Identifying Neolithic animal management practices in the Adriatic using stable isotopes

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ABSTRACT – *We synthesise reported stable isotope values for domesticates and wild herbivores from sites spanning the Neolithic in coastal Croatia, Slovenia, and Italy (6000–3500 calBC). Carbon and nitrogen stable isotope values are analyzed as proxies of diet and environment, with differences between species possibly indicating anthropogenic influence. Results are used to characterise diets and address questions of the origin and development of husbandry strategies, especially transhumance, in early farming communities. Changes in pig carbon and nitrogen isotope values through time suggest alterations in practices, whereas values remain relatively constant for cattle and ovicaprids during most of the Neolithic, despite assumptions of seasonal mobility.*

IZVLEČEK – *V prispevku sintetiziramo vrednosti stabilnih izotopov domačih in divjih (rastlinojedih) živali iz neolitskih obmorskih najdišč na Hrvaškem, v Sloveniji in v Italiji (v časovnem obdobju od 6000 do 3500 calBC). Vrednosti stabilnih izotopov ogljika in dušika smo analizirali kot približke za podatke o prehrani in okolju; razlike v teh vrednostih med vrstami živali morda kažejo na antropogene vplive. S pomočjo rezultatov teh analiz smo lahko prepoznali značilnosti prehrane v zgodnje poljedelskih skupnostih na teh območjih in odgovorili na vprašanja o izvoru in razvoju živinorejskih strategij, predvsem transhumance. Spremembe v vrednostih ogljika in dušika pri prašičih v različnih časovnih obdobjih kažejo na spremembe v postopkih prašičereje, medtem ko so te vrednosti za govedo in ovce/koze ostale relativno nespremenjene skozi celoten neolitik, kljub temu da se za te živali predvideva sezonska mobilnost.*

KEY WORDS – *Neolithic; Adriatic; transhumance; domestication; stable isotopes*

Introduction

New stable isotope and lipid residue studies have begun to map and characterise the spread of livestock management practices throughout the Adriatic and Balkans during the Neolithic (*c.* 6000–3500 calBC; *Budja* et al. *2013; Evershed* et al. *2008; Lelli* et al. *2012; Lightfoot* et al. *2011; Šoberl* et al. *2008; Zavodny* et al. *2014*). Scientific advances have also allowed for a more fine-grained view of how Neolithic lifeways varied by site and region, with emphasis placed on secondary product exploitation or the seasonal movement of animals. However, some integral aspects of livestock management (*e.g.*, foddering and grazing) are less visible through traditional archaeological methods. Stable isotope studies offer a systematic approach to mapping these activities both temporally and geographically, and have been applied successfully in a variety of contexts (*e.g., Bocherens* et al. *2000; 2001; Makarewicz, Tuross 2006; Pearson* et al. *2007*).

Stable carbon and nitrogen isotope analyses are especially important for inferring changes in diet and

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environment indicative of anthropogenic influence in the absence of a complete archaeological record. Here we synthesise published stable carbon and nitrogen isotope data from open-air settlements and cave sites in the Adriatic region spanning the Early to Late Neolithic (see Fig. 1; *Lelli* et al. *2012; Lightfoot* et al. *2011; Ogrinc, Budja 2005; Zavodny* et al. *2014*). Comparison of these data can help to identify differences in animal diet between species and through time that may be linked to changes in animal management and exploitation, providing a framework for interpreting management strategies and issues of domestication on a regional scale.

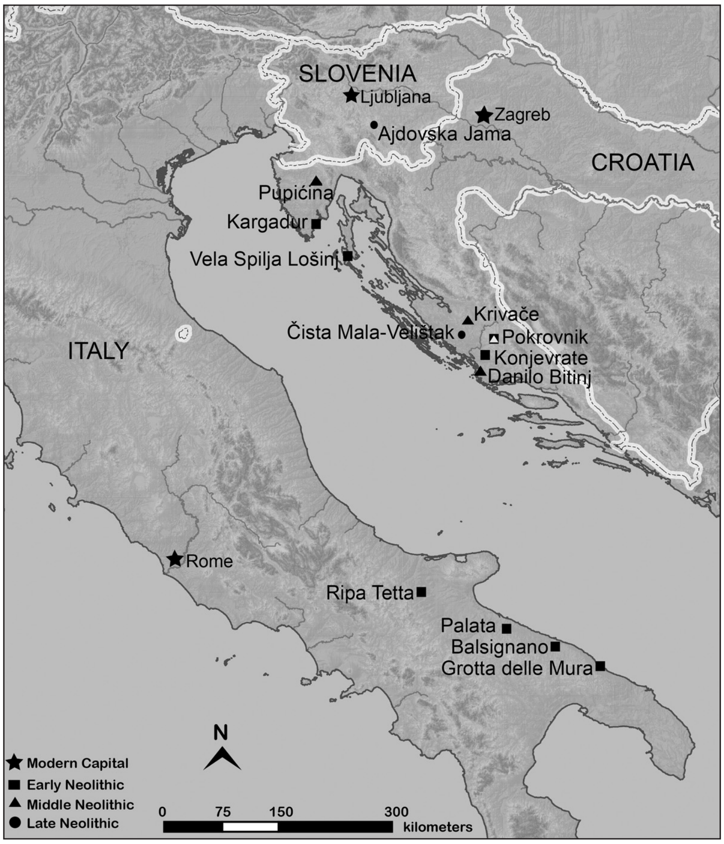

Fig. 1. Map of Neolithic sites mentioned in the text.

Background

Stable isotope studies of domesticated faunal remains have recently advanced our understanding of the origin and spread of agriculture in the Mediterranean world (*Lelli* et al. *2012; Lightfoot* et al. *2011*). Ongoing archaeological studies focus on the introduction, adoption, and adaptation of domesticates by early farming communities and hunter-gatherer groups (*Bass 2008; Lelli* et al. *2012; Lightfoot* et al. *2011; Miracle, Forenbaher 2005; 2006*). However, the precise timing of these transformative events remains poorly defined, in part due to an ephemeral and uneven Mesolithic record in the Adriatic region (*Biagi 2003; Komšo 2006; Lelli* et al. *2012; Miracle, Forenbaher 2005; Moore* et al. *2007a; 2007b*). In most regions, there is also an observable gap between Mesolithic and Neolithic occupational layers that prevents more definitive conclusions about the spread of farming technology and domesticates in the Early Neolithic (*Bonsall* et al. *2013; Biagi* et al. *2008; Forenbaher, Miracle 2006; Malone 2003; McClure 2013; Mlekuž* et al. *2008; Rowley-Conwy* et al. *2013*).

Consequently, the advent of farming in the region has been variously explained with diffusionist, migratory, or native developmental models (*e.g., Bass 2008; Chapman* et al. *1996; Forenbaher, Miracle 2005; Marijanović 2009; Mlekuž 2003; Moore* et al. *2007a; 2007b*). While developed Neolithic lifeways at key sites, such as Pokrovnik in Dalmatia, point to a rapid spread of a complete farming package (*Legge, Moore 2011; McClure* et al. *2014; McClure, Podrug 2015; Moore* et al. *2007a; 2007b*), evidence at other sites along the Mediterranean and Adriatic coasts suggests a much more gradual spread (*Miracle, Forenbaher 2005*). The role of local hunter-gatherer groups in bringing agriculture to the region has also been inconsistently defined, with some arguing for acculturation or adoption (*Bonsall* et al. *2013; Zvelebil, Lillie 2000*) versus displacement by migratory farmers (*Rowley-Conwy* et al. *2013*).

Despite these ambiguities, however, current archaeological survey and excavation along the Adriatic coast is clarifying the temporal and spatial trajectories of the spread of domesticated plants and animals and associated farming technology in the area (Dalmatia: *Marijanović 2009; McClure* et al. *2014; McClure, Podrug 2015; Miracle, Forenbaher 2006; Moore* et al. *2007a; 2007b; Teoh* et al. *2014*; Istria: *Forenbaher, Kaiser 2008; Forenbaher* et al. *2013*; Italy: *Biagi 2003; Biagi* et al. *2008; Malone 2003*; Slovenia: *Bonsall* et al. *2007; Tomaž 2010*). Though there are regional differences in the appearance of the standard Neolithic package, which included domestic wheat, barley, sheep, goats, pigs, and cattle, the Neolithic can generally be divided into Early, Middle, and Late sub-periods, and are often associated with regionally different but characteristic pottery styles.

Impresso ware had arrived in Dalmatia with the first farming groups by the early 6th millennium calBC (for new radiocarbon dates of Dalmatian Neolithic, see *Forenbaher, Kaiser 2008; Forenbaher* et al. *2013; Marijanović 2009; McClure* et al. *2014; Miracle, Forenbaher 2006; Moore* et al. *2007a; 2007b; Podrug 2010*), and reached southern Istria by 5750 calBC (*Forenbaher, Miracle 2006*). The Middle Neolithic period in Dalmatia and southern Istria is marked by the appearance of Danilo pottery (*c.* 5300–4900 calBC), and the Late Neolithic by the use of Hvar style ware that lasts throughout most of the 5th millennium and into the 4th millennium BC (*Forenbaher* et al. *2013; Forenbaher 2014*). The first signs of the Neolithic in northern Istria and the Trieste Karst, however, do not appear until the second half of the 6th millennium BC with the appearance of Danilo-Vlaška pottery style (*Miracle 2006; Forenbaher, Miracle 2006; Forenbaher 2014*). In northeastern Italy, a local iteration of the Danilo and Hvar culture elements, as well as those from the Po valley is reported (*Ferrari* et al. *2014*). In central and southeastern Italy, regional Early Neolithic impressed wares had appeared along the coast by the 6th millennium BC (*Malone 2003*).

Neolithic animal management in the Adriatic

Despite more recent stable isotope studies (*Lelli* et al. *2012; Lightfoot* et al. *2011; Ogrinc, Budja 2005; Zavodny* et al. *2014*) and ceramic residue analyses (*Budja* et al. *2013; Evershed* et al. *2008; Šoberl* et al. *2008*), zooarchaeology remains the primary method for identifying Neolithic economies and animal exploitation strategies in the Adriatic since domesticated species dominate most faunal assemblages at both village and cave sites (*Legge, Moore 2011; McClure 2013; Miracle, Forenbaher 2005; Miracle, Pugsley 2006; Moore* et al. *2007a; 2007b; Radović* et al. *2008; Rowley-Conwy* et al. *2013*). Population profiles and mortality curves act as proxies for herd management, and are used to estimate birthing and culling seasons for different species. Additionally, age-at-death profiles built from tooth eruption and wear patterns can be used to compare observed slaughter patterns with idealised curves for milk, wool, and meat exploitation (*Payne 1973*). According to Payne, when a species is managed primarily for milk production, very young individuals are slaughtered at a higher rate than adults. This contrasts with a strategy concentrated on meat production, where larger numbers of animals survive to be older juveniles or adults (*e.g., Legge, Moore 2011; Payne 1973; Vigne, Helmer 2007*), or a wool-driven economy, where as many animals are allowed to reach adulthood as possible.

Recent work at the cave sites of Pupićina (*Miracle, Forenbaher 2006; Miracle, Pugsley 2006*) and Vela Spila (*Radović* et al. *2008*) in Istria have used mortality profiles to identify changes in herd composition and exploitation from the Middle Neolithic onwards. Radović and colleagues (*2008*) argue that ovicaprid remains at Vela Spila most closely resemble Payne's milk-curve, with juveniles likely being culled between early spring and late fall. Mortality curves of faunal remains at nearby Pupićina, however, have been interpreted as indicative of both meat and milk exploitation according to the season of site use (*Miracle, Pugsley 2006; Rowley-Conwy* et al. *2013*). In Dalmatia, sheep age data from Pokrovnik suggest that early farmers practiced a mixed or meat-focused strategy (*Legge, Moore 2011.187–188*), while in Italy, Rowley-Conwy *et al.* (*2013*) argue that southern Italian farmers exploited ovicaprids for milk and cows for meat.

However, kill-off models provide only an approximation of animal management, and other factors such as accidental mortality, disease (*e.g., Legge, Moore 2011.187*), mixed management strategies, and statistical similarities between some practices may complicate interpretations of the archaeological record (*e.g., Bréhard* et al. *2010; Brochier 2013; Greenfield 2005; Vigne, Helmer 2007*). Stable isotope and lipid residue analyses can provide complimentary evidence of animal exploitation practices. For instance, analyses of lipid residues at sites in the Near East and southeastern Europe suggest that the processing of dairy products was present in some regions before the 7th millennium BC (*Evershed* et al. *2008*). In the Adriatic, dairy lipids have been identified on the inside of ceramics from the Middle Neolithic site Mala Triglavca, indicating the use of milk products by Vlaška groups (*Budja 2014; Budja* et al. *2013; Šoberl* et al. *2008*).

The question of transhumance

Seasonal transhumance, or annual rounds of herds between different grazing grounds, is a historically well-documented pastoral adaptation in the Mediterranean and Adriatic (*Moore* et al. *2007b; Porčić 2008; Šašel 1980*). In the case of central Dalmatia, the seasonal movement of livestock to temporary pastures played a fundamental role in local farming adaptations well into the 20th century (*Moore* et al. *2007b*). Recent ethnographic work at the modern village of Pokrovnik, in Dalmatia, demonstrates the existence of a transhumant management strategy as recently as the past century, with herders pasturing sheep in the nearby Dinaric Alps during the summer months and wintering in the coastal valley alongside the village (*Moore* et al. *2007b*). In this system, animals are able to graze on fresh grass, while allowing the land surrounding each village to regenerate from winter pasturing. Elsewhere in southeastern Europe, sedentary pastoralists have been identified in Neolithic Romania (*Greenfield, Jongsma 2008*), but transhumance as a pastoral strategy is not documented until the Bronze Age in the region (*Arnold, Greenfield 2006*).

The role of transhumance in the Neolithic is less clear. The distribution of archaeological sites suggests that higher elevation and/or rockier terrain in the Adriatic region were primarily used by pastoralists during the Neolithic (*e.g.*, Istria, Slovenia; see *Miracle 2006; Mlekuž 2003, 2005*; see also *Dennell 1978; Halstead 2006*). Known cave sites like Pupićina and Vela Spila may have acted as seasonal outposts for shepherds and their flocks (*Rowley-Conwy* et al. *2013*), and there is some evidence that ovicaprids and cows were stabled in caves at different points in prehistory (*Bonsall* et al. *2013; Boschian, Montagnari Kokelj 2000; Mlekuž 2005; Mlekuž* et al. *2008*). The predominance of ovicaprids at these and other cave sites (*Rowley-Conwy* et al. *2013*) also implies a transhumant strategy, as cows and pigs were less likely to make seasonal rounds.

In one regional study of the northern Balkans, Arnold and Greenfield (*2006*) tested the hypothesis that a transhumant economy would cull more juveniles during springtime in the highlands, and more adults would die during the winter while pasturing near lowland villages. Similarly, analyses of the Pupičina assemblage have identified the majority of ovicaprid remains as belonging to neonates and juveniles (60–81%; *Miracle, Pugsley 2006*). Assuming a single birthing season in the early spring, researchers suggest that Neolithic shepherds brought their flocks to the cave sites in the spring and summer to graze, before moving back into the lowlands during the colder months.

Stable isotopes, diet, and animal management

Stable carbon and nitrogen isotopes in bone collagen can be used as proxies of diet, and reflect the average dietary protein during the last several years of an animal's life (*DeNiro, Epstein 1978; 1981*). Animal diet is inferred based on the isotopic composition of food at the trophic level of foods consumed. Anticipated differences in stable isotope values between species and over time can be attributed to changing patterns of mobility, residence, and, by extension, management strategies during the Neolithic as communities invested more time and energy in agricultural lifeways (see Fig. 2). Local environmental variation in basal productivity and water availability, as well as metabolic factors, can alter the stable isotope composition of bone and collagen (*DeNiro, Epstein 1978; 1981; Towers* et al. *2011*).

We expect that animal management strategies and their corresponding isotopic signatures will remain similar throughout the circum-Adriatic during this time period, but that there will be clear differences between species due to different exploitation goals and practices. We hypothesise that ovicaprids participated in a seasonal pattern of transhumance between the coast and mountains, while cattle and pigs remained in coastal valleys near permanent settlements throughout the year (*Marković 1987; Nimac 1940; Perišić 1940*). Carbon and nitrogen stable isotope values should reflect this difference if the practice was indeed implemented during the Neolithic in the Adriatic (see Fig. 2). We also suggest that if caves were used as seasonal sites for penning and culling practices, we should also see differences between values from cave and open-air settlement sites.

Finally, we expect wild local herbivores (deer and hare) to have isotopic signatures noticeably different from domestic animals, as their diet should reflect the local environment with limited anthropogenic influence. Deer (*Capreolus capreolus* and *Cervus elaphus*) isotope values are reported from Pupićina, Karagadur, and Vela Spila Lošinj, while hare (*Lepus* sp.) isotope values are from Vela Spilja Lošinj and Ajdovska Jama. These samples represent the Early to Late Neolithic and most of the geographic region under consideration, but for this paper we present them as one group, with the assumption that all environments are similar (terrestrial C_3) and do not change over time (*Bailey 2000.139*).

Neolithic sites in the Adriatic region

The similar ecological and environmental landscapes across the Adriatic region allow us to contextualise results from multiple studies reporting values for domesticated animals at Neolithic sites in Dalmatia (Croatia), Istria (Croatia), Italy, and Slovenia. The background of each site sampled in this study is given below.

Dalmatia

Five Neolithic sites in central Dalmatia have archaeological evidence of intensive use of domestic animals and crops, suggesting that human populations were dependent on agriculture and livestock throughout the Neolithic. Isotope values are from Zavodny and colleagues' (*2014*) study on Neolithic transhumance in this coastal region.

Konjevrate is an Early Neolithic village located less than 10km from Pokrovnik. The site is currently under a modern churchyard (Fig. 1). Test excavations from the 1990s remain unpublished (for a short description see *Menđušić 1998*), though recovered pottery, stone tools, and animal bones are curated by the Šibenik City Museum. The presence of Impresso style pottery places the site in the Early Neolithic and AMS radiocarbon dates attest to Early and Middle Neolithic occupations (*McClure* et al. *2014; McClure, Podrug 2015*).

Pokrovnik, a village roughly three hectares in size, was occupied continuously throughout the Early and Middle Neolithic, and is located only a few kilometers from the Middle Neolithic site of Danilo Bitinj (Fig. 1; *Moore* et al. *2007b*). Excavations were undertaken in 1979 (*Brusić 2008*), and more recently in 2006 (*Moore* et al. *2007b*) and in 2010–2013 (*unpublished*). Reported radiocarbon dates suggest the site was occupied circa 6000–5100 calBC (*Legge, Moore 2011; McClure* et al. *2014*), making it one of the earliest dated open-air Neolithic villages in Dalmatia. Recent studies have identified over 90% of the faunal assemblage (n = 2400) as domesticated species (*Legge, Moore 2011; Moore* et al. *2007b*).

The Middle Neolithic settlement of Danilo Bitinj is located in a valley several kilometres from the Adriatic coast, and is thought to have been one of the most extensive sites of its type in southern Europe (Fig. 1; *Moore* et al. *2007a*). Past excavations in 1953, 1955 (*Korošec 1958; 1964*), and 1992 (*Menđušić 1998*) provided a wealth of material, although more recent excavations have focused especially on the recovery and identification of over 1600 animal bones, most belonging to domesticates (*Legge, Moore 2011; Moore* et al. *2007a*).

Krivače is another Middle Neolithic village located in the Bribir Valley (Fig. 1) and was first excavated in 1963 (*Korošec, Korošec 1974*), again during the early 2000s (*unpublished*), and most recently in 2013 (*Podrug* et al. *2013;* see also *McClure* et al. *2014; McClure, Podrug 2015*).

Čista Mala-Velištak is currently the only excavated Late Neolithic village in the region (Fig. 1; *Podrug 2010*). The available radiocarbon dates (4900–4700 calBC) place occupation at this site firmly in the early phase of the Hvar culture (*McClure* et al. *2014; McClure, Podrug 2015; Podrug 2010*).

Istria

Carbon and nitrogen values are reported for domesticates from Neolithic sites located north of central Dalmatia in the coastal region of Istria (Fig. 1; *Lightfoot* et al. *2011*). Lightfoot *et al.* (*2011*) focused on human dietary changes during the Mesolithic-Neolithic transition, finding a higher degree of dietary overlap between these periods than originally thought. Three sites have comparable isotopic data for domesticated animals: Kargadur, Vela Spilja-Lošinj, and Pupićina.

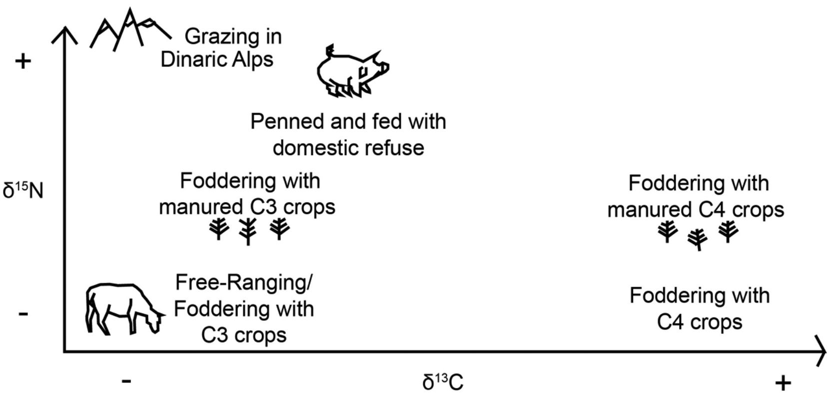

Fig. 2. Expected stable isotopic shifts according to different management strategies. Assuming free-ranging grazing or foddering with C_3 plants as a baseline, a switch to foddering with C_4 plants will enrich $\delta^{13}C$ by roughly 10–15‰ (**DeNiro, Epstein 1978*****). Foddering with manured crops, either C_3 or C_4, will enrich $\delta^{15}N$ by 1–3‰ (*****Bogaard et al. 2013*****). Animals fed with domestic refuse will shift to a higher trophic level, enriching $\delta^{13}C$ by 1–3‰ and $\delta^{15}N$ by 3–5‰ (*****Schoeninger, DeNiro 1984*****). Grazing exclusively at higher arid elevations, such as in the Dinaric Alps, will enrich $\delta^{15}N$ in relation to lowland grazing individuals (*****Ambrose 1991*****).***

Kargadur is a coastal open-air village site that is one of the most recently excavated of its kind in Istria (*Komšo 2006b*). Vela Spilja-Lošinj is a prehistoric cave site, located on the island of Lošinj off the coast of Istria. Excavations during the 1950s uncovered a Mesolithic occupation (*Mirosavljević 1962; 1968; 1974*), and more recent studies have also focused on Neolithic components of the site, including the identification of Early Impresso wares (*Komšo* et al. *2004*).

Pupićina Cave, in inland Istria, was occupied numerous times throughout prehistory, and excavations have uncovered a significant Neolithic presence (*Miracle, Forenbaher 2006*). Zooarchaeological analysis of Neolithic animal remains have determined that domesticates comprised over 80% of identified taxa throughout the Neolithic (*Miracle, Pugsley 2006*). Ovicaprids comprise the majority of these domesticated faunal remains, although the presence of cattle and pigs increased in the Late Neolithic.

Slovenia

Located in southeastern Slovenia, Ajdovska Jama is an inland cave site that was infrequently occupied from the Paleolithic until the Middle Ages, though a series of archaeological excavations undertaken from 1884 onwards have uncovered a substantial Neolithic component (*Bonsall* et al. *2007; Horvat 1989*). Early radiocarbon testing dated approximately 31 human burials to two periods within the Late Neolithic (*Ogrinc, Budja 2005*), although more recently published radiocarbon values for these same human remains cluster between 3485–3340 calBC (*Bonsall* et al. *2007.732*). Domesticated sheep, goat, and cattle bones, many with clear cut marks, were found in burial contexts alongside hearths containing carbonised grain. A recent paleodietary study determined that Ajdovska Jama humans ate a 'terrestrial diet' of mostly domestic animals and C_3 plants (*Ogrinc, Budja 2005*), a conclusion echoed by Clive Bonsall *et al.* (*2007*).

Italy

Recent research suggests that farming practices first spread along the eastern Adriatic coast and then crossed the sea to Italy by the start of the 6th millennium BC (*Lelli* et al. *2012; Miracle, Forenbaher 2005; Skeates 2000; Starnini 2002*). Similar to central Dalmatia, southeastern Italy also exhibits little evidence of a strong Mesolithic tradition (*Biagi 2003; Lelli* et al. *2012*), making it an ideal point of comparison for mapping possible introductions and changes in animal husbandry among first farmers along the Adriatic coast.

Here we include stable carbon and nitrogen isotope values reported for domestic animals from four early Neolithic sites by Roberta Lelli *et al.* (*2012*; see Fig. 1) as part of a human paleodietary study. Radiocarbon dates indicate a Neolithic date for village sites: Ripa Tetta (5860–5600 calBC), Palata (5620–5470 calBC), and Balsignano (5570–5480 calBC). All of these sites are open-air settlements that were surrounded by ditch structures and whose inhabitants participated in an early agricultural economy. Palata and Balsignano are situated on the Adriatic coast, whereas Ripa Tetta is located farther inland. The fourth site, Grotta delle Mura, is a coastal cave dated

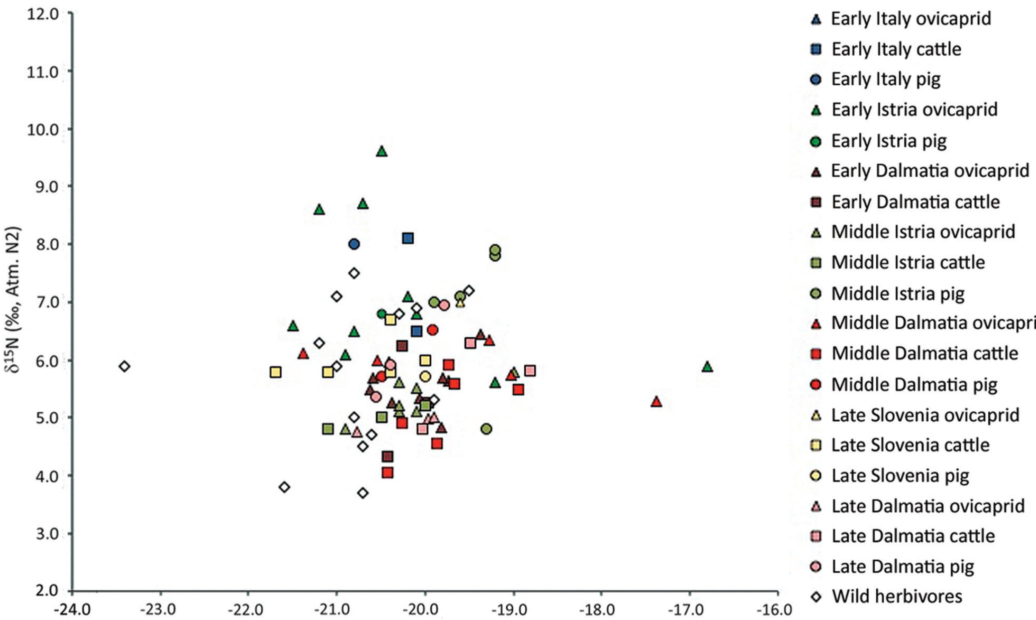

Fig. 3. Stable carbon and nitrogen values for all Neolithic samples discussed in this paper (*Lelli *et al.* 2012; Lightfoot *et al.* 2011; Ogrinc, Budja 2005; Zavodny *et al.* 2014*).

to the Early Neolithic on the basis of Impressed Ware pottery associated with domesticated fauna. Collectively, these assemblages offer an opportunity to detect possible management differences on each side of the Adriatic.

Discussion

Here we compare the stable carbon and nitrogen isotope values for cows, ovicaprids, and pigs across the Neolithic Adriatic, as well as reported isotope values for local indigenous herbivores (hare and deer) as a control for non-human influenced diet in the environment. Values are reported in Table 1 and Figure 3.

Despite our initial predictions of temporal and species-specific changes in stable isotope signatures throughout the Neolithic period, Figure 3 demonstrates that such differences are not actually present over time or by region. We see a tight cluster of points, suggesting that cattle, ovicaprids, and pigs had largely similar diets throughout the Neolithic period regardless of region (Slovenia, Istria, Italy or Dalmatia). Reported isotope values for contemporary wild deer and hare in Istria and Slovenia also appear to overlap with domesticated values, suggesting that there may not have been much difference between human-managed and wild diets during this period. However, a uniform diet space does not necessarily mean that animal management remained the same through time or was the same for all species. Very little is known about the degree of uniformity in vegetation in the region, though indigenous plants were overwhelmingly C_3 and evidence from Neolithic sites indicates that early agricultural staples – wheat, primarily einkorn and emmer, barley, and legumes – were also all C_3 pathway plants as well (*Bailey 2000. 139*). C_4 plants, such as millet, were presumably not in wide use by Neolithic communities in this region (*Hunt* et al. *2008*), despite their presence in very small quantities at some sites (*Legge, Moore 2011; Moore* et al. *2007b*).

Given zooarchaeological evidence consistent with seasonal rounds of ovicaprids between upland caves and lowland settlements (*Miracle, Pugsley 2006; Radović* et al. *2008*), we might also expect isotopic differences according to archaeological context. If ovicaprids were lambed on their way to higher pastures and then culled there (*Arnold, Greenfield 2006; Miracle, Pugsley 2006*), ovicaprids from cave assemblages should have higher nitrogen values because of the majority of life spent at higher elevations (*Ambrose 1991*) and/or continued nursing until death (*Nehlich* et al. *2009; Richards* et al. *2001*). As seen in Figure 4, however, ovicaprid stable carbon and nitrogen values are clustered regardless of archaeological context and through time. Two-tailed t-tests (assuming unequal variances, *Ruxton 2006*) show no significant differences in carbon or nitrogen values between caves and settlements when compared ($p = 0.436$ and $p = 0.472$, respectively). When caves and settlements are grouped according to period, however, there is a significant difference in reported stable nitrogen values for the Middle Neolithic Pupićina cave and contemporary settlements of Danilo-Bitinj, Krivače, and Pokrovnik ($p = 0.042$). However, when a more conservative non-parametric Mann-Whitney U test is applied because of the small sample size (*Fagerland 2012*), this significance disappears ($U = 8.5$, $n_1 = 5$, $n_2 = 5$, $p > 0.05$, two-tailed). Given these findings, we cannot confidently conclude whether the seasonal movement of ovicaprids was a mainstay of Neolithic economies in the circum-Adriatic region.

In addition, comparison of ovicaprids with wild herbivores generally, and between Middle Neolithic ovicaprids and all wild herbivores specifically, show

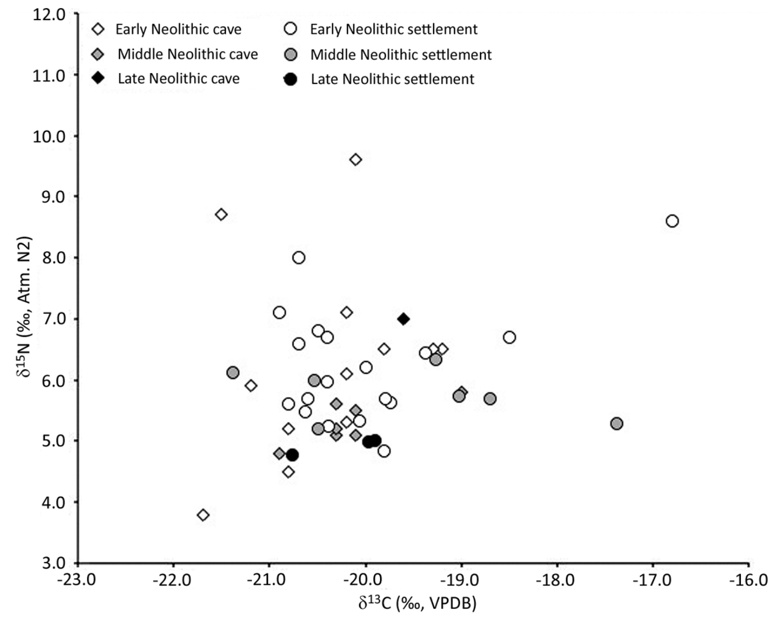

Fig. 4. Stable carbon and nitrogen isotope values of all Neolithic ovicaprids according to period and context (**Lelli *****et al.***** 2012; Lightfoot *****et al.***** 2011; Ogrinc, Budja 2005; Zavodny *****et al.***** 2014*).**

statistically significant differences in carbon values (t-test, unequal variances, p = 0.012 and 0.014, respectively), but not nitrogen. A Mann-Whitney U test comparing all wild herbivores, Middle Neolithic cave ovicaprids, and Middle Neolithic settlement ovicaprids similarly shows a significant difference in carbon (p = 0.045) but not nitrogen values (p = 0.320). We suggest the differences in carbon isotope values may be a result of different feeding strategies between species (*e.g.*, browsing versus grazing or forest versus pasture; *Bocherens* et al. *2015; Lohse* et al. *2014*), although it is unclear whether these differences have anything to do with human intervention in animal diets.

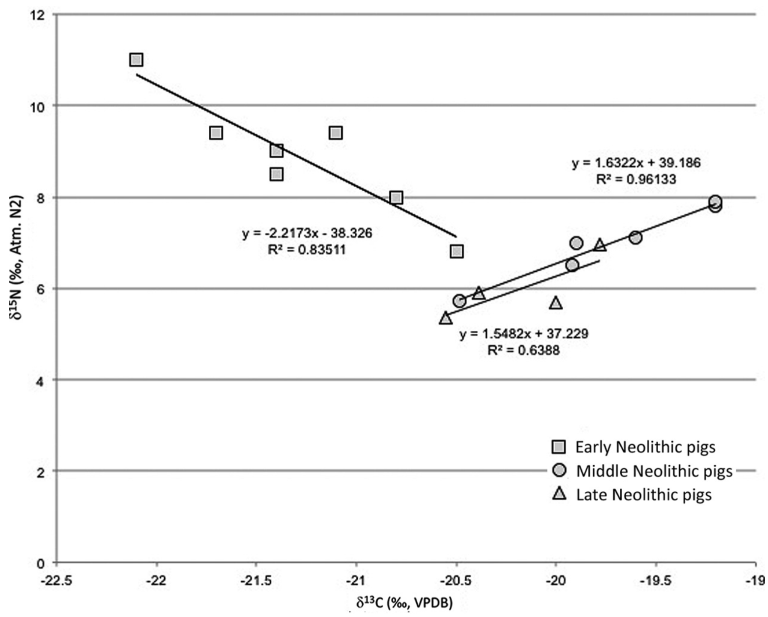

Fig. 5. Stable carbon and nitrogen isotope values of all Neolithic pigs (*Lelli *et al.* 2012; Lightfoot *et al.* 2011; Ogrinc, Budja 2005; Zavodny *et al.* 2014*).

One explanation for a similar diet space between cave and village animals is foddering. In this case, farmers provide animals with much of their subsistence, creating a very different kind of animal management system that may well have a similar isotopic signature regardless of the position of the herd in the seasonal round. Furthermore, the extent to which coastal valleys may have been preferred transhumance routes as opposed to transhumance to inland areas during the Neolithic is unknown, as current theories rely heavily on historical models in the region.

In short, current stable isotope data fall short in assessing the degree of transhumance during this period for ovicaprids.

A closer look at isotope values reported for pigs, however, reveals some differences in the species across time and space. Pigs are present in all regions during all periods (Figs. 3 and 5), and there appears to be a signal of changing management strategies between the Early and Middle-Late Neolithic. Statistical analyses highlight a significant difference in stable carbon values between Early and Middle Neolithic pigs (t-test assuming unequal variances, *Ruxton 2006*; p = 0.0002) and Early and Late Neolithic pigs (p = 0.003), although carbon and nitrogen values are not significantly different between Middle and Late Neolithic pigs (p = 0.122 and p = 0.068, respectively). We suggest that these differences in stable carbon and nitrogen signatures may reflect a shift in the foddering or management strategy of pigs between Early and Middle-Late Neolithic times throughout the Adriatic.

Elevated nitrogen in pigs may reflect increased manuring practices in fields (*Bogaard* et al. *2013; Madgwick* et al. *2012*), penning (*Bogaard* et al. *2013*), or different climatic and environmental settings (*Madgwick* et al. *2012*). Statistically different carbon values for pigs between time periods may signal a change in foddering practices, such as the inclusion of small amounts of C_4 species. *Panicum miliaceum* (broomcorn millet) is the most likely C_4 candidate, having been recovered from archaeological contexts in Europe prior to 5000 calBC (*Hunt* et al. *2008*), including Middle Neolithic contexts at Pokrovnik (*Legge, Moore 2011; Moore* et al. *2007b*) and at sites in neighbouring Serbia (Gomolava, *c.* 3700–3600 calBC). However, just across the Adriatic, varieties of millet were not known in northern Italy until the early Bronze Age (*c.* 1700–1500 calBC; *Tafuri* et al. *2009; Zohary, Hopf 2000*) or in southern Italy until Classical times (*Tafuri* et al. *2009*). While it is possible that Middle and Late Neolithic sites in Dalmatia and Istria obtained and utilized domestic millet, either for feeding animals or as part of the human diet, the spread and adoption of this millet species in southeastern Europe remains unclear and the results presented here can neither support nor refute the clear presence of millet in the Adriatic Neolithic.

Conclusion

Stable carbon and nitrogen isotope analyses provide a valuable tool for inferring changes in diet and environment. We find that the carbon and nitrogen isotope values reported in this paper remained largely stable for ovicaprids and cattle over the majority of the Neolithic, suggesting that livestock husbandry for these species remained fundamentally the same throughout the period in much of the Adriatic. Stable isotope data for domesticated pigs, on the other hand, may indicate different foddering or management practices as the Neolithic period progressed. Despite faunal data and other types of archaeological evidence, we also cannot definitively argue for or against ovicaprid transhumance on the basis of current stable isotope results. Future studies should focus on expanding sample sizes for domesticated animals at sites reported here and other Neolithic occupations throughout the circum-Adriatic region. Additionally, there is a need for background isotopic information on vegetation, either wild or domesticated, that may have been used for foddering or grazing by early farmers. Our results demonstrate the utility of isotope studies for addressing important questions regarding the Neolithic in the Adriatic, and highlight the need to continue quantitative scientific studies in the region.

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Tab. 1. Summary of stable isotope results for samples included in this study, organised by region.

Region	Site	Period	Sample #	Species	Δ¹³C	Δ¹⁵N	C:N	Reference
Dalmatia, Croatia	Konjevrate	Early	KON-2	*Ovis aries*	−19.8	4.8	3.24	*Zavodny* et al. 2014
		Early	KON-4	*Ovis aries*	−19.4	6.4	3.20	
		Early	KON-5	*Bos taurus*	−20.3	6.2	3.26	
	Pokrovnik	Early	PK-3	*Ovis aries*	−20.6	5.7	3.19	
		Early	PK-4	*Ovis aries*	−19.8	5.7	3.16	
		Early	PK-5	*Ovis aries*	−20.4	6.0	3.18	
		Early	PK-7	*Bos taurus*	−20.4	4.3	3.16	
		Early	PK-15	*Ovis aries*	−20.1	5.3	3.17	
		Early	PK-19	*Ovis aries*	−19.7	5.6	3.17	
		Early	PK-21	*Ovis aries*	−20.4	5.2	3.18	
		Early	PK-22	*Ovis aries*	−20.6	5.5	3.17	
		Early	PK-37	*Bos taurus*	−20.0	5.3	3.17	
		Middle	PK-14	*Bos taurus*	−19.7	5.6	3.2	
		Middle	PK-27	*Sus scrofa*	−19.9	6.5	3.3	
		Middle	PK-31	*Ovis aries*	−20.5	6.0	3.3	
		Middle	PK-36	*Bos taurus*	−18.9	5.5	3.0	
		Middle	PK-39	*Bos taurus*	−19.7	5.9	3.2	
	Danilo	Middle	DA-6	*Ovis aries*	−19.0	5.7	3.21	*Zavodny* et al. 2014
		Middle	DA-13	*Ovis aries*	−17.4	5.3	3.21	
	Krivače	Middle	KRI-1	*Ovicaprid*	−19.3	6.3	3.2	*Zavodny* et al. 2014
		Middle	KRI-2	*Sus scrofa*	−20.5	5.7	3.3	
		Middle	KRI-3	*Bos taurus*	−20.4	4.0	3.1	
		Middle	KRI-9	*Ovis aries*	−21.4	6.1	3.2	
		Middle	KRI-10	*Bos taurus*	−19.9	4.6	3.2	
		Middle	KRI-11	*Bos taurus*	−20.3	4.9	3.2	
	Čista Mala-Velištak	Late	CMV-1	*Sus scrofa*	−20.6	5.4	3.2	*Zavodny* et al. 2014
		Late	CMV-2	*Bos taurus*	−19.5	6.3	3.2	
		Late	CMV-3A	*Bos taurus*	−18.8	5.8	3.1	
		Late	CMV-4	*Sus scrofa*	−20.4	5.9	3.2	
		Late	CMV-5	*Ovis aries*	−20.8	4.8	3.2	
		Late	CMV-6	*Sus scrofa*	−19.8	7.0	3.2	
		Late	CMV-7	*Bos taurus*	−20.0	4.8	3.2	
		Late	CMV-28	*Capra hircus*	−20.0	5.0	3.2	
		Late	CMV-38	*Capra hircus*	−19.9	5.0	3.2	
Istria, Croatia	Kargadur	Early	BB13	*Ovicaprid*	−20.9	7.1	3.2	*Lightfoot* et al. 2011
		Early	BB14	*Ovis aries*	−16.8	8.6	3.1	
		Early	BB16	*Ovis aries*	−20.8	5.6	3.2	

Region	Site	Period	Sample #	Species	Δ13C	Δ15N	C:N	Reference
		Early	BB17	*Ovicaprid*	−20.7	6.6	3.1	
		Early	BB18	*Ovicaprid*	−20.5	6.8	3.1	
		Early	BB12	*Cervus elaphus*	−20.6	4.7		
		Early	BB20	*Cervus elaphus*	−21.2	6.3		
	Vela Spilja Lošinj	Early	BB26	*Sus scrofa*	−20.5	6.8	3.1	*Lightfoot* et al. *2011*
		Early	BB29	*Ovicaprid*	−19.2	6.5	3.1	
		Early	BB30	*Ovicaprid*	−21.2	5.9	3.1	
		Early	BB34	*Ovicaprid*	−20.2	6.1	3.1	
		Early	BB36	*Ovicaprid*	−21.5	8.7	3.1	
		Early	BB39	*Ovicaprid*	−20.1	9.6	3.1	
		Early	BB27	*Lepus* sp.	−21.0	5.9	3.0	
		Early	BB28	*Lepus* sp.	−21.0	7.1	3.0	
		Early	BB37	*Lepus* sp.	−20.3	6.8	3.1	
		Early	BB41	*Lepus* sp.	−20.8	5.0	3.1	
		Early	BB32	*Capreolus capreolus*	−20.8	7.5	3.1	
		Early	BB33	*Capreolus capreolus*	−19.5	7.2	3.1	
		Early	BB38	*Capreolus capreolus*	−19.9	5.3	3.1	
		Early	BB40	*Capreolus capreolus*	−20.1	6.9	3.1	
	Pupićina	Middle	BB50	*Ovis aries*	−20.3	5.1	3.0	*Lightfoot* et al. *2011*
		Middle	BB51	*Ovis aries*	−20.1	5.1	3.1	
		Middle	BB52	*Ovis aries*	−20.3	5.2	3.0	
		Middle	BB53	*Ovis aries*	−20.3	5.6	3.0	
		Middle	BB54	*Ovis aries*	−20.1	5.5	3.0	
		Middle	BB55	*Capra hircus*	−19.0	5.8	3.0	
		Middle	BB56	*Capra hircus*	−20.9	4.8	3.1	
		Middle	BB57	*Bos taurus*	−21.2	4.8	3.2	
		Middle	BB58	*Bos taurus*	−20.0	5.2	3.1	
		Middle	BB59	*Bos taurus*	−20.5	5.0	3.1	
		Middle	BB62	*Sus scrofa*	−19.6	7.1	3.1	
		Middle	BB63	*Sus scrofa*	−19.9	7.0	3.1	
		Middle	BB64	*Sus scrofa*	−19.2	7.8	3.0	
		Middle	BB65	*Sus scrofa*	−19.3	4.8	3.2	
		Middle	BB66	*Sus scrofa*	−19.2	7.9	3.1	
		Middle	BB60	*Cervus elaphus*	−20.7	4.5	3.1	
		Middle	BB61	*Cervus elaphus*	−20.7	3.7	3.2	
Italy	Basignano	Early	Bal III	*Ovis aries*	−20.0	6.2	3.4	*Lelli* et al. *2012*
	Grotta delle Mura	Early	GM 1	*Ovicaprid*	−19.5	6.5	3.4	Lelli et al. 2012
		Early	GM 2	*Ovicaprid*	−20.2	5.3	3.3	
		Early	GM 3	*Ovicaprid*	−20.2	5.3	3.3	
		Early	GM 4	*Ovicaprid*	−20.2	7.1	3.4	
		Early	GM 5	*Ovicaprid*	−20.8	5.2	3.4	
		Early	GM 6	*Ovicaprid*	−21.7	3.8	3.5	
		Early	GM 7	*Ovicaprid*	−20.8	4.5	3.5	
		Early	GM 8	*Ovicaprid*	−19.8	6.5	3.4	
	Palata	Early	Pal B5	*Bos taurus*	−20.1	8.1	3.4	*Lelli* et al. *2012*
		Early	Pal II fauna	*Ovicaprid*	−18.5	6.7	3.4	
		Early	Pal US7	*Ovicaprid*	−20.4	6.7	3.4	
	Ripa Tetta	Early	Rp 5	*Sus scrofa*	−20.8	8.0	3.4	*Lelli* et al. *2012*
		Early	Rp 6	*Bos taurus*	−20.2	6.5	3.5	
		Early	Rp 7	*Ovicaprid*	−20.7	8.0	3.3	
Slovenia	Ajdovska jama	Late		*Bos taurus*	−21.1	5.8	3.4	*Ogrinc, Budja 2005*
		Late		*Bos taurus*	−20.4	6.7	3.4	
		Late		*Bos taurus*	−21.7	5.8	3.4	
		Late		*Bos taurus*	−20.4	5.8	3.2	
		Late		*Bos taurus*	−20.0	6.0	3.2	
		Late		*Ovis aries*	−19.6	7.0	3.2	
		Late		*Sus scrofa*	−20.0	5.7	3.3	
		Late		Deer*	−23.4	5.9	3.7–3.9	
		Late		*Lepus* sp.	−21.6	3.8	3.3	

* Ogrinc and Budja (2005) average stable isotope values for three deer.

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back to contents