Cremonini, S., Labate, D., Curina, R., 2013. The late-antiquity environmental crisis in Emilia region (Po river plain, Northern Italy): geoarchaeological evidence and paleoclimatic considerations. *Quat. Int.* 316, 162–178. <https://doi.org/10.1016/j.quaint.2013.09.014>.
- Cupito, M., Dalla Longa, E., Donadel, V., Leonardi, G., 2012. Resistances to the 12th century BC crisis in the Veneto region: the case studies of fondo paviani and montebello vicentino. In: Kneisel, J., Kirleis, W., Dal Corso, M., Taylor, N., Tiedtke, V. (Eds.), *Collapse or Continuity? Environment and Development of Bronze Age Human Landscapes. Proceedings of the International Workshop "Socio-Environmental Dynamics over the Last 12,000 Years: the Creation of Landscapes II (14th-18th March 2011)"* in Kiel. Verlag Dr. Rudolf Habelt GmbH, Bonn, pp. 55–70.
- Curina, R., Malnati, L., Manzelli, V., Rossi, F., Spagnolo Garzoli, G., Tirelli, M., 2015. La Cisalpina tra III e I secolo a.C. alla luce dell'archeologia. In: Malnati, L., Manzelli, V. (Eds.), *Brixia. Roma e le genti del Po*. Giunti, Florence, pp. 42–54.
- Davis, S., 1981. The effects of temperature change and domestication on the body size of Late Pleistocene to Holocene mammals of Israel. *Palaeobiology* 7, 101–114.
- De Franceschini, M., 2003. Le ville romane della X regio. *Venetia et Histria. Catalogo e carta archeologica dell'insediamento romano nel territorio, dall'età repubblicana al tardo impero*. L'Erma di Bretschneider, Rome.
- De Grossi Mazzorin, J., 2013. Considerazioni sullo sfruttamento animale in ambito terramaricolo. In: De Grossi Mazzorin, J., Curci, A., Giacobini, G. (Eds.), *Economia e ambiente nell'Italia padana nell'età del Bronzo. Le indagini bioarcheologiche*. Edipuglia, Bari, pp. 257–263.
- de Haas, T., 2017. Managing the marshes: an integrated study of the centuriated landscape of the Pontine plain. *J. Archaeol. Sci.: Report* 15, 470–481. <https://doi.org/10.1016/j.jasrep.2016.07.012>.
- Duval, C., Clavel, B., 2018. Bœufs gaulois et bœufs français: morphologies animales et dynamiques économiques au cours de La Tène et des périodes historiques. *Gallia* 75, 141–171. <https://doi.org/10.4000/gallia.3904>.
- Erdkamp, P., 2019. War, food, climate change, and the decline of the Roman Empire. *Journal of Late Antiquity* 12, 422–465. <https://doi.org/10.1353/jla.2019.0021>.
- Farello, P., 1995. L'Emilia dal VI e V secolo a.C.: caccia e allevamento, Atti del I° convegno nazionale di archeozoologia, Rovigo 5–7 marzo 1993. Centro Polesano di Studi Storici. Archeologici ed Etnografici, Rovigo, pp. 209–234.
- Fick, S.E., Hijmans, R.J., 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *Int. J. Climatol.* 37, 4302–4315. <https://doi.org/10.1002/joc.5086>.
- Fontana, A., Frassine, M., Ronchi, L., 2020. Geomorphological and geoarchaeological evidence of the medieval deluge in the tagliamento river (NE Italy). In: Herget, J., Fontana, A. (Eds.), *Palaeohydrology: Traces, Tracks and Trails of Extreme Events*. Springer International Publishing, Cham, pp. 97–116. https://doi.org/10.1007/978-3-030-23315-0_5.
- Forin, C., 2017. Ville e fattorie nell'Italia settentrionale in epoca romana (II sec. a.C. - V sec. d.C.): architettura, economia e società. University of Padova, Padova.
- Frey, O.-H., 1995. The celts in Italy. In: Green, M.J. (Ed.), *The Celtic World*. Routledge, London, pp. 515–532.
- Frisia, S., Borsato, A., Spötl, C., Villa, I.M., Cucchi, F., 2005. Climate variability in the SE Alps of Italy over the past 17 000 years reconstructed from a stalagmite record. *Boreas* 34, 445–455. <https://doi.org/10.1080/03009480500231336>.
- Fryirs, K.A., Brierley, G.J., Brierley, G.J., 2012. *Geomorphical Analysis of River Systems: an Approach to Reading the Landscape*. John Wiley & Sons, Chichester.
- Furlanetto, G., Ravazzi, C., Pini, R., Vallè, F., Brunetti, M., Comolli, R., Novellino, M.D., Garozzo, L., Maggi, V., 2018. Holocene vegetation history and quantitative climate reconstructions in a high-elevation oceanic district of the Italian Alps. Evidence for a middle to late Holocene precipitation increase. *Quat. Sci. Rev.* 200, 212–236. <https://doi.org/10.1016/j.quascirev.2018.10.001>.
- Gaaster, J.S., Vander Linden, M., 2018. Farming data: testing climatic and palaeoenvironmental effect on Neolithic Adriatic stockbreeding and hunting through zooarchaeological meta-analysis. *Holocene* 28, 1181–1196. <https://doi.org/10.1177/0959683618761543>.
- Gandini, G.C., Villa, E., 2003. Analysis of the cultural value of local livestock breeds: a methodology. *J. Anim. Breed. Genet.* 120, 1–11. <https://doi.org/10.1046/j.1439-0388.2003.00365.x>.
- Giraudi, C., 2009. Late Holocene glacial and periglacial evolution in the upper Orco Valley, northwestern Italian Alps. *Quat. Res.* 71, 1–8. <https://doi.org/10.1016/j.yqres.2008.08.004>.
- Govi, E., 2014. Etruscan urbanism at bologna, marzabotto and in the Po valley. In: Robinson, E.C. (Ed.), *Papers on Italian Urbanism in the First Millennium B.C.* Journal of Roman Archaeology, pp. 81–111. Portsmouth, Rhode Island.
- Haldon, J., Elton, H., Huebner, S.R., Izdebski, A., Mordechaj, L., Newfield, T.P., 2018. Plagues, climate change, and the end of an empire: a response to Kyle Harper's the Fate of Rome (1): Climate. *Hist. Compass* 16, e12508. <https://doi.org/10.1111/hic3.12508>.
- Halstead, P., 2014. *Two Oxen Ahead: Pre-mechanized Farming in the Mediterranean*. Wiley-Blackwell, Chichester.
- Hogan, J.P., Phillips, C.J.C., 2016. Starvation of ruminant livestock. In: Phillips, C.J.C. (Ed.), *Nutrition and the Welfare of Farm Animals*. Springer International Publishing, Cham, pp. 29–57. https://doi.org/10.1007/978-3-319-27356-3_3.
- Holzhauser, H., Magny, M., Zumbühl, H.J., 2005. Glacier and lake-level variations in west-central Europe over the last 3500 years. *Holocene* 15, 789–801. <https://doi.org/10.1191/0959683605hl853ra>.
- Huet, T., Nieto-Espinet, A., 2022. ZooWork (v1.0.0.0). <https://doi.org/10.5281/zenodo.6850736> [R package].
- Hunter, C.L., Millar, J., Lml Toribio, J.-A., 2022. More than meat: the role of pigs in Timorese culture and the household economy. *Int. J. Agric. Sustain.* 20, 184–198. <https://doi.org/10.1080/14735903.2021.1923285>.
- Hutchinson, S., 1992. The cattle of money and the cattle of girls among the Nuer, 1930–83. *Am. Ethnol.* 19, 294–316. <https://doi.org/10.1525/ae.1992.19.2.02a00060>.
- Ivanova, M., De Cupere, B., Ethier, J., Marinova, E., 2018. Pioneer farming in southeast Europe during the early sixth millennium BC: climate-related adaptations in the exploitation of plants and animals. *PLoS One* 13, e0197225. <https://doi.org/10.1371/journal.pone.0197225>.
- Jarvis, A., Reuter, H.I., Nelson, A., Guevara, E., 2008. Hole-filled SRTM for the globe Version 4, available from: the CGIAR-CSI SRTM 90m Database. <http://srtm.csi.cgiar.org>.
- Kassambara, A., 2021. Rstatix: pipe-friendly framework for basic statistical tests. R package version 0.7.0. <https://CRAN.R-project.org/package=rstatix>.
- King, A.C., 1999. Diet in the Roman world: a regional inter-site comparison of the mammal bones. *J. Rom. Archaeol.* 12, 168–202. <https://doi.org/10.1017/S1047759400017979>.
- Lê, S., Josse, J., Houson, F., 2008. FactoMineR: an R package for multivariate analysis. *J. Stat. Software* 25, 1–18. <https://doi.org/10.18637/jss.v025.i01>.
- Lyman, R.L., 2008. *Quantitative Palaeozoology*. Cambridge University Press, Cambridge.
- Macheridis, S., Magnell, O., 2020. Disentangling taphonomic histories at old uppsala, a late iron age central place in Sweden, using multiple correspondence analysis (MCA). *J. Archaeol. Sci.: Report* 33, 102536. <https://doi.org/10.1016/j.jasrep.2020.102536>.
- MacKinnon, M., 2004. Production and consumption of animals in roman Italy: integrating the zooarchaeological and textual evidence. *J. Rom. Archaeol.* (Portsmouth), Supplementary series, no. 54.
- MacKinnon, M., 2010. "Romanizing" ancient Carthage: evidence from zooarchaeological remains. In: Campana, D.V., Crabtree, P., deFrance, S.D. (Eds.), *Anthropological Approaches to Zooarchaeology: Colonialism, Complexity and Animal Transformations*. Oxbow Books, Oxford, pp. 168–177.
- Magny, M., Joannin, S., Galop, D., Vannièr, B., Haas, J.N., Bassetti, M., Bellintani, P., Scandolari, R., Desmet, M., 2012. Holocene palaeohydrological changes in the northern Mediterranean borderlands as reflected by the lake-level record of lake ledro, northeastern Italy. *Quat. Res.* 77, 382–396. <https://doi.org/10.1016/j.yqres.2012.01.005>.
- Manning, K., Downey, S.S., Colledge, S., Conolly, J., Stopp, B., Dobney, K., Shennan, S., 2013. The origins and spread of stock-keeping: the role of cultural and environmental influences on early Neolithic animal exploitation in Europe. *Antiquity* 87, 1046–1059. <https://doi.org/10.1017/S0003598X00049851>.
- Marazzi, F., 1997. The destinies of the Late Antique Italies: politico-economic developments of the sixth century. In: Hodges, R., Bowden, W. (Eds.), *The Sixth Century. Production, Distribution and Demand*. Brill, Leiden, pp. 119–159.
- Marchetti, M., 2002. Environmental changes in the central Po Plain (northern Italy) due to fluvial modifications and anthropogenic activities. *Geomorphology* 44, 361–373. [https://doi.org/10.1016/S0169-555X\(01\)00183-0](https://doi.org/10.1016/S0169-555X(01)00183-0).

- Matteazzi, M., 2017. All the roads to Patavium: morphology, genesis and development of the Roman road network around Padua. *Open Archaeol.* 3, 83–100. <https://doi.org/10.1515/opar-2017-0005>.
- McConnell, J.R., Sigl, M., Plunkett, G., Burke, A., Kim, W.M., Raible, C.C., Wilson, A.I., Manning, J.G., Ludlow, F., Chellman, N.J., Innes, H.M., Yang, Z., Larsen, J.F., Schaefer, J.R., Kipfstuhl, S., Mojtabavi, S., Wilhelms, F., Opel, T., Meyer, H., Steffensen, J.P., 2020. Extreme climate after massive eruption of Alaska's Okmok volcano in 43 BCE and effects on the late Roman Republic and Ptolemaic Kingdom. *Proc. Natl. Acad. Sci. USA* 117, 15443. <https://doi.org/10.1073/pnas.2002722117>.
- McInerney, J., 2010. *The Cattle of the Sun: Cows and Culture in the World of the Ancient Greeks*. Princeton University Press, Princeton.
- Meadow, R., 1999. The use of size index scaling techniques for research on archaeozoological collections from the Middle East. In: Becker, C., Manhart, H., Peters, J., Schibler, J. (Eds.), *Historia Animalium ex Ossibus. Festschrift für Angela von den Driesch*. Verlag Marie Leidorf GmbH, Rahden/Westf., pp. 285–300.
- Meiri, S., 2011. Bergmann's Rule – what's in a name? *Global Ecol. Biogeogr.* 20, 203–207. <https://doi.org/10.1111/j.1466-8238.2010.00577.x>.
- Mercuri, A.M., 2014. Genesis and evolution of the cultural landscape in central Mediterranean: the 'where, when and how' through the palynological approach. *Landscape Ecol.* 29, 1799–1810. <https://doi.org/10.1007/s10980-014-0093-0>.
- Mercuri, A.M., Mazzanti, M.B., Torri, P., Vigliotti, L., Bosi, G., Florenzano, A., Olmi, L., N'siala, I.M., 2012. A marine/terrestrial integration for mid-late Holocene vegetation history and the development of the cultural landscape in the Po valley as a result of human impact and climate change. *Veg. Hist. Archaeobotany* 21, 353–372. <https://doi.org/10.1007/s00334-012-0352-4>.
- Mihovilić, K., 2013. Castellieri-gradine of the northern adriatic. In: Harding, A., Fokkens, H. (Eds.), *The Oxford Handbook of the European Bronze Age*. Oxford University Press, Oxford, pp. 863–876.
- Nieto-Espinete, A., 2018. Element Measure Standard Biometrical Data from a Cow Dated to the Early Bronze Age (Minferri, Catalonia) [digital Resource]. <https://doi.org/10.13140/RG.2.2.13512.78081>.
- Nieto-Espinete, A., Huet, T., Trentacoste, A., Guimarães, S., Orenco, H., Valenzuela-Lamas, S., 2021. Resilience and livestock adaptations to demographic growth and technological change: a diachronic perspective from the Late Bronze Age to Late Antiquity in NE Iberia. *PLoS One* 16, e0246201. <https://doi.org/10.1371/journal.pone.0246201>.
- Orton, C., 2004. Point pattern revisited. In: Moscati, P. (Ed.), *New Frontiers of Archaeological Research. Languages, Communication, Information Technology*, vol. 15. *Archeologia e Calcolatori*, pp. 299–315.
- Orton, D., Gaastra, J., Vander Linden, M., 2016. Between the Danube and the deep blue Sea: zooarchaeological meta-analysis reveals variability in the spread and development of Neolithic farming across the Western Balkans. *Open Quat.* 2 <https://doi.org/10.5334/oq.28>.
- Petrucchi, G., 2007. Sfruttamento della fauna nel territorio di Aquileia: trasformazione, consumo e distribuzione dei prodotti. I dati dell'archeozoologia. In: Cusico, G., Zaccaria, C. (Eds.), *Aquileia dalle origini alla costituzione del ducato longobardo: storia, amministrazione, società*. Atti della XXXIII Settimana di studi aquileiesi, 25–27 aprile 2002. Editreg, Trieste, pp. 755–782.
- Peyron, O., Goring, S., Dormoy, I., Kotthoff, U., Pross, J., de Beaulieu, J.-L., Drescher-Schneider, R., Vannière, B., Magny, M., 2011. Holocene seasonality changes in the central Mediterranean region reconstructed from the pollen sequences of Lake Accesa (Italy) and Tenaghi Philippon (Greece). *Holocene* 21, 131–146. <https://doi.org/10.1177/0959683610384162>.
- Pozo, J.M., Trentacoste, A., Nieto-Espinete, A., Guimarães, S., Valenzuela-Lamas, S., 2022. *zoolog* R package: Zooarchaeological analysis with log-ratios. *Quat. Int.* in press <https://doi.org/10.1016/j.quaint.2022.11.006>.
- Pozo, J.M., Valenzuela Lamas, S., Trentacoste, A., Nieto Espinete, A., Guimarães Chiarelli, S., 2021. *zoolog*: zooarchaeological analysis with log-ratios. <https://github.com/josempozo/zoolog>. Version 0.4.1.
- R Core Team, 2020. R: a language and environment for statistical computing. Vienna. <https://www.R-project.org/>. Version 4.0.3.
- Ravazzi, C., Marchetti, M., Zanon, M., Perego, R., Quirino, T., Deaddis, M., De Amicis, M., Margaritora, D., 2013. Lake evolution and landscape history in the lower Mincio River valley, unravelling drainage changes in the central Po Plain (N-Italy) since the Bronze Age. *Quat. Int.* 288, 195–205. <https://doi.org/10.1016/j.quaint.2011.11.031>.
- Riedel, A., 1994a. Archeozoological investigations in north-eastern Italy: the exploitation of animals since the Neolithic. *Preistoria Alp.* 30, 43–94.
- Riedel, A., 1994b. Roman animal bones from the area near the Forum of Aquileia. In: Verzar-Bass, M. (Ed.), *Scavi ad Aquileia I. L'area a Est del Foro. Rapporto degli Scavi 1989-91*. Quasar, pp. 583–591. Roma.
- Roberts, N., Brayshaw, D., Kuzucuoğlu, C., Perez, R., Sadori, L., 2011. The mid-Holocene climatic transition in the Mediterranean: causes and consequences. *Holocene* 21, 3–13. <https://doi.org/10.1177/0959683610388058>.
- Roncaglia, C.E., 2018. *Northern Italy in the Roman World: from the Bronze Age to Late Antiquity*. John Hopkins University Press, Baltimore.
- Rubel, F., Brugger, K., Haslinger, K.I.A., 2017. The climate of the European Alps: shift of very high resolution Köppen–Geiger climate zones 1800–2100. *Meteorol. Z.* 26, 115–125. <https://doi.org/10.1127/metz/2016/0816>.
- Russell, N., 2012. *Social Zooarchaeology: Humans and Animals in Prehistory*. Cambridge University Press, Cambridge.
- Sabatini, S., 2020. Modelling Bronze Age sheepherding and wool production: the case of the Terramara settlement at Montale, Italy. *Prähistorische Z.* 95, 187–204. <https://doi.org/10.1515/pz-2020-0005>.
- Scholz, D., Frisia, S., Borsato, A., Spötl, C., Fohlmeister, J., Mudelsee, M., Miorandi, R., Mangini, A., 2012. Holocene climate variability in north-eastern Italy: potential influence of the NAO and solar activity recorded by speleothem data. *Clim. Past* 8, 1367–1383. <https://doi.org/10.5194/cp-8-1367-2012>.
- Sfameni, C., 2004. Residential villas in Late Antique Italy: continuity and change. In: Bowden, W., Lavan, L., Machado, C. (Eds.), *Recent Research on the Late Antique Countryside*. Brill, Leiden, pp. 333–375. <https://doi.org/10.1163/22134522-90000029>.
- Slim, F.G., Çakırlar, C., 2022. Pigs and politics in iron age and roman anatolia: an interregional zooarchaeological analysis. *Quat. Int.* <https://doi.org/10.1016/j.quaint.2022.05.013>.
- Smith, C., 2017. J.B. Ward-Perkins, the BSR and the landscape tradition in post-war Italian archaeology. *Papers of the British School at Rome* 86, 271–292. <https://doi.org/10.1017/S006824621700037X>.
- Sullivan, A.P., Bird, D.W., Perry, G.H., 2017. Human behaviour as a long-term ecological driver of non-human evolution. *Nature ecology & evolution* 1, 0065. <https://doi.org/10.1038/s41559-016-0065>.
- Tinner, W., Lotter, A.F., Ammann, B., Conedera, M., Hubschmid, P., van Leeuwen, J.F.N., Wehrli, M., 2003. Climatic change and contemporaneous land-use phases north and south of the Alps 2300 BC to 800 AD. *Quat. Sci. Rev.* 22, 1447–1460. [https://doi.org/10.1016/S0277-3791\(03\)00083-0](https://doi.org/10.1016/S0277-3791(03)00083-0).
- Trentacoste, A., 2016. Etruscan foodways and demographic demands: contextualizing protohistoric livestock husbandry in Northern Italy. *Eur. J. Archaeol.* 19, 279–315. <https://doi.org/10.1179/1461957115X.0000000015>.
- Trentacoste, A., Nieto-Espinete, A., Guimarães, S., Wilkens, B., Petrucci, G., Valenzuela-Lamas, S., 2021. New trajectories or accelerating change? Zooarchaeological evidence for Roman transformation of animal husbandry in Northern Italy. *Archaeological and Anthropological Sciences* 13, 25. <https://doi.org/10.1007/s12520-020-01251-7>.
- Trentacoste, A., Nieto-Espinete, A., Valenzuela-Lamas, S., 2018. Pre-Roman improvements to agricultural production: evidence from livestock husbandry in late prehistoric Italy. *PLoS One* 13, e0208109. <https://doi.org/10.1371/journal.pone.0208109>.
- Vaiglova, P., Hartman, G., Marom, N., Ayalon, A., Bar-Matthews, M., Zilberman, T., Yasur, G., Buckley, M., Bernstein, R., Tepper, Y., Weissbrod, L., Erickson-Gini, T., Bar-Oz, G., 2020. Climate stability and societal decline on the margins of the Byzantine empire in the Negev Desert. *Sci. Rep.* 10, 1512. <https://doi.org/10.1038/s41598-020-58360-5>.
- Valenzuela-Lamas, S., 2020. Circulación de animales en Iberia durante la Prehistoria reciente y la época clásica: métodos de análisis, primeros datos y retos de futuro. *Pyrenae* 51, 7–27.
- Valenzuela-Lamas, S., Albarella, U., 2017. Animal husbandry in the western roman empire: a zooarchaeological perspective. *Eur. J. Archaeol.* vol. 20 <https://doi.org/10.1017/ea.2017.22>. Special Issue 3, 07/17 Cambridge University Press.
- Valsecchi, V., Tinner, W., Finsinger, W., Ammann, B., 2006. Human impact during the Bronze age on the vegetation at lago Lucone (northern Italy). *Veg. Hist. Archaeobotany* 15, 99–113. <https://doi.org/10.1007/s00334-005-0026-6>.
- Veenman, F.A., 2002. *Reconstructing the Pasture. A Reconstruction of Pastoral Landuse in Italy in the First Millennium BC*. Vrije Universiteit Amsterdam, Amsterdam.
- Vicenzutto, D., 2015. L'età del bronzo in Italia settentrionale. In: Tasca, G., Putzolu, C., Vicenzutto, D. (Eds.), *Un castelliere nel medio Friuli. Gradisce di Codroipo, 2004–2014*. IPAC, Pasian di Prato, pp. 16–45.
- Weaver, M.E., Ingram, D.L., 1969. Morphological changes in swine associated with environmental temperature. *Ecology* 50, 710–713. <https://doi.org/10.2307/1936264>.
- Wilkens, B., 1997. La faune du site romain de Calvatone, Cremona (Italie). *Anthropozoologica* 25–26, 611–616.
- Zanchetta, G., Bini, M., Bloomfield, K., Izdebski, A., Vivoli, N., Regattieri, E., Isola, I., Drysdale, R.N., Bajo, P., Hellstrom, J.C., Wiśniewski, R., Fallick, A.E., Natali, S., Luppichini, M., 2021. Beyond one-way determinism: san Frediano's miracle and climate change in Central and Northern Italy in late antiquity. *Climatic Change* 165, 25. <https://doi.org/10.1007/s10584-021-03043-x>.
- Zanchetta, G., Regattieri, E., Isola, I., Drysdale, R.N., Bini, M., Baneschi, I., Hellstrom, J.C., 2016. The so-called "4.2 event" in the central Mediterranean and its climatic teleconnections. *Alpine and Mediterranean Quaternary* 29, 5–17.
- Zanchettin, D., Traverso, P., Tomasino, M., 2008. Po River discharges: a preliminary analysis of a 200-year time series. *Climatic Change* 89, 411–433. <https://doi.org/10.1007/s10584-008-9395-z>.
- Zohary, D., Tchernov, E., Horwitz, L., 1988. The role of unconscious selection in the domestication of sheep and goats. *J. Zool.* 245, 129–135. <https://doi.org/10.1111/j.1469-7998.1998.tb00082.x>.