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Human-cattle interactions in PPNB and Early-Middle Bronze Age Cyprus: Integrating zooarchaeological and stable isotope data

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Abstract

Cattle domestication and subsequent spread caused unprecedented biological, economic, ecological and social transformations in human history. Cyprus was one of the first places domestic taurine cattle were transported to outside of their core domestication region, making it a “hotspot” in which to investigate cattle acclimatisation and management practices. Accumulated archaeological, iconographic and zooarchaeological evidence has shed much light on the economic and socio-ideological significance of cattle in prehistoric Cypriot society, particularly from the Early Bronze Age onwards. However, little information exists on the mechanisms through which prehistoric cattle breeders experimented with this new, large, multifunctional and symbolically potent animal. Here, we use an integrated approach that combines zooarchaeological and stable isotopic data to reconstruct human-cattle interactions and cattle management in an island context. Stable carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) isotopes were applied to a small sample (n = 16) of cattle and caprine teeth from three key sites**,** including the Pre Pottery Neolithic B, when cattle were first introduced on the island, and the Early-Middle Cypriot Bronze Age, when cattle re-appeared on the island after three millennia of absence. We identified differences in patterns of isotopic variation between Bronze Age caprine and cattle, likely reflecting differences in mobility and the more intensive management of cattle (i.e. foddering). Additionally, we observe differences in the isotope values of cattle through time (Neolithic vs. Bronze Age) and therefore provide new data on animal management during key periods in Cypriot prehistory.

1. Introduction

Since their domestication during the Neolithic, cattle have been among the most important livestock species (Felius et al. 2014), providing humans with a package of animal products, including meat, blood, skin and a sustainable milk supply. Taking advantage of their muscle power and size, prehistoric societies also used cattle as agricultural “engines” and means of transportation (Arbuckle and Makarewicz 2009: 669; Gaastra et al. 2018; Greenfield 2010) and adored them as symbols of wealth, power and fertility. Cyprus was among the first places to receive domestic cattle from the Near East during the Pre-Pottery Neolithic B period (PPNB; Vigne et al. 2014) and the only Mediterranean island that experienced the disappearance of cattle by the Late Neolithic, roughly two thousand years after their first introduction (Croft 2003). Even though much is known today about the symbolic and socioideological significance of cattle and oxen in Bronze Age Cyprus (for an overview see: Webb 2017), the processes by which these large and multifunctional animals were incorporated into early Neolithic and Early/Middle Bronze Age subsistence economy and society need to be further explored. Traditional zooarchaeological approaches, including biometric, demographic, and palaeopathological studies can shed much light on the way prehistoric cattle breeders were interacting with their livestock. However, there are certain aspects of human-animal interactions, including diet and mobility, which cannot be reconstructed through traditional zooarchaeological approaches alone. During the last decade, biochemical approaches, namely stable isotope analyses of cattle bone and teeth have enhanced our understanding regarding the emergence of cattle dairying practices (Balasse et al. 2021; Gillis et al. 2013; Kamjan et al. 2020), birth seasonality (Balasse et al. 2021; Groot et al. 2021), winter foddering, and herding (Balasse et al. 2012), and revealed the role of cattle in large-scale feasting events (Vaiglova et al. 2018). The majority of these studies, however, focus on northern and central Europe while little information exists for the Mediterranean (but see: Vaiglova et al. 2018). Here, we apply stable carbon (δ13C) and oxygen (δ18O) isotope analysis to 16 teeth belonging to cattle (Bos sp.) and goat (Capra hircus) from three key sites, dating to the PPNB and Early– Middle Bronze Age, to study aspects of cattle management practices in this Mediterranean island context. In doing so we hope to fill a significant gap in the study of prehistoric cattle management practices, with wider ramifications for economic and social transformations. The main research questions that this study seeks to address are: 1. How did livestock management practices differ between the PPNB and Early/Middle Bronze Age periods? 2. How did livestock management practices differ between sites and why? 3. How did management practices differ between small (caprine) and large livestock (cattle)? 4. To what extent did the physical landscape shape animal management strategies in prehistoric Cyprus? We seek to integrate existing zooarchaeological and novel stable isotope data in order to provide a better understanding of human-cattle interactions in prehistoric Cyprus and to add to the expanding datasets of stable isotope studies available for prehistoric Cyprus (DiBenedetto 2010; Hadjikoumis 2019; Pilaar Birch et al. 2022; Scire-Calabrisotto et al. 2020).

2. Archaeological Background

Human-cattle interactions in PPNB- Early/Middle Bronze Age Cyprus

As a typical oceanic island, Cyprus has never been connected or land bridged to any of the surrounding continents, at least for the last 14,000 years (Henson *et al*. 1949; Held 1989; Vigne et al. 2014: 159). As a result of its geological evolution, the island has been a hotspot for palaeontological and zooarchaeological research. All of the main, economically-significant domestic and wild animal species utilised by humans, including standing weaned calves (Vigne *et al.* 2014: 157), were deliberately transported to Cyprus by humans on open rafts or dugout canoes (Knapp 2020: 421; Vigne *et al.* 2014: 167-171). The early introduction of cattle during the 8th millennium cal BC (Vigne *et al*. 2014: 165) demonstrates advanced management of these large animals by early farmers and highlights the seafaring capabilities of the Neolithic colonists.

On Cyprus, taurine cattle appear briefly at three early aceramic or Pre Pottery Neolithic (hereafter PPNB) sites: Parekklisia *Shillourokambos* (Guilaine *et al.* 2011) in the southern part of the island, Akanthou *Arkosykos* (Sevketoglu 2002) on the north coast, and Kritou Marottou *Ais Giorkis* (Simmons *et al.* 2018) in the western uplands (**Figure 1**). These remains are among the earliest known evidence of domesticated cattle in the Eastern Mediterranean and the Near East. On the mainland, cattle are found at PPNB Halula in Syria (7700–7600 cal BC), at Tel Aswad (8000 cal BC), and at Dja'de (8400 cal BC; Helmer *et al.* 2009; Helmer and Gourichon 2008:136–141) and are roughly contemporary with the Cypriot sites. Bone measurements taken from the *Shillourokambos* and *Ais Giorkis* cattle bones respectively show that the original cattle lineage, appearing first at *Shillourokambos*, may have been replaced with a new lineage which persisted until its extinction (Vigne 2011). Cyprus is the only Eastern Mediterranean island to have experienced the disappearance of a large terrestrial mammal, for reasons unknown. Several hypotheses have been proposed with researchers emphasising functional, economic (Davis 2003; Horwitz *et al.* 2004: 39), ecological (Simmons 2009: 6; Wasse 2007: 61) or even ideological reasons (Ronen 1995, Simmons 2009).

Studies of cattle biology have shown that taurine cattle require more forage and surface water than sheep and goat (Miller and Marston 2012: 99), since the latter are better adapted to withstand dehydration. In contrast to its sister subspecies, *Bos indicus or* zebu cattle, *Bos taurus* has restricted thermotolerance (Hansen 2004) and at temperatures above 26°C, the animals will go into heat stress, resulting in a decrease in food consumption and milk production, and eventual death (Ekesbo 2011: 69). While it is impossible to estimate the exact number of cattle during the early Aceramic Neolithic, the relatively low numbers of cattle bones recovered from these early sites suggest that the cattle population on the island was small, meaning less genetic diversity (Lande 1988). The small, isolated populations of cattle on the island, separated from sources of replenishment, would have probably been at the mercy of occasional catastrophes, including climatic extremes. Although further research on the topic is required, it is possible that the disappearance of cattle by the later Aceramic Neolithic may have been related to the fact that taurine cattle were not well-suited to the hot and arid environments of Cyprus (Spyrou 2021: 163).

Cattle re-emerged during the mid-third millennium BC alongside a series of radical changes in material culture, economy, technology and society (see summaries of the various aspects in: Knapp 2013: 260-177). This period, known as the Philia cultural facies (*c.* 2500–2200 BC; Webb and Frankel 1999), encompasses the transition from the Late Chalcolithic to the Early Bronze Age. The most significant innovations of the period include the first systematic exploitation of Cypriot copper ore (Kassianidou 2013), a shift from single-celled circular houses to multi-roomed rectilinear dwellings (Crewe 2015; Webb and Frankel 1999), the appearance of chamber tombs and extramural cemeteries (Frankel and Webb 2006), new textile technologies (Webb 2013) and the appearance of the distinctive Red polished pottery tradition (Webb and Frankel 1999, 2007). There is an ongoing debate to what extent external influences, including the arrival of migrant populations from south-western Anatolia or Cilicia (Dikaios 1962: 202–3; Frankel *et al*. 1995; Webb & Frankel 1999; Webb & Frankel 2007; Webb 2002, 2013) or indigenous/local processes (Knapp 1990) transformed Cypriot lifeways during this important period. Others have suggested that some of these key changes in material culture occurred earlier, during the Late Chalcolithic period, and were a combination of both external influences and local developments (Bolger 2013; Peltenburg 2007). Along with the re-establishment of cattle, the newcomers brought equids as well as a new species of screw-horned goats (Croft 2006).

The most fundamental shift in agricultural technologies was the introduction of cattle-plough farming (Knapp 1990:157), which provided the means for agricultural extensification (Lucas and Fuller 2020) impacting not only diet but also the nature of interactions with the landscape (Crewe 2015: 136). As multifunctional and multipurpose animals, cattle (and oxen) played a foundational role in surplus-producing Bronze Age agricultural systems (Knapp 1990: 156), providing traction for ploughing and dung for fertilising the fields and provisioning settlements with a wide range of animal products for both subsistence and craft activities (Zeder 1991; Nissen, Damerow and Englund 1993; Damerow 1996; Wilkinson 1989; Sherratt 1983; Halstead 1995). Even though direct evidence for penning, in the form of structures or enclosures is currently lacking for Bronze Age Cyprus, indirect evidence is provided by stable isotope studies (Pilaar Birch *et al.* 2022:9), while the collection and use of animal dung as fuel has also been suggested through palaeobotanical analysis (see: Lucas 2012: 179-180). The major investment in cattle-keeping practices would have also strengthened the animals' social importance with cattle becoming a medium to growing political centralisation (Keswani 1994: 269) and cultural iconography, especially from the Early Bronze Age onwards (Knox 2013: 50; Webb and Frankel 2001; Webb 2017). Maintaining both the economic and social benefits derived from cattle necessitated increased human influence on cattle mortality, mobility and feeding schedules. In order to explore changing aspects of cattle management practices in the island context of Cyprus we now turn to stable isotope approaches to examine how cattle may inform on wider questions of economic and social transformation.

3. Stable carbon and oxygen isotopic studies

Applications of stable isotope analysis in zooarchaeology are numerous and have substantially progressed over the past decade, offering a systematic approach to mapping a wide range of activities relevant to animal management, including domestication, pastoral mobility, transhumance, foddering practices, water sources and vegetation composition (e.g. Balasse 2002; 2003; Lee-Thorp 2008; Makarewicz 2018). Zooarchaeological and stable isotopic approaches, when employed simultaneously, can provide insights into human-animal interaction that would have been undetectable to either technique applied in isolation (Makarewicz 2016: 190). Until recently, only a handful of stable isotopic studies have been undertaken on animal bones and teeth from archaeological sites in Cyprus, with the majority focusing on the Neolithic period (DiBenedetto 2018; Hadjikoumis 2017, 2018; Hadjikoumis *et al.* 2019; but see: Scire-Calabrisotto *et al.* 2020; Pilaar Birch *et al.* 2022). However, given that it represents a period of major social and economic developments, accompanied by human migrations, technological innovations and new animal introductions discussed above, the Cypriot Bronze Age provides an important point of comparison to these earlier Neolithic records.

$\delta^{13}C$ values of herbivore tooth bioapatite are determined by the $\delta^{13}C$ values of ingested plants (Ambrose and Norr 1993; Lee-Thorp *et al.* 1989). On the basis of their photosynthetic pathway, the majority of plants can be divided into C_3 and C_4 plants. C_3 and C_4 plants respond differently to changes in atmospheric carbon dioxide concentration and changes in temperature and water availability. On Cyprus, the majority of economically important and edible C_3 plants include cereal and crop species such as wheat, barley and lentils and have $\delta^{13}C$ values ranging from -20 to -37‰, with an average of c. -27‰ (Cerling *et al.* 1997). C_4 plants include cereals like sorghum, millet and maize, sugar cane and arid-adapted grasses and have $\delta^{13}C$ values ranging from -9 to -17‰, with an average around -12‰ (Cerling *et al.* 1997). In modern semi-arid and arid environments receiving less than 500 mm of rainfall per year, terrestrial C_3 plants have been shown to yield higher $\delta^{13}C$ values up to about –21‰ (Kohn, 2010;

Hartman and Danin, 2010). In addition, controlled animal feeding studies have reported a $\delta^{13}C$ enamel-diet offset of approximately 15‰ for cattle (Passey *et al.* 2005), so we would therefore predict herbivores with a predominantly C_3-based diet to have $\delta^{13}C$ values (enamel) of around -12‰, while an animal with a predominantly C_4 diet should have values of around 0‰ (Lee-Thorp et al., 1989; Levin et al., 2008).

Subtle differences in $\delta^{13}C$ values of plants can be detected in the tissues of higher trophic-level consumers that form incrementally over the course of an annual cycle (Vaiglova *et al*. 2018: 7). These intra-annual variations can be used to assess the seasonal or inter-annual dietary and mobility patterns of animals (Bocherens *et al*. 2001; Balasse 2002). Large $\delta^{13}C$ ranges can only be attributed to large variations in the local plants, soil and in the animals themselves. It could also imply that animals were moved across a landscape that varies isotopically (Pearson *et al*. 2007). In both contemporary and pre-industrial times, Cyprus was characterised by a C_3-dominated biomass (Fall 2012; Lucas 2014). Several archaeobotanical studies conducted on different prehistoric sites on the island (e.g. Lucas 2014; Willcox 2003) confirmed the dominance of C_3 plant species, such as wheat, barley, oats and legumes while economically important C_4 plants (e.g. millet) seem to be uncommon (Fall 2012; Lucas 2014). However, arid-adapted C_4 plant species such as the wild amaranth (*Amaranthus graecizans*) and foxtail millet (*Setaria italica*) are quite common on the island today (Savvides 2000), with the latter being identified in several Neolithic and Chalcolithic archaeobotanical assemblages (Lucas 2014). Additional factor, which should be considered when studying the distribution of $\delta^{13}C$ values is the "pre-weaning effect" and post-weaning dietary changes that are visible along cattle first molars (Towers *et al.* 2014). As prior to weaning, mother and calf occupy two different trophic levels, M1 enamel $\delta^{13}C$ values are expected to reflect a progressive enrichment in ^{13}C, due to rumen development. For the current study, we mostly included cattle second and third molars (the only exception was M8, see below).

$\delta^{18}O$ values are well-suited to archaeological questions relating to calving season (Balasse *et al*. 2021), mobility and herding ecology. $\delta^{18}O$ values of tooth enamel are determined largely by the $\delta^{18}O$ values of ingested water, including plant water, drinking water, inspired air and water in food (Ayliffe and Chivas, 1990). As meteoric waters are influenced by a combination of environmental inputs (see: Clark and Fritz, 1997), $\delta^{18}O$ values in animal tissues can potentially delineate patterns of movement in environments characterised by high $\delta^{18}O$ variability (Makarewicz and Sealy 2015: 153). In middle and high latitudes, a key factor is ambient temperature and its seasonal variations leading to higher $\delta^{18}O$ values in warmer, and lower in cooler, periods of the year (Rozanski *et al.* 1993). Cyprus is characterised by a Mediterranean-type climate, with short and cold winters and long dry summers. In such a climatic context, the $\delta^{18}O$ of precipitation fluctuates predictably, exhibiting higher $\delta^{18}O$ values in the dry/warm summers and lower $\delta^{18}O$ values in the cold/wet winters (Vaiglova *et al*. 2018: 7). Shifts in the sequential isotopic values of $\delta^{18}O$ and $\delta^{13}C$ of cattle and caprine molars may therefore be used to explore changing patterns of mobility at different points of intra-annual and inter-annual management practices (Balasse 2002; Balasse *et al.* 2013).

3. Materials And Methods

The 16 analysed teeth of *Bos sp*. and Capra *hircus* derive from three open-air sites (**Table 1**) dating to the PPNB, Philia and Early–Middle Bronze Age periods. A short description of the sites is provided below.

3.1. The sites

3.1.1 Kritou Marottou -*Ais Giorkis* (PPNB)

Kritou Marottou *Ais Giorkis* (hereafter AG) is a PPNB site, located in the foothills of the Troodos Mountains in western Cyprus overlooking the Ezousas River. It differs significantly from all other Cypro-PPNB sites because of its upland location (Simmons *et al*. 2018: 171). Radiocarbon dates place occupation within the Middle Cypro-PPNB, ca. 7900–7500 cal. BC. AG is characterised by a rich material culture, with several exotic items including obsidian bladelets, several picrolite and other ornamental objects and a rich chipped stone assemblage. Zooarchaeological studies at the site are ongoing and a large number of animal bones has been retrieved and recorded by Paul Croft (Croft 2015). Over 21,600 pieces of mammalian bone have been identified, with deer (Dama *mesopotamica*; 54.5%) and pig (Sus *scrofa/domesticus*; 26.7%) dominating the assemblage. Domestic caprines are less numerous (16.4%), while domestic cattle (*Bos taurus*) contribute modestly to the sample (1.8%) (Croft 2003; Simmons 2010, 2012). The function of the site is not yet clearly understood (Simmons 2012:1), but it is unlikely it was occupied year-round.   However, the presence of structures, the abundance of the material culture and fauna in combination with the exotic artifacts found at the site (e.g. two carnelian beads; Moutsiou and Kassianidou 2019) suggests fairly intense, if potentially seasonal, habitation (Simmons *et al.* 2018:379). Archaeobotanical analyses show an abundance of two-grained einkorn while *T. diococcum* is completely absent (Lucas 2014). A recent isotopic study focusing on early Neolithic land use practices (DiBenedetto 2015: 262), using bone collagen to examine $\delta^{13}C$ and $\delta^{15}N$ isotopic signatures, demonstrated that cattle were most probably kept at or near the settlement and shared very similar pastures with at least some of the domestic caprine at the site (Di Benedetto 2018: 262).

3.1.2. Kissonerga *Skalia (Early-Middle Bronze Age)*

Kissonerga *Skalia* (hereafter KS)is an Early/Middle Bronze Age coastal site in the west of the island (**Figure 1**). The site was founded during the transitional period of Late Chalcolithic to the Early Bronze Age (*c.* 2500 BC) and has yielded evidence of terrestrial (cattle, deer, sheep/goat, pig) and marine (crab and shellfish) animal exploitation, and some well-preserved botanical remains, including grape and lentil (Lucas 2014). While not yet completed, zooarchaeological analysis shows that cattle played a significant role in the economy of the KS settlement, representing 22% of the identified mammals (Croft *pers. comm*). Cattle seem also to have played an important symbolic role at the site, with a deliberately damaged cattle figurine deposited in the base of a pyrotechnical feature (Crewe 2015), and a pit filled with five shaped cattle skulls associated with the construction of the industrial complex (Crewe and Souter forthcoming).

3.1.3. Marki *Alonia* (Philia to Early/Middle Bronze Age)

Marki *Alonia* (hereafter MA) was occupied from the Philia facies of the Early Bronze Age to the Middle Bronze Age and is the most extensively excavated Cypriot settlement of this period (Frankel and Webb 2012: 475), with its faunal assemblages being fully studied and published (Croft 2006). Despite the distinct predominance of domestic caprine at the site, Croft (2000: 271), based on bone weights rather than counts, argues that cattle represented the most important and productive livestock species within the Bronze Age economy at Marki, providing more meat, milk, traction and dung than all other species combined. Patterns of cattle mortality, based on epiphyseal fusion of long bones, suggest that only a small proportion (2-5%) died as infants, prior to about 1.5 years of age, and a further 11-20% died between about 1.5 and 2-3 years of age, as juveniles. In the later age stages mortality was more variable, with the majority of cattle having been culled as subadults (2-3 to 3.5-4 years), and about half living on into adulthood (<3.5-4 years). This harvest profile shows an emphasis on mature animals (>24 months), a rather conservative management plan linked to the growing importance of animals in agricultural labour and their potential use as beasts of burden (see Grigson 1995). Kill-off patterns might also highlight the significance of cattle as a form of social capital and mobile wealth, which should not be immediately expended and consumed but rather preserved and increased to be exchanged, including for smaller stock, grain and, potentially, in the context of bridewealth transactions (Russel 1998; Russel 2012: 308-309).

Beyond their purely economic importance, domestic cattle played a fundamental role in the cultural/symbolic life of the settlement, as suggested by the recovery of a number of small, solid, freestanding cattle figurines, the majority of which (60%) show evidence of deliberate exposure to fire prior to deposition (Webb and Frankel 2001). A recent stable isotopic study (Scire-Calabrisotto *et al*. 2020), focusing on animal diet during the Early/Middle Cypriot Bronze Ages, highlights the possibility that some of the MA cattle were kept in the vicinity of the settlement and probably foddered by humans with crop by-products (Scire-Calabrisotto *et al*. 2020). Aiming to further test this hypothesis and compare the MA data with other sites of the same period as well as earlier Neolithic material, we sampled several well-preserved cattle teeth. The choice of tooth enamel over bone collagen was related to thepreservation longevity of the former, making it an ideal candidate for stable isotope work in zooarchaeology (Lee-Thorp 2008), especially for areas where bone preservation is not ideal.

3.2. Stable Isotopic Analysis

Incremental samples of tooth enamel from molar crowns were obtained from *Bos sp*. (n = 13) and *Capra hircus* (n = 3). For cattle, the following periods of life were captured by enamel sampling: 1.4-3.5 years of age (M2) and 1.4-3.5 years of age (M3). Where possible, M2/M3s were preferentially sampled although there was one exception, sample MA8. For this individual an M1 was analysed. In cattle, the crown of M2 forms at 1-13 months old while the crown for M3 at 9-24 months (Brown *et al.* 1960; Towers *et al.* 2013). We also sampled goat M2s and M3s representing 1.4-2.4 years of age and 2-3 years of age, respectively.Sample selection for each site was determined by the length of the tooth crown and the overall preservation of different dental elements while also including individuals from all occupational horizons. Ages of the individuals were estimated from tooth eruption and wear following Payne (1973) for domestic caprine and an adaptation of Payne's method for cattle (Halstead 1985; Jones and Sadler 2012). Individuals ranged in age between older juveniles and adults (**see Table 1**).

Enamel surfaces were cleaned with a laboratory sandblaster (using aluminium oxide as the abrasive) and powdered enamel samples weighing 5–10mg were taken approximately every 2-3mm along the growth axis on the buccal side of each tooth, starting at the cusp and ending at the enamel root junction (ERJ), following procedures outlined in Balasse (2012) and Ventresca-Miller *et al*. (2019). Horizontal bands were drilled perpendicular to the growth axis, and each sample resulted in a 1-2mm wide groove through the thickness of the enamel layer. The tooth crown heights of the teeth ranged between 42–61mm for *Bos sp*. and 26–32mm for *Capra hircus*. Depending on the length of the tooth, 8–12 samples were taken, starting from the crown and continuing to the enamel root junction (ERJ). All necessary permits were obtained from the Department of Antiquities, Republic of Cyprus, for the described study, complying with all relevant regulations.

The sampled enamel powder was then pretreated to remove organic and secondary carbonate contamination. Samples were suspended in 1% sodium hypochlorite for 60 minutes then vortexed, centrifuged, and rinsed three times with purified water before suspension in 0.1M acetic acid for 10 minutes. Then, they were rinsed three more times before freezing overnight. Once frozen, samples were freeze-dried until fully dry and weighed into glass tubes and flushed filled with helium. They were then left to react for one hour with 100% phosphoric acid. The gases evolved from the samples were then analyzed for stable carbon and oxygen isotopic composition using a Thermo Gas Bench II connected to a Thermo Delta V Advantage Mass Spectrometer at the Max Planck Institute for Geoanthropology (formerly the Max Planck Institute for the Science of Human History), Jena, Germany. Results were corrected using a three-point calibration against International Standards (IAEA-603 ($\delta^{13}C$ = 2.46‰; $\delta^{18}O$ = -2.37‰); IAEA-CO-8 ($\delta^{13}C$ = -.8‰; $\delta^{18}O$ = -22.7‰); IAEA NBS 18 ($\delta^{13}C$ = 5.014‰, $\delta^{18}O$ = -23.2‰). USGS44 ($\delta^{13}C$ = -42.2‰) was run as an internal standard. The data from these standards suggest that the machine measurement error is c. ± 0.24‰ for $\delta^{13}C$ and ± 0.36‰ for $\delta^{18}O$. An equid enamel standard was run to access systemic error (accuracy). Measurement bias due to systematic error was determined to be ±0.3 ‰ for $\delta^{13}C$ and ±0.2 ‰ for $\delta^{18}O$.

Table 1: Description of each individual tooth sampled from the three archaeological sites. Eruption/wear stages and approximate ages at death were assigned following Payne (1973) for goat and Halstead (1985) and Jones and Sadler (2012) for cattle.

SAMPLE NAME	CHRONOLOGY	SPECIES	TOOTH	Crown height (mm)	Wear Stage	Estimated age at death
AG1	PPNB	*Bos taurus*	M3	53	D	1.4-2.4 years
AG2	PPNB	*Bos taurus*	M2	60	E	2-3 years
KS1	MCIII-LC	*Bos sp.*	M2	58	E	2-3 years
KS2	MCIII-LC	*Bos sp.*	M2	61	EF	2-3.5 years
KS3	ECI-II	*Bos sp.*	M2	55	D	1.4.-2.4 years
KS4	MCIII-LC	*Bos sp.*	M2	53	D	1.4.-2.4 years
KS5	MCIII-LC	*Capra hircus*	M3	27	E	2-3 years
MA1	Philia	*Capra hircus*	M2	32	D	1.4-2.4 years
MA2	ECI-II	*Bos sp.*	M3	60	G	4-6 years
MA3	ECI-II	*Capra hircus*	M2	58	D	1.4-2.4 years
MA4	ECI-II	*Bos sp.*	M2	52	D	1.4-2.4 years
MA5	ECI-II	*Bos sp.*	M3	55	D	1.4-2.4 years
MA6	Philia	*Bos sp.*	M3	54	E	2-3 years
MA7	Philia	*Bos sp.*	M2	61	E	2-3 years
MA8	Philia	*Bos sp.*	M1	57	4	2-3 YEARS
MA9	Philia	*Bos sp.*	M3	53	EF	2-3.5 years

Table 2: Summary statistics of *Bos sp*. and *Capra hircus* incremental tooth enamel carbonate $\delta^{13}C$ and $\delta^{18}O$ mean values from the three archaeological sites. Both $\delta^{13}C$ and $\delta^{18}O$ values are reported relative to VPDB. All data are presented in the **Supplementary Materials** section.

Tooth ID	Max $\delta^{13}C$ (‰)	Min $\delta^{13}C$ (‰)	Mean $\delta^{13}C$ (‰)	Max $\delta^{18}O$ (‰)	Min $\delta^{18}O$ (‰)	Mean $\delta^{18}O$ (‰)
AG1	-9.8	-10.5	0.7	-1.9	-4.8	-2.9
AG2	-9.4	-11.1	1.7	-1.3	-4.6	-3.3
KS1	-10.3	-11.1	0.8	-1.7	-3.3	-1.6
KS2	-10.3	-11.6	1.3	-1.8	-2.9	-1.1
KS3 (caprine)	-10.5	-12.6	2.1	0.5	-2.4	-1.9
KS4	-10.0	-11.6	1.6	-1.3	-2.5	-1.2
KS5	-11.1	-12.1	1.1	-0.8	-3.6	-2.8
MA1 (caprine)	-9.8	-11.4	1.6	-0.4	-2.3	-1.9
MA2	-6.3	-9.1	2.8	-1.8	-3.7	-1.5
MA3 (caprine)	-9.8	-12.6	2.8	-0.6	-4.1	-3.5
MA4	-5.7	-7.4	1.7	-0.3	-3.8	-3.5
MA5	-7.1	-8.4	1.3	-1.7	-4.6	-2.9
MA6	-9.0	-10.2	1.2	0	-3.7	-3.7
MA7	-6.3	-11	4.8	-0.9	-4.9	-4
MA8	-9.9	-10.7	0.8	-2.5	-10.7	-8.2
MA9	-9.4	-11.1	1.7	-2.4	-10.7	-8.3

4. Results

Overall, the average $\delta^{13}C$ values for cattle (-9.7‰) and goat (-10.3‰) at the three sites fall within the expected range for animals consuming a C_3-dominated diet, with the exception the three cattle from MA (M2, M4, M7, discussed below), the mean $\delta^{13}C$ values of which are particularly high. The two cattle molars from the PPNB site of AG yielded enamel $\delta^{13}C$ values ranging from -11.1‰ to -9.4‰, with mean amplitude of intra-tooth variation at 1.2‰ and $\delta^{18}O$ values ranging from -4.8‰ to -1.3‰, with a mean amplitude of intra-tooth variation at 3.1‰ (**Table 2; Figure 2**). Both $\delta^{13}C$ and $\delta^{18}O$ values are relatively homogeneous with limited inter- and intra-tooth variation.

Cattle molars from the BA site of KS yielded enamel $\delta^{13}C$ values ranging from -12.6 ‰ to -10.0‰, with mean amplitude of intra-tooth variation being 1.5‰ and $\delta^{18}O$ values ranging from -3.6‰ to -0.8‰, with mean amplitude of intra-tooth variation of 1.6‰. The single *Capra hircus* molar (KS3) yielded $\delta^{13}C$ values ranging from -12.6 ‰ to -10.5‰, with mean amplitude of intra-tooth variation being 2.1‰ and oxygen values ranging from -2.4‰ to 0.5‰ with mean amplitude of intra-tooth variation being 1.9‰ (**Table 2; Figure 3**). The molar enamel $\delta^{13}C$ values for KS support that both cattle and caprine were feeding in areas dominated by C_3 vegetation. Amongst the possible C_3 food plants are leafy crops as well as crop byproducts which undoubtedly represented an important grazing component of the animal diet at the site (Lucas 2014).

Cattle molars from the BA site of MA yielded enamel $\delta^{13}C$ values ranging from –11.1 ‰ to -5.7‰, with mean amplitude of intra-tooth variation of 2‰ and oxygen $\delta^{18}O$ values ranging from -10.7‰ to -3.7‰ with mean amplitude of intra-tooth variation of 4‰. The two caprine molars (M1 and M3) yielded enamel values ranging from -12.6 **‰** to -9.8 **‰** with mean amplitude of intra-tooth variation being 2.2 **‰** and $\delta^{18}O$ values ranging from -4.1**‰** to 0.4**‰** with mean amplitude of intra-tooth variation being 2.7**‰ (Table 2; Figure 4)**. The isotopic enamel data from the Bronze Age site of MA show some interesting patterns, regarding both inter and intra-species variation. The most noteworthy observation is that caprine and cattle display different average and dispersion isotope values which either reflect different dietary habits and/or different herding practices in which at least some of the cattle were subjected to different keeping practices and feeding schedules.

5. Discussion

The results of this study suggest some degree of variability in cattle management practices among the three sites, which might be related to the micro-environment of each site as well as to different human choices. At AG, even though our Neolithic sample is small, $\delta^{13}C$ values suggest cattle were feeding in areas exclusively dominated by C_3 vegetation while the limited fluctuations observed in $\delta^{13}C$ values indicate pasturing in the local area. These results are in agreement with previous isotopic studies at AG. By using bone collagen (DiBenedetto 2018: 262), these studies provided very similar results, suggesting that Neolithic cattle were not herded across a wide landscape, but were rather kept at or near the settlement. Palaeobotanical studies (Lucas 2014) confirm the domination of C_3 vegetation at Neolithic AG, through the identification of a wide variety of C_3 edible plants, domesticated cereals and pulses which, along with their byproducts, could be consumed by cattle. Considering the location of AG, in a more wooded setting and in an area that received the greatest annual precipitation compared to other contemporary and later Bronze Age sites, the scenario of pasturing in the vicinity of the settlement seems plausible. On the other hand, the sequential curve of $\delta^{18}O$ values is almost flattened, with the seasonal signature being almost absent, indicating that the animals were perhaps consuming mixed water sources including perhaps a heavy reliance on aquifers or wells (Henton et al. 2014: 123).

Comparison between the Neolithic AG cattle and the Bronze Age KS cattle suggests that Bronze Age $\delta^{13}C$ and $\delta^{18}O$ variation is much higher at the latter, perhaps suggesting that Bronze Age cattle at KS were exploring more diversified areas within the landscape and were exposed to higher levels of mobility. It may be that we are here observing the process of cattle incorporation into Cypriot ecologies. Early colonists may have chosen to keep these animals close to their settlements and close to available water sources. Early Neolithic reliance on aquifers and wells has been documented on other Mediterranean islands such as Malta (Grima 2016). Subsequent settlement expansion, and management of the landscape, including hydrological infrastructure, may have enabled Bronze Age cattle to move more widely. In addition, this shift may be reflective more economically diverse landscapes on Cyprus as certain areas became more dedicated to crop production and others to different herding activities. This is further highlighted by the differences between cattle and caprine isotope patterns at the Bronze Age site of MA. In particular, the higher mean $\delta^{13}C$ values observed for the three *Bos sp*. molars from MA is intriguing and in agreement with previous isotopic studies at the site (Scire-Calabrisotto *et al.* 2020). MA is located in an area, where average yearly precipitation is very low, with soils being relatively poor (Xenophontos, 1996). In order to deal with summer shortfalls, fodder provisioning might have represented an essential strategy. Even though economically important C_4 plants have not yet been identified in the palaeobotanical record of prehistoric Cyprus, several C_4 grasses and chenopods, indigenous to the island, occur in present-day vegetation (Hand *et al.*, 2011). Amaranth, a perennial plant species that is still present on the island today is a potential candidate and could have been used in different ways, as a grain and as fresh, dried or even as ensiled forage (Rodríguez et al. 2011; Abbasi *et al.* 2012). Wild amaranth and its leaves have been used as forage or silage crop for a wide variety of domestic animals across the world, including cattle, chickens, pigs and rabbits, both in the past and in the present. Today, in ruminant farms in Cyprus, silage is mainly made of corn (A. Georgiadis pers. comm.). During prehistoric and pre-industrial times, alternative silage could have included several drought-resistant wild grasses, such as the local amaranth species *Amaranthus graecizans*. Slightly enriched $\delta^{13}C$ values for cattle have also been highlighted through a recent isotopic study by Calabrisotto *et al.* (2020). This study used bone collagen instead of tooth enamel to explore Early/Middle Bronze Age human and animal diets at MA and even though sample size was particularly small (N = 3) noteworthy patterns and differences in the isotopic signatures between small and large livestock led the authors to explore the possibility that at least some of the cattle at the settlement might have received fodder (Calabrisotto *et al.* 2020: 5). Lastly, a new stable isotopic study, conducted on the herbivore bones from the Early/Middle Bronze Age settlement of Politiko *Troullia* (Fig. 1), lying just 8km to the east of MA, showed particularly higher $\delta^{15}N$ values for cattle compared to caprine, leading researchers to argue for more intensive management of the large livestock, including the possibilities of grazing on manured fields or feeding of penned cattle. In addition, researchers working at Troullia suggested that the limited range of variation in $\delta^{13}C$ might indicate that cattle were penned and therefore accessed more limited vegetation resources. Taking into account the old and more recent isotopic evidence from the Bronze Age settlement of Marki *Alonia* along with the recent evidence from Politiko *Troullia* (Pilaar Birch et al. 2022) we can assume that at least some of the Bronze Age cattle were closely managed by humans. The fact that only some animals have been subjected to more intensified management by humans is interesting and may imply that cattle could potentially have different functions at Bronze Age settlements, with some of them being used for dairying, others for meat and dungs production but also for ploughing the land.

6. Conclusion

The stable carbon and oxygen isotope data produced in the current study provide the first direct comparative insights into Neolithic and Early-Middle Bronze Age cattle management practices on the island of Cyprus. Despite a number of stable isotopic studies focusing on animal herding practices in Neolithic and Bronze Age Cyprus, no attempt has been made so far to compile and compare isotopic data from these two critical periods in Cypriot prehistory. The animal isotope data present suggest different management practices for cattle during the Neolithic and Bronze Age periods, and between domestic cattle and caprine for the Bronze Age. The different isotopic values between the two species can be attributed to either different mobility practices and or to some cattle being more closely managed by humans during the Bronze Age through the provision of fodder and/or silage. These results, although based on a limited sample set, are in agreement with other isotopic studies, which also support that cattle were subjected to closer management practices by humans, living in more constrained grazing spaces and potentially being provisioned with fodder, self-fertilized hay or silage. Future research, including larger samples from various archaeological sites and time periods, along with coordinated systematic palaeobotanical research, should further elucidate cattle and caprine foddering practices in prehistoric Cyprus.

Declarations

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Author Declarations

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Conflicts of interest

The authors declare no competing interests

Ethics approval/declarations (include appropriate approvals or waivers)

Not applicable

Consent to participate (include appropriate statements)

Not applicable

Consent for publication (include appropriate statements)

Not applicable

Availability of data and material

Yes (shared excel spreadsheet)

Author Contribution

A. S. conceptualized the project and wrote the main manuscript text. P.R supervised the project and contributed to the writing of the main manuscript text. M.B. contributed to the interpretation of isotopic data, the creation of graphs and to the writing of the manuscript text. M.L. supervised stable isotopic analysis and processed the stable isotopic data. L.C., A.S. and J.W. provided the zooarchaeological samples for the stable isotopic analysis and edited the Cultural Background section. All authors read and approved the manuscript.

Supplementary Material (provided as an excel spreadsheet):

Incremental tooth enamel carbonate $\delta^{13}C$ and $\delta^{18}O$ values for *Bos sp*. and *Capra hircus* from the three archaeological sites. **SD** stands for Standard Deviation (of ten gas pulses of the same measurement). Both $\delta^{13}C$ and $\delta^{18}O$ are reported relative to VPDB.

Code Availability: Not applicable

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Figures

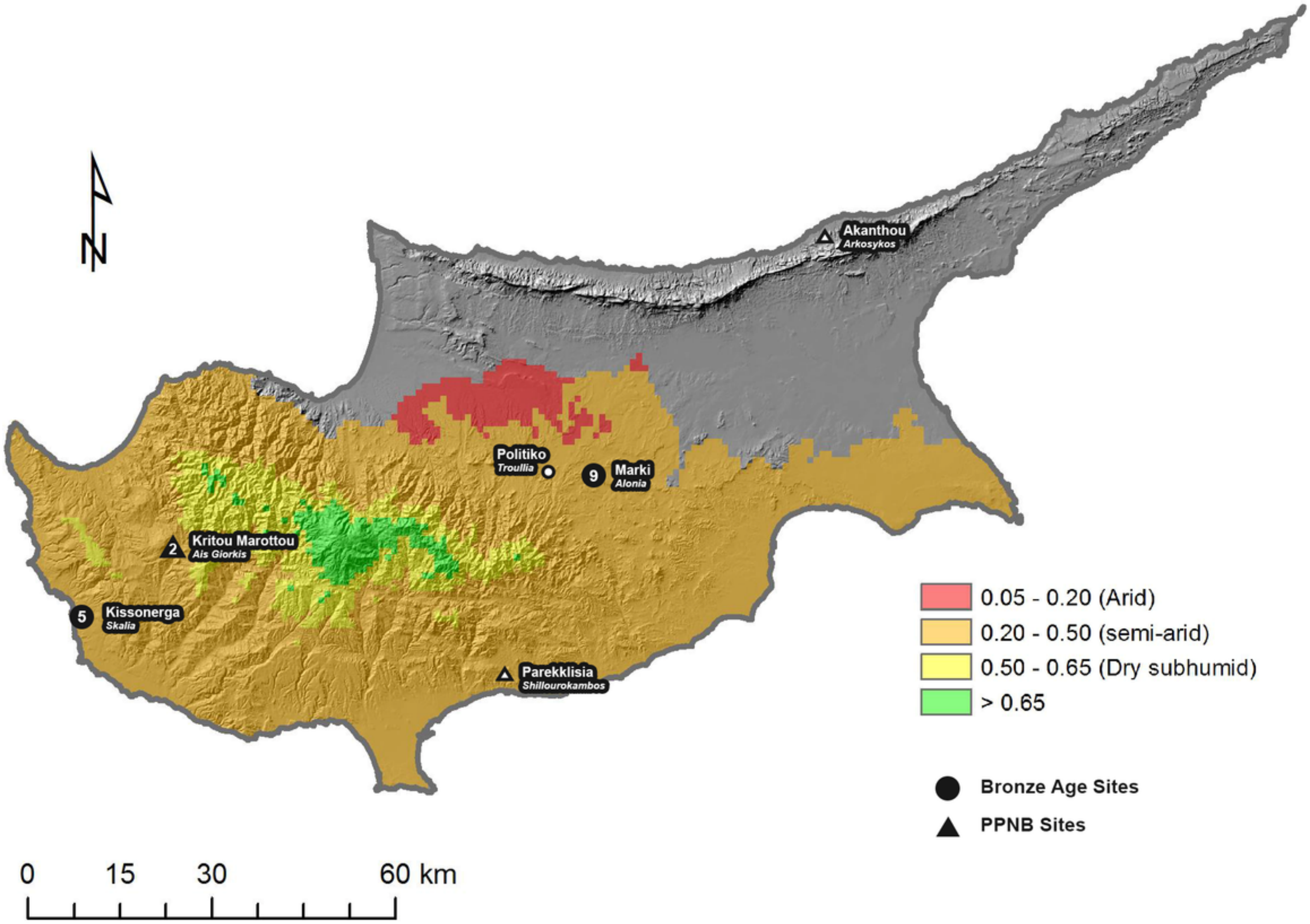

Figure 1

Map of Cyprus showing aridity gradients. PPNB sites from which samples have been obtained are marked with filled triangles while PPNB sites only mentioned in the text are marked with outlined triangles. Bronze Age sites from which samples have been obtained are marked with filled circles while Bronze Age sites only mentioned in the text are marked with outlined circles (Adopted from: Camera *et al.* 2014).

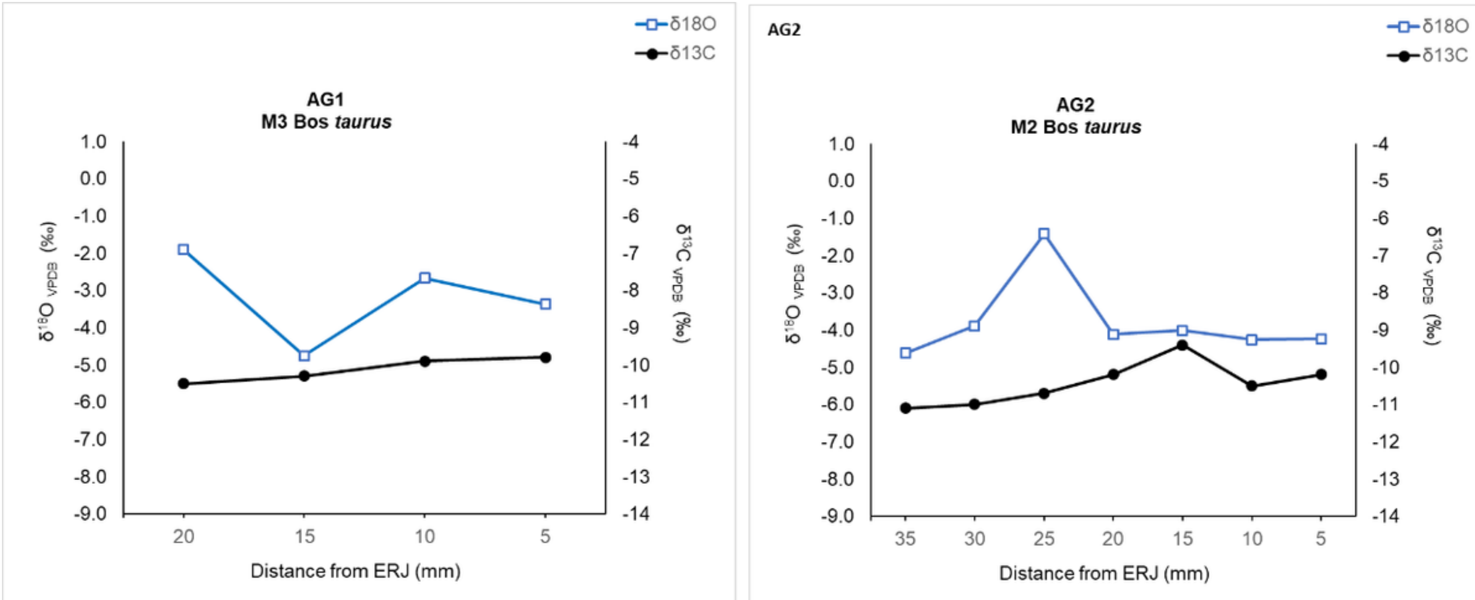

Figure 2

Stable carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) values for the Neolithic AG cattle

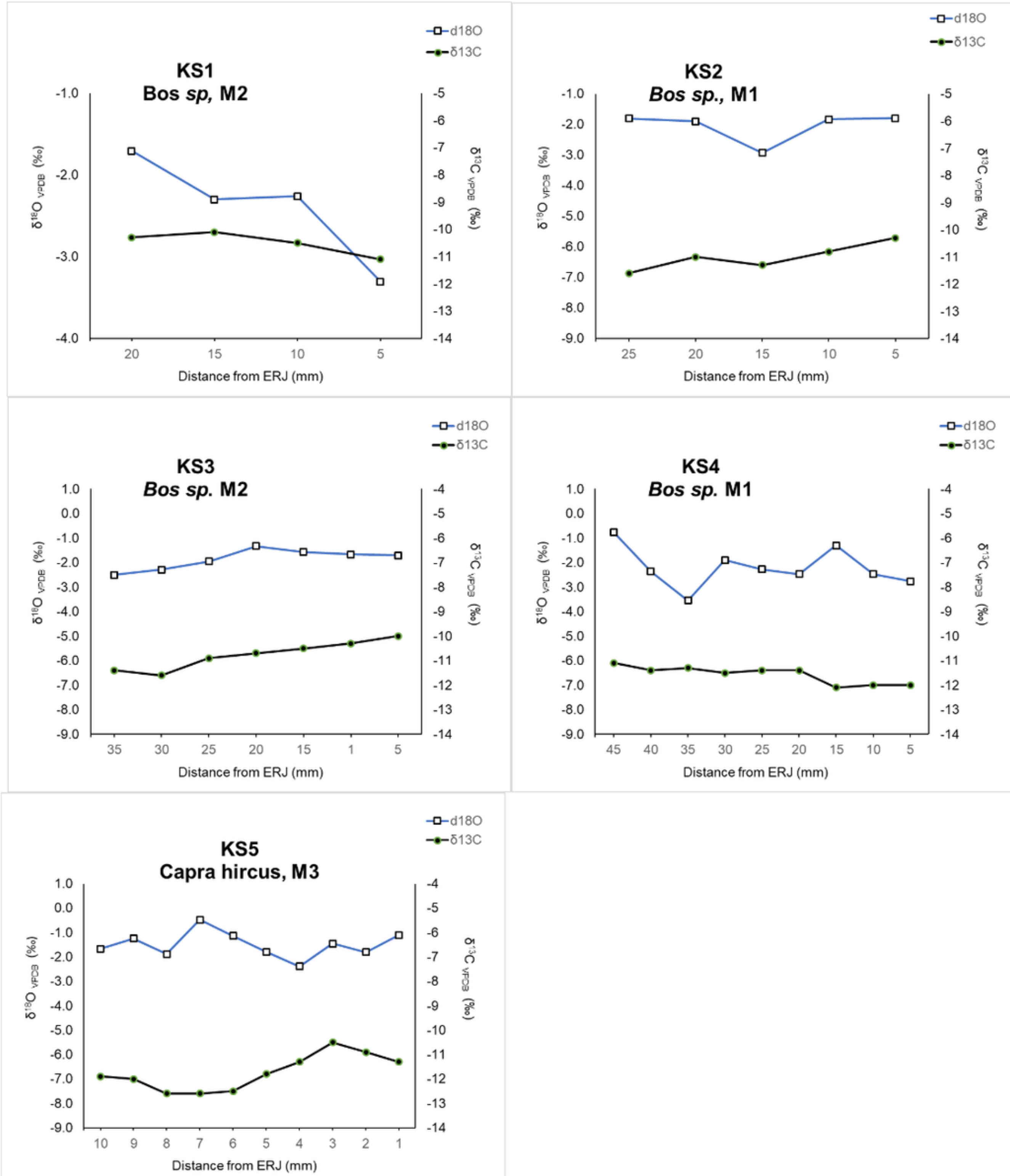

Figure 3

Stable carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) values for the Bronze Age KS cattle and caprine.

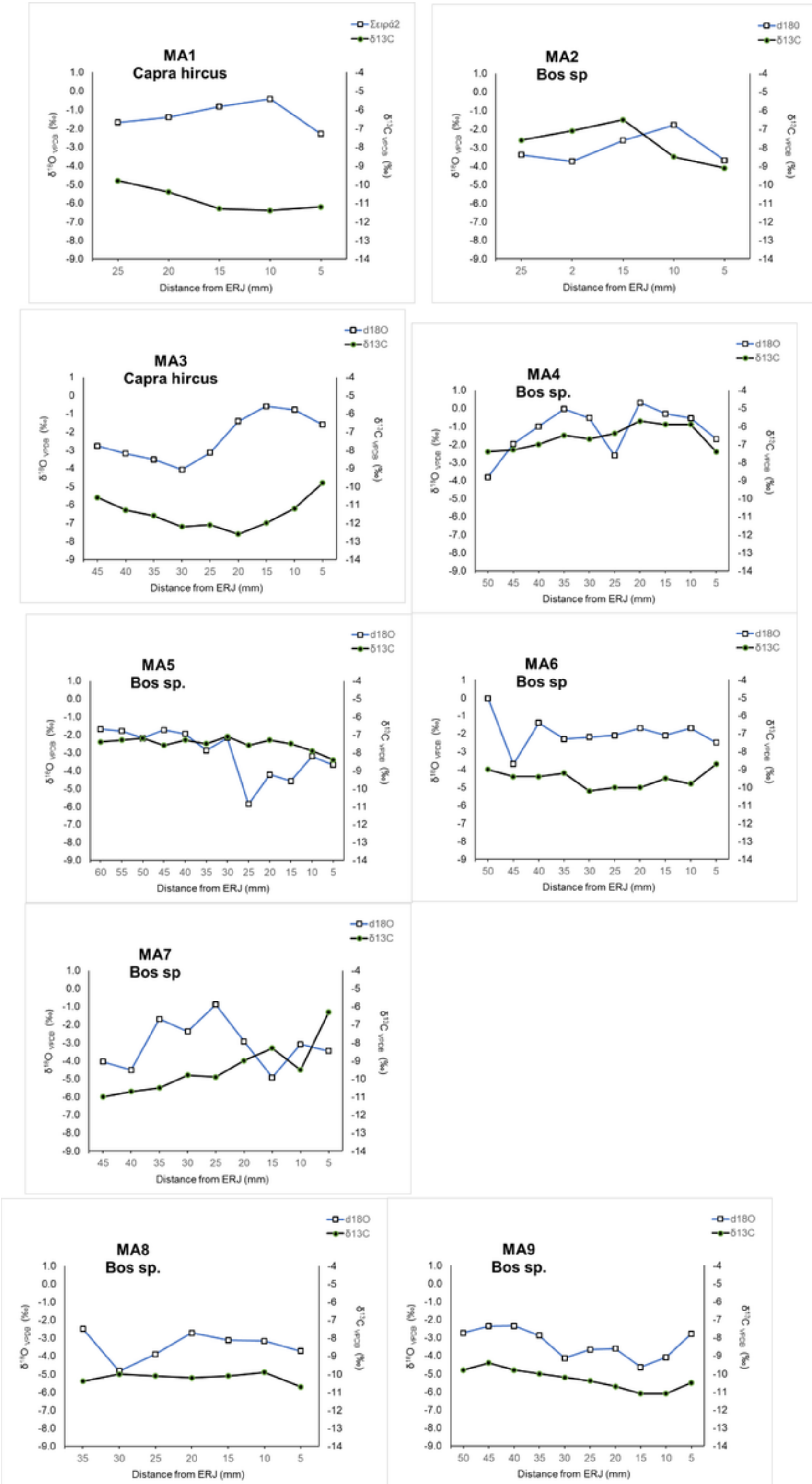

Figure 4

Carbon δ^{13}C and oxygen δ^{18}O isotopic values for Bronze Age MA

Supplementary Files

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- SupplementaryMaterial1.xlsx