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Diet and herding strategies in a changing environment: stable isotope analysis of Bronze Age and Late Antique skeletal remains from Ya‘amūn, Jordan

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Abstract

Carbon and nitrogen stable isotope ratios of 45 human and 23 faunal bone collagen samples were measured to study human diet and the management of domestic herbivores in past Jordan, contrasting skeletal remains from the Middle and Late Bronze Age and the Late Roman and Byzantine periods from the site of Ya‘amūn near Irbid. The isotope data demonstrate that the management of the sheep and goats changed over time, with the earlier animals consuming more plants from semi-arid habitats, possibly because of transhumant herding strategies. The isotope data for fish presented here are the first from archaeological contexts from the Southern Levant. Although fish of diverse provenance was available at the site, human diet was predominately based on terrestrial resources and there was little dietary variability within each time-period. Isotopic variation between humans from different time-periods can mostly be explained by ‘baseline shifts’ in the available food sources; however, it is suggested that legumes may have played a more significant role in Middle and Late Bronze Age diet than later on.

Keywords: carbon and nitrogen isotopes; bone collagen; Bronze Age; Roman period; Byzantine period; fish;

Highlights

$\delta^{13}C$ and $\delta^{15}N$ values were employed to reconstruct herd management and human diet in past Jordan

Bronze Age ovicaprids consumed more plants from semi-arid habitats than Late Roman/Byzantine animals

The data suggest drier conditions or transhumant herd management in the Bronze Age

Differences in the human data can mostly be explained by environmental changes.

1. Introduction

The archaeology of the Near East is one of the areas where carbon and nitrogen isotope analysis has made a considerable impact in recent years, contributing, for example, to our understanding of early husbandry practices (Makarewicz and Tuross, 2012; Pearson *et al.*, 2007;), the heterogeneous origins of people and animals (Hartman *et al.*, 2013, Thompson *et al.* 2008), the contribution to human diet of specific food resources (Lösch, *et al.*, 2006, Richards *et al.*, 2003, Thompson *et al.*, 2005) and the development of social complexity (Makarewicz, 2013, Pearson *et al.*, 2013). One of the key strengths of the method is where it permits diachronic comparisons of isotope data from individual sites, enabling the tracing of continuity or change of subsistence strategies and environmental contexts through time. Using this approach, carbon stable isotope analysis of dental enamel of Bronze Age and Byzantine burials from the sites of Ya‘amūn, Sa‘ad and Yasieleh in North Jordan suggested remarkable homogeneity in diet across time and sites (Al-Shorman, 2003, 2004). A complementary study of carbon and nitrogen stable isotope ratios in dentinal collagen of human teeth recovered from Ya‘amūn, Sa‘ad and Yasieleh also indicated continuity (King, 2001). Because of the samples chosen, both studies explored diet only over the relatively short period of tooth formation in childhood and early adolescence and the lack of site- and period-specific faunal baseline data did not allow monitoring for differences in environmental settings in this ecologically diverse region. Building on this previous research, the present study adds new evidence from carbon and nitrogen stable isotope analysis of bone collagen of human and faunal remains from Ya‘amūn, in an attempt to reconstruct animal and human long-term adult diet at the site during two profoundly different time periods. We aim to explore how Bronze Age and Late Antiquity consumption profiles reflect changes in landscape exploitation and economic strategies, which are of great significance for understanding the way of life in northern Jordan in the past.

2. The site of Ya‘amūn

Jordan’s territory is characterised by high variability in vegetation, physiography, hydrology, and climate. Four of the five vegetation regions identified in the Middle East, the Mediterranean region, the Irano-Turanian steppe, the Saharo-Arabian region and the Sudanian region are present in Jordan (Zohary, 1973; Palmer 2013, Figure 1a). Ya‘amūn is located in the northern part of the Western Highlands at about eight hundred metres above sea level, 23 km southeast of Irbid. Here, current mean annual precipitation is ~400mm (Cordova, 2007). However, within few tens of kilometres of Ya‘amūn the amount of rainfall decreases drastically to less than 200 mm, with the dry Jordan River Valley to the west and the steppe and desert landscapes to the east (Figure 1b). The region around Ya‘amūn therefore presents as a mosaic of ecosystems, where oak forests, Mediterranean low vegetation and steppe habitats are in relative close proximity (Al-Eisawi, 1985).

Occupation at Ya‘amūn spanned from the Early Bronze Age, beginning at c. 3600 cal BCE to the Ayyubid-Mamluk period, thirteenth to sixteenth century CE (dates as in Adams, 2008). Since the first season of excavation, several tombs of variable type, chamber and shaft tombs as well as natural caves used for burial have been identified and excavated (Renfro and Cooper, 2000, Rose, 2002, Rose *et al*., 2007, Rose *et al*., 2003). As most of these have been robbed in modern times and/or reused during the Islamic and later periods a detailed description of burial rites is not available (Rose, 2005). Excavations of the tombs and of the Bronze Age settlement have produced Mycenaean and Cypriot ceramic sherds, Egyptian scarabs and a Mittanian cylinder seal, which demonstrate trade and contact with different areas of the Mediterranean (Rose, 2001). During Late Antiquity (approx. 4th– 7th century CE (Watson, 2008)), Ya‘amūn was a thriving agricultural settlement which contributed to the evidently booming economy in the Late Roman and particularly the Byzantine period (Cameron, 1993, Freeman, 2008, Kennedy, 2007, Parker 1999, Rosen, 2007). The prosperity of Ya‘amūn is shown by various olive and wine presses and by numerous carved water cisterns (El-Najjar and Rose, 2003, Rose *et al.*, 2007). Furthermore, the mosaics of the Ya‘amūn Byzantine church are of equally high quality as those in contemporaneous churches of the nearby Decapolis cities (El-Najjar *et al.*, 2001, Rose *et al.*, 2007).

3. Diet and environmental reconstruction by carbon and nitrogen stable isotope analysis of bone collagen

The ratios of the stable isotopes of carbon ($^{13}C/^{12}C$) and nitrogen ($^{15}N/^{14}N$) are amongst the most frequently measured in ancient skeletal remains for diet and environmental reconstruction. These ratios are conventionally referred to relative to a standard as $\delta^{13}C$ and $\delta^{15}N$ values, respectively. Due to isotope partitioning, isotopes of the same element are unequally distributed in different types of soils, and in different water bodies, plants and animals (Ehleringer and Rundel, 1989, Hoefs, 2009). As a result, organisms from different ecosystems can have distinct isotopic signatures and, similarly, their isotopic composition may vary according to their trophic level (Kelly, 2000). Feeding experiments have shown that the stable isotope ratios measured in human and animal bone collagen reflect the isotopic composition of plant and animal foods, and especially of the dietary protein (Ambrose and Norr, 1993, Tieszen and Fagre, 1993, Froehle *et al*., 2010), consumed over several years of life (Hedges *et al.*, 2007).

Photosynthesis is the main source of carbon isotopic variation in terrestrial ecosystems. According to their photosynthetic pathway, terrestrial plants fall into two main groups, C_3 and C_4 plants. C_3 plants are characteristic of the temperate environments and include most plants used for human consumption such as wheat, barley, most fruits, legumes and nuts. In contrast, C_4 plants are adapted to high light intensity, high temperatures and frequent water shortages. They include many tropical grasses and the cultural crops millet, sorghum, maize and sugar cane (van der Merwe, 1989). During photosynthesis, C_3 plants tend to incorporate less ^{13}C by discriminating more than C_4 plants against $^{13}CO_2$. The tissues of C_3 plants therefore have lower $\delta^{13}C$ values than C_4 plants. Mean $\delta^{13}C$ values are –26 ‰ and –12.5 ‰ for C_3 and C_4 plants, respectively (Smith and Epstein, 1971). These differences in the isotope values of the plants are reflected in the isotopic signature of the consumers, although absolute values are slightly changed by different metabolic pathways (DeNiro and Epstein, 1978 and studies summarised in Ambrose and Norr 1993). The carbon isotope composition of bone collagen therefore provides an indication of the relative contributions of C_3 and C_4 plants to the diet of herbivores and, in turn, may give indication of their abundance in the environment. For the humans, who in most cases eat an omnivorous diet, $\delta^{13}C$ values can reflect either direct consumption of plants or the isotopic composition of meat and dairy products derived from C_3- or C_4-fed animals (Ambrose, 1993). $\delta^{13}C$ values are also used to identify consumption of marine resources as marine foods have substantially higher $\delta^{13}C$ than terrestrial C_3 foods (Richards and Hedges, 1999, Schoeninger and DeNiro, 1984). However, within the environmental context of Jordan, it is the variable reliance on C_3 and C_4 plants that is likely to explain most carbon isotope variation in animals and humans.

Bone collagen $\delta^{15}N$ values are mainly used as an indicator of the trophic position of an organism in the foodweb, an attribute which is based on the enrichment of consumer tissues in ^{15}N with each step up the food chain (DeNiro and Epstein, 1981, Minagawa Wada, 1984, Schoeninger and DeNiro, 1984), breastfeeding mammals being at the top of this sequence (Fuller *et al.*, 2006).

Although trophic level enrichments are consistently observed in modern foodwebs, estimating the relative contributions of plant and animal protein in omnivorous diets is complicated by a number of factors, not the least uncertainty about the exact mechanisms behind the trophic level effect and how the diet-tissue spacing is affected by various nutritional and metabolic factors (Vanderklift and Ponsard, 2003, Caut *et al.*, 2009). While a full trophic offset in collagen stable isotope studies is commonly estimated as between 3 and 5‰ (Bocherens and Drucker, 2003), higher values in humans have also been suggested (Hedges and Reynard, 2007, O'Connell *et al.*, 2012). It is generally acknowledged that, because most plants are relatively low in protein, their contribution to the diet will be underrepresented in the collagen stable isotope signal; however, another issue that has been raised more recently is the fact that the isotopic composition of plant foods usually needs to be estimated from the bone collagen values of domestic herbivores which may not always give a truthful reflection of the plants used for human consumption (Fraser *et al.*, 2013). Despite these issues, studies have shown that the use of $\delta^{15}N$ as a broad indicator of the level of animal protein consumption in humans is overall sound, even though they cannot distinguish between different foods of animal origin such as between meat and dairy products (O'Connell and Hedges, 1999, Petzke *et al.*, 2005).

Although bone stable isotope data are primarily a reflection of diet, isotope analysis of faunal, specifically herbivore remains has also been used to indirectly reconstruct environmental conditions, the underlying principle being that herbivore data provide an averaged isotope value for the local vegetation, the isotopic composition of which will vary according to a number of environmental and climatic factors (Hedges *et al.*, 2004, van Klinken *et al.*, 1994). Most obviously, herbivore $\delta^{13}C$ values may give information about the proportion of C_3 *versus* aridity-adapted C_4 plants in an area – although the feeding preferences of individual species must also be taken into account (Ambrose and DeNiro, 1986, Hartman *et al.*, 2013). Variations in temperature or rainfall patterns, among others, also affect the isotopic composition of C_3 plants and may therefore be traceable in herbivore tissues (Hartman and Danin, 2010, van Klinken *et al.*, 1994). For nitrogen isotope ratios, a marked inverse correlation has been demonstrated between bone collagen $\delta^{15}N$ values and rainfall, so that herbivores living in arid environments show elevated $\delta^{15}N$ values (Ambrose and DeNiro, 1986, Heaton *et al.*, 1986). While physiological mechanisms have been proposed in explanation (Ambrose, 1991, Sealy *et al.*, 1987), it is now thought most likely that the 'rainfall effect' is due to the ^{15}N-enrichment of plants, through the effects of denitrification and ammonia volatilization in the soil (Hartman, 2011, Heaton, 1987, Murphy and Bowman, 2006, Schwarcz *et al.*, 1999). A linkage has also been found between high $\delta^{15}N$ values in cultivated plants and use of manure on fields (Bogaard *et al*., 2007, Fraser *et al*., 2011) and should be kept in mind when comparing the $\delta^{15}N$ values of humans and their domestic animals.

4. Materials and Methods

The excavation of the Ya'amūn tombs led to the identification of Middle Bronze Age, Late Bronze Age, Late Roman and Byzantine burials, with dating achieved through a systematic study of pottery fragments and grave goods, and of the architectural features (Al-Shorman, 2004, Barnes, 2003, Burke and Rose, 2001, El-Najjar and Rose, 2003, El-Najjar *et al*., 2001, Rose *et al*., 2007). From the skeletal remains made accessible at the Department of Archaeology and Anthropology of the University of Yarmouk (Irbid, Jordan), it was possible to sample 45 individuals. Of these, 22 date to the Middle-Late Bronze Age, while 23 date to the Late Roman-Byzantine period. A further 23 samples were obtained from the remains of adult domestic ungulates and fishbone recovered from well-dated contexts. The entire assemblage was highly fragmented. In the case of the human remains, this prevented the assessment of age and sex. For the faunal remains, it was usually problematic to distinguish between sheep (*Ovis aries*) and goats (*Capra hircus*) on morphological grounds. These are therefore collectively referred to as domestic ovicaprids or as sheep/goats (for more information on sampling processing and analysis see Supplementary Information). Isotopic differences between the two species on account of their feeding ecology are not expected in the environmental context of the southern Levant (see Hartman et al., 2013: S1).

5. Results

The $\delta^{13}C$ and $\delta^{15}N$ isotope data and quality indicators of the faunal and human bone samples from Ya‘amūn are reported in Tables S1 and S2 (see Supplementary Materials), respectively. Fifty (18 faunal and 32 humans samples) out of 68 bone specimens yielded good quality collagen (Ambrose 1990; DeNiro 1985). Descriptive statistics for each of the sample groups are presented in Table 1. The highest variability was found amongst the Bronze Age (MBA and LBA combined) animals, while the Late Antique (LR-Byz) sheep/goats presented the lowest. The δ-values of the domestic herbivores, illustrate a clear difference in the diet of Bronze Age and Late Antique sheep/goats with apparently decreased $\delta^{13}C$ and $\delta^{15}N$ in the later periods (Figure 2). Although the difference is statistically significant for $\delta^{15}N$ only (Independent Samples Mann-Whitney test with exact probabilities to account for small sample sizes: U=11.5, p=0.537 for $\delta^{13}C$; U=1.0, p=0.009 for $\delta^{15}N$), the $\delta^{13}C$ and $\delta^{15}N$ values of the MBA/LBA sheep-goats are clearly correlated (r^2=0.75). While the later ovicaprids had a more monotonous diet, the two LR/Byz *Bos* specimens plot relatively far apart, with a 3.2‰ difference in $\delta^{13}C$ and a 4.3‰ difference in $\delta^{15}N$ values. In Figure 3, the human values are compared to the terrestrial fauna. No statistically significant differences were found between human isotope values from MBA and LBA (Independent samples Mann-Whitney test, U=22.5, p=0.536 for $\delta^{13}C$ and U=18.0, p=1.0 for $\delta^{15}N$), and Late Roman and Byzantine Ya‘amūn (U=8.5, p=0.667 for $\delta^{13}C$ and U=4.5, p=1.83 for $\delta^{15}N$). Consequently these were pooled into one Bronze Age and one Late Antique group. The differences between the Bronze Age and Late Antique humans are statistically significant for both carbon and nitrogen

(Independent-sample Mann-Whitney test, $U=49.0$, $p=0.002$ for $\delta^{13}C$ and $U=55.5$, $p=0.005$ for $\delta^{15}N$).

6. Discussion

6.1 The fauna from Ya'amūn

Overall, the range of $\delta^{13}C$ values of the domestic ungulates from Ya'amūn indicates that they were grazing in an environment where C_3 vegetation dominates over C_4 vegetation. These results are in agreement with the data presented previously by Al-Shorman (2004, 2003) and King (2001) on the human diet and are also consistent with the vegetation composition around the site in modern times (Al-Eisawi 1996, Shomer-Ilan *et al*., 1981, Vogel *et al*., 1986, Winter, 1981). Nevertheless, the most positive $\delta^{13}C$ (-16.6‰ for sheep/goat and -15.6‰ for cattle, Table 1) indicate the inclusion of varying and sometimes substantial amounts of C_4 plants in the animals' diet. These higher $\delta^{13}C$ values are correlated with raised $\delta^{15}N$ values which are also consistent with grazing in arid regions (Hartman and Danin, 2010, Heaton, 1987, see section 3 above).

The differences observed in the sheep/goat data from the Bronze Age and Late Antiquity (Figure 2) are consistent with suggestions that climate in the MBA and LBA in the Southern Levant was dry and similar to present conditions, while sedimentological and palynological evidence as well as speleothem oxygen isotope analyses unequivocally indicate wetter conditions in the Roman and Byzantine periods (Bookman et al., 2004; Enzel et al., 2003; Neumann et al., 2007; Orland et al., 2009; Finné et al., 2011; Rambeau and Black 2011). Nevertheless, if climatic conditions in the MBA/LBA were indeed similar to the present day and even more so if, as has also been suggested, they were slightly wetter (see Rambeau and Black 2011: 99), it is unlikely that the MBA/LBA sheep/goats with elevated carbon and/or nitrogen isotope values (at least half of what is, admittedly, a small sample) could have acquired these by freely foraging in the immediate hinterland of the site.

Ya‘amūn itself is situated in the xeric Mediterranean phytogeographic zone which receives modest rainfall (currently ~400mm/year) and therefore has little C_4 vegetation, which only becomes notable in areas with less than ~350mm annual precipitation . The observed δ-values are therefore consistent with animals grazing in much drier environments and these indeed provide the best parallels among published data. According to the large reference data-set compiled by Hartman *et al.* (2013), the MBA/LBA sheep/goats from Ya‘amūn are most consistent with ovicaprids feeding in the desert zone, although similar isotope values have also been produced for goats from a semi-arid steppe environment (Makarewicz and Tuross, 2012). In any case, the Bronze Age herbivore data from Ya‘amūn suggest that sheep/goat were herded away from the site for at least part of the year. The isotope values for the sheep/goat from Ya‘amūn are almost identical to another small data-set of MBA sheep from Tell Al-Husn, only a few kilometres to the north (Al-Bashaireh and Al-Muheisen, 2011). Here, elevated isotope values were only observed in three very young individuals and the ^{15}N-enrichment was consequently attributed to a ‘suckling effect’; however, the consumption of mother ewes’ milk cannot easily explain the relatively large difference in $\delta^{13}C$ between the young and adult sheep (Balasse *et al.*, 1999), which approaches 2‰. Instead, the bones of the suckling sheep may record a seasonal shift in the diet of the mothers, during the gestation period and early life of their lambs, to include ^{13}C-enriched graze. Transhumance is standard practice amongst the traditional pastoralists in the southern Levant who, usually, spend the months between November and April leading herds to the green pastures that develop in arid and semi-arid areas during the rainfall season. This system has the added advantage of keeping the animals away from agricultural fields during the crop growing season (Levy, 1983, Safrai, 2004, 93). Texts dated to the Middle and Late Bronze periods of Syria-Palestine and Anatolia describe various strategies for managing domestic herbivores (Liverani, 1988, 374, 437), and how, for instance, the sheep owned by the elites spent most of the year away from the city to return only for the shearing season (Snell, 1997, 72, 126). Another scenario is that animals raised at sites in the more arid zones were brought to Ya‘amūn, which fits with artefactual evidence that the site was part of a network of commercial exchanges connecting north Jordan with the wider eastern Mediterranean (Bourke *et al.*, 2006, Strange, 2008), and would also explain why only part of the MBA/LBA sheep/goat sample exhibit the raised stable isotope values.

In contrast, the Late Roman/Byzantine animals were feeding almost entirely, if not exclusively, on C_3 plants and their $\delta^{15}N$ values are significantly lower than in the earlier animals. Assuming, as Hartman *et al.* (2013: 4372) argue, that the wetter climatic conditions in Late Antiquity did not significantly shift the boundaries of environmental zones in the region, this suggests that the sheep/goats of this later period were more restricted in their mobility. They would have grazed on unused fields and between the orchards in the surroundings of Ya‘amūn where conditions were relatively moist because of wide-ranging irrigation. It is known that vine leaves and trimmings were sometimes used as animal fodder (Horden and Purcell, 2000, 214) and these must have been abundant at Ya‘amūn, where vine cultivation was extensive (see above).

There are too few cattle data to attempt reconstructing husbandry regimes, but it is nevertheless interesting to observe that the two Late Antique cattle have sharply diverging $\delta^{13}C$ and $\delta^{15}N$ values (Figure 2). While one plots close to the contemporaneous sheep/goats, the other has substantially higher $\delta^{13}C$ and $\delta^{15}N$ values, suggesting that it fed in a much drier environmental zone and/or an area where C_4 fodder crops had been adopted (Copley *et al.*, 2004). The animal therefore suggests that livestock was brought to Late Antique Ya‘amūn from the outside.

Ya‘amūn freshwater and marine fish isotope values (Table S1, Figure 4) are comparable with results from archaeological fish from Greece (Vika & Theodoropoulou 2012). The values for the marine species, in particular, add to a growing corpus of data that show fish from the Mediterranean to be ^{13}C-enriched and ^{15}N-depleted compared to animals from the North Atlantic. The observed differences in $\delta^{15}N$ between the fish samples can be explained by differences in trophic level

(Froese and Pauly, 2014) and variation in the isotopic composition of aquatic primary producers (Ambrose 1993; France 1995; Fuller 2012b; Katzenberg & Weber 1999; Schoeninger & DeNiro 1984).Particularly notable is the stark difference in $\delta^{13}C$ between the two LR/Byz samples of the freshwater genus *Tilapia*, which exceeds 10‰ and indicates that these specimens lived in very different environments. The $\delta^{13}C$ values for modern *Tilapia* from Lake Tiberias (Zohary *et al.*, 1994), once corrected for the offset between muscle and bone collagen as well as lipid content, are very close to the relatively ^{13}C-depleted value observed for YMNTfb100. An origin from the river Jordan or the Lake itself therefore appears plausible. The same may then be true for the specimen of *Claridae* (catfish, YMNTfb102), as variation between the two could mostly be accounted for by differences in trophic level. *Tilapia* are also known to inhabit coastal rivers, including those of the southern Levant (Van Neer *et al.*, 2000) and a significant input from marine biomass could explain why specimen YMNTfb101 is substantially ^{13}C-enriched over YMNTfb100. Nevertheless, Vika and Theodoropoulou (2012) have observed similar carbon isotope values for freshwater fish from Greece. *Tilapia* are bottom feeders and it is possible that their foodwebs are ^{13}C-enriched by poor availability of CO_2 in warm and stagnant waters (France, 1995, Hecky and Hesslein, 1995), perhaps combined with a hard water effect in a region where marine carbonate is the dominant geological substrate (Day, 1996). Further isotope studies on freshwater fish from the Levant will be necessary to test this hypothesis.

6.2 The inhabitants of Ya‘amūn

The isotope values show that terrestrial C_3-derived resources dominated human diet at Ya’amūn. The isotopic differences between Bronze Age and Late Antique humans mirror those between the sheep/goats from both periods and suggest that much of what first appears as dietary variation can instead be explained by a baseline-shift in the isotopic composition of available food sources (Figure 3). Because of the impact of water availability on carbon isotope discrimination of C_3 plants during photosynthesis (Farquhar *et al.*, 1989), it is likely that the plant foods available at Ya‘amūn in the Bronze Age were also ^{13}C-enriched over those cultivated under the wetter conditions of the Late Roman/Byzantine period. It should be noted that the same cannot necessarily be assumed for plant $\delta^{15}N$ values as these are determined by numerous complex mechanisms (Evans, 2001, Högberg, 1997). Cultivated fields especially may be subject to additional measures such as the application of animal fertilizers (Fraser *et al.*, 2011). Despite significant differences in the isotopic composition of the bone collagen, human diet between the two time periods may therefore not have varied greatly in terms of the actual staple foods consumed and their relative proportions.

In this context, the relatively large difference in the average $\delta^{15}N$ human-herbivore offset ($\Delta^{15}N_{human\text{-}herbivore}$), which is 3.5‰ in the Late Antique but only 0.3‰ in the Bronze Age sample, requires some discussion. If herbivore $\delta^{15}N$ were used to estimate the nitrogen isotope composition of plants consumed by humans and the spacing between humans and animals was therefore taken as an indicator for the relative contributions of plant and animal protein to the human diet (Hedges and Reynard, 2007), these data would suggest that Bronze Age diet was almost entirely based on plant foods, while humans in Late Antiquity habitually consumed large amounts of animal protein (~ 70% of the dietary protein according to Hedges and Reynard’s (2007) ‘standard model’, even if a generous trophic level offset of +5‰ is used). Either of these extreme scenarios seems unlikely in light of evidence for diet in these periods available from other sources (Grigson, 1998, 256; Safrai, 2004, 96).

The human isotope data from MBA/LBA Ya‘amūn are almost identical to those obtained from EBA/MBA Tell Al-Husn (mean $\delta^{13}C$ and $\delta^{15}N$ values ±1 s.d.: -18.5±0.4‰ and 8.7±0.8, n=10), and suggest that the subsistence regime reflected was typical for the wider region (Al-Bashaireh and Al-Muheisen, 2011). It cannot be denied that staple foods derived from C_3 cereals such as wheat and barley made up the bulk of the diet at this time (Zohary and Hopf, 2000; see Snell, 1997; for Jordan see Bourke *et al.*, 2003; McNicoll *et al.*, 1992; Tubb 1988; Tubb *et al.*, 1997). Nevertheless, the faunal assemblage from BA Ya‘amūn itself as well as nearby sites such as Pella (Bourke *et al.*, 1994, Bourke *et al.*, 1998) demonstrate that sheep and goat husbandry was well-established in the region during the Bronze Age. While the emphasis may have been on wool production processing of surplus dairy and the consumption of meat from animals that had outlived their usefulness would have been an integrated part of this economy (Grigson, 1998, 256). If it is therefore unlikely that the human diet was almost entirely plant-based, the relatively low $\delta^{15}N$ values in the BA humans compared to the animal data need additional explanation. Pulses, especially lentils, were important protein-rich foods and a means of crop and diet diversification in the entire Mediterranean area since the beginning of agriculture (Grigson, 1998, Horden and Purcell, 2000, 203). Like other leguminous plants, they are able to fix nitrogen directly from the atmosphere and, as a result, are habitually ^{15}N-depleted compared to other crops. Their regular inclusion in the diet would therefore have the effect of lowering the $\delta^{15}N$ of human consumers, potentially masking the consumption of animal products (Fraser *et al.*, 2013).

If the human-herbivore $\delta^{15}N$ offset therefore likely underrepresents the role of animal products in the Bronze Age diet at least to an extent, the opposite may be true for the Late Roman/Byzantine sample. It is well-established that cereals, in the form of wheat or barley bread, contributed the majority of the daily caloric intake in Roman-period Palestine, while the degree to which animal products were part of everyday diet varied according to wealth and, particularly for fish, to the distance from the place of production (Broshi, 1986, Dar, 1995, Garnsey, 1999:16, Safrai 2004, Wilkins and Hill, 2006). Ya‘amūn in Late Antiquity was the site of intensive agriculture, and manuring was widely practiced in Romano-Byzantine Palestine (Almagro, 2007). The herbivore $\delta^{15}N$ may therefore well underestimate the nitrogen isotope composition of the cultivated plants (see Fraser *et al.*, 2013). Written sources from the region also describe a system of crop rotation where wheat fields were periodically turned over to leguminous plants and used as animal pasture (Safrai, 2004, 98). Alternatively, dietary diversification may be responsible for the human-herbivore spacing. In the Roman period, domestic fowl and chicken especially gained economic importance in the Southern Levant and it has been suggested that egg consumption was considerable (Safrai 2004: 101-102). Quantitative data from Ya'amūn do not exist, but at nearby Pella, reliance on poultry, mostly chicken, increases sharply during the Byzantine period (McNicoll *et al.*, 1982, 110). The isotopic composition of eggs depends on the diet of the chicken (Hobson, 1995); however, because of their omnivorous feeding ecology, these can be significantly ^{15}N-enriched over herbivores (Müldner and Richards, 2007).

There are numerous sources emphasizing the importance of fish and fish products in Roman and Byzantine Palestine (Garnsey, 1999, Lev-Tov, 2003, Marzano, 2013, Purcell, 1995, Van Neer and Parker, 2008). Based on the fishbone isotope data assembled here, there is little conclusive evidence that fish made any measurable contribution to Roman-Byzantine diet at Ya'amūn. Lack of isotopic separation between freshwater fish and terrestrial animals makes it very difficult to convincingly demonstrate the consumption of freshwater fish, and although the δ^{15}N values of the Late Antique humans could theoretically be explained by small-scale consumption of higher trophic level marine fish (such as the specimen of *Sciaenidae*, YMNfb88), Ya'amūn's inland location and the fact that YMNfb88 (which actually dates to the MBA) plots at the top end of δ^{15}N values measured for Mediterranean fish to date (and is therefore not necessarily representative of any marine fish that reached the site), make significant consumption of marine protein at the site very unlikely .

The isotope data from Ya'amūn are very similar to those from other Late Antique sites in the Levant (Al-Bashaireh and Al-Muheisen, 2011, Fuller *et al*., 2012a, Gregoricka and Sheridan, 2013),, suggesting again a similar subsistence base for the wider region. Unlike some other bone collagen data-sets (Bourbou *et al*., 2011, Iacumin *et al*., 1998, Thompson *et al*., 2008), the sample from Ya'amūn does not have any statistical outliers that would suggest that individuals moved from ecologically different regions, although the sample size is too small for any far-reaching conclusions and carbon and nitrogen isotopes are not well suited to identify migrants in a population in any case.

7. Conclusions

Despite the small sample sizes which are, unfortunately, a common limitation of bone isotope investigations in arid and semi-arid regions, this study has established a number of clear trends. Of particular importance are differences in animal husbandry between the Middle and Late Bronze Age and Late Antiquity, which involved Bronze Age sheep/goats spending at least part of the year in arid or semi-arid regions, while Romano-Byzantine animals evidently stayed in the same phytogeographic zone. The reason behind this significant economic change may be the greater abundance of suitable fodder in the slightly wetter climate of Late Antiquity or else the need to keep the human workforce on-site to concentrate on other agricultural tasks, including the work-intensive viticulture (Horden and Purcell, 2000, 215). The cattle data from this period nevertheless show that the site was still connected to the drier regions to the East and South, possibly reflecting the move to expand agricultural production to the more marginal areas in the Byzantine period (Watson, 2008). As expected based on the results of previous studies, the human diet in both periods was based almost exclusively on C_3-based resources. While most isotopic differences between the human groups can be explained in terms of a baseline shift due to climatic change between the two periods, the Middle and Late Bronze Age inhabitants of Yaʻamūn may have consumed a greater proportion of leguminous plants, while the diet in Late Antiquity could have included a wider range of foods. Alternatively, their isotopic data may reflect the documented agricultural intensification in this period. Neither freshwater nor marine fish seem to have contributed significantly to the food intake of the sampled individuals. Overall, this study illustrates the need to analyse coeval faunal remains for human palaeodietary studies and confirms the great value of carbon and nitrogen stable isotope analysis of herbivores for reconstructing environmental conditions in relation to changes in geographical location and climate.

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Table

Table 1. Descriptive statistics (group sizes, mean δ^{13}C and δ^{15}N, standard deviations and minimum and maximum values) for human and faunal samples from Ya'amūn

Group	n	mean δ^{13}C (‰) (min – max)	s.d.	mean δ^{15}N (‰) (min – max)	s.d.
MB and LB sheep/goats	6	-18.6 (-20.1 – -16.6)	1.4	8.5 (5.8 – 11.4)	1.9
LR/Byz sheep/goats	5	-19.3 (-20.1 – -19.6)	0.5	5.3 (4.0 – 6.4)	0.9
LR/Byz cattle	2	-18.8 – -15.6		5.4 – 9.7	
MB and LB humans	15	-18.8 (-19.4 – -18.3)	0.3	8.8 (7.4 – 9.8)	0.7
LR/Byz humans	17	-19.1 (-19.8 – -18.5)	0.3	8.1 (7.3 – 9.0)	0.6
Freshwater fish	3	-16.8 (-21.5 – -10.3)	5.8	6.9 (6.1 – 9.3)	2.0
Marine fish	2	-7.2 (-9.7 0 -4.7)	3.5	10.4 (8.2 – 12.6)	3.1

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Figure Legends

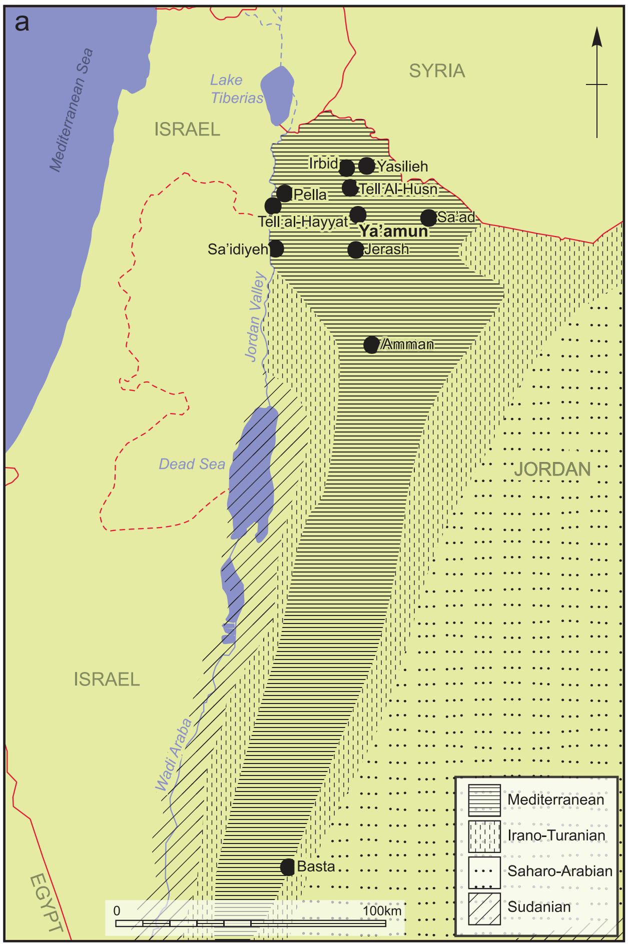
Figure 1. Map of Jordan with sites mentioned in the text superimposed on (**1.a**) the modern phytogeographic zones (based on data from Zohary 1973 and Al-Eisawi 1985, redrawn from Cordova 2007, Figure P.1, and Palmer 2013, Figure I.18) and (**1.b**) a rainfall map of modern Jordan (redrawn from Kennedy 2007, fig. 3.4a).

Figure 2. Carbon and nitrogen isotope data of Mid- and Late Bronze Age and Late Roman/Byzantine sheep/goats from Ya'amūn. $\delta^{13}C$ and $\delta^{15}N$ values of the Bronze Age sheep/goats are positively correlated (Pearson's r=0.87, p=0.026) and therefore consistent with varying consumption of plants from arid and semi-arid environments.

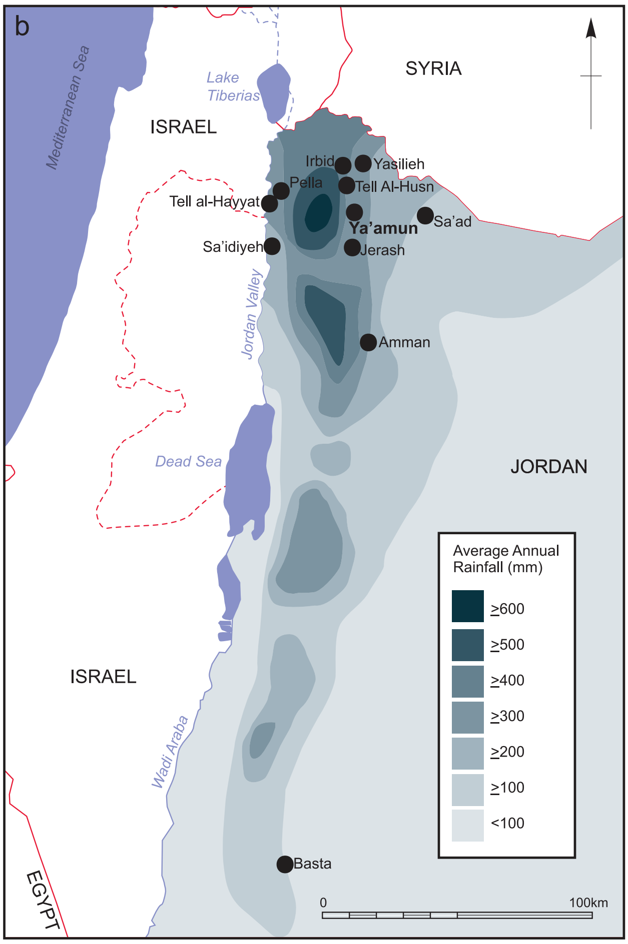
Figure 3. Carbon and nitrogen isotope data of Mid- and Late Bronze Age and Late Roman/Byzantine humans from Ya'amūn in comparison with mean values (± 1sd) for sheep/goats from these time periods. The variation in human values to a large extent mirrors that observed in the fauna.

Figure 4. Carbon and nitrogen isotope data for humans (individual data) and sheep/goats (mean values ± 1sd) from Ya'amūn in comparison with $\delta^{13}C$ and $\delta^{15}N$ values for marine (one specimen each of family *Scienidae* and *Mugilidae*) and freshwater fish (two specimens of Tilapia sp. and one of *Clarias* (catfish)) from the same site.

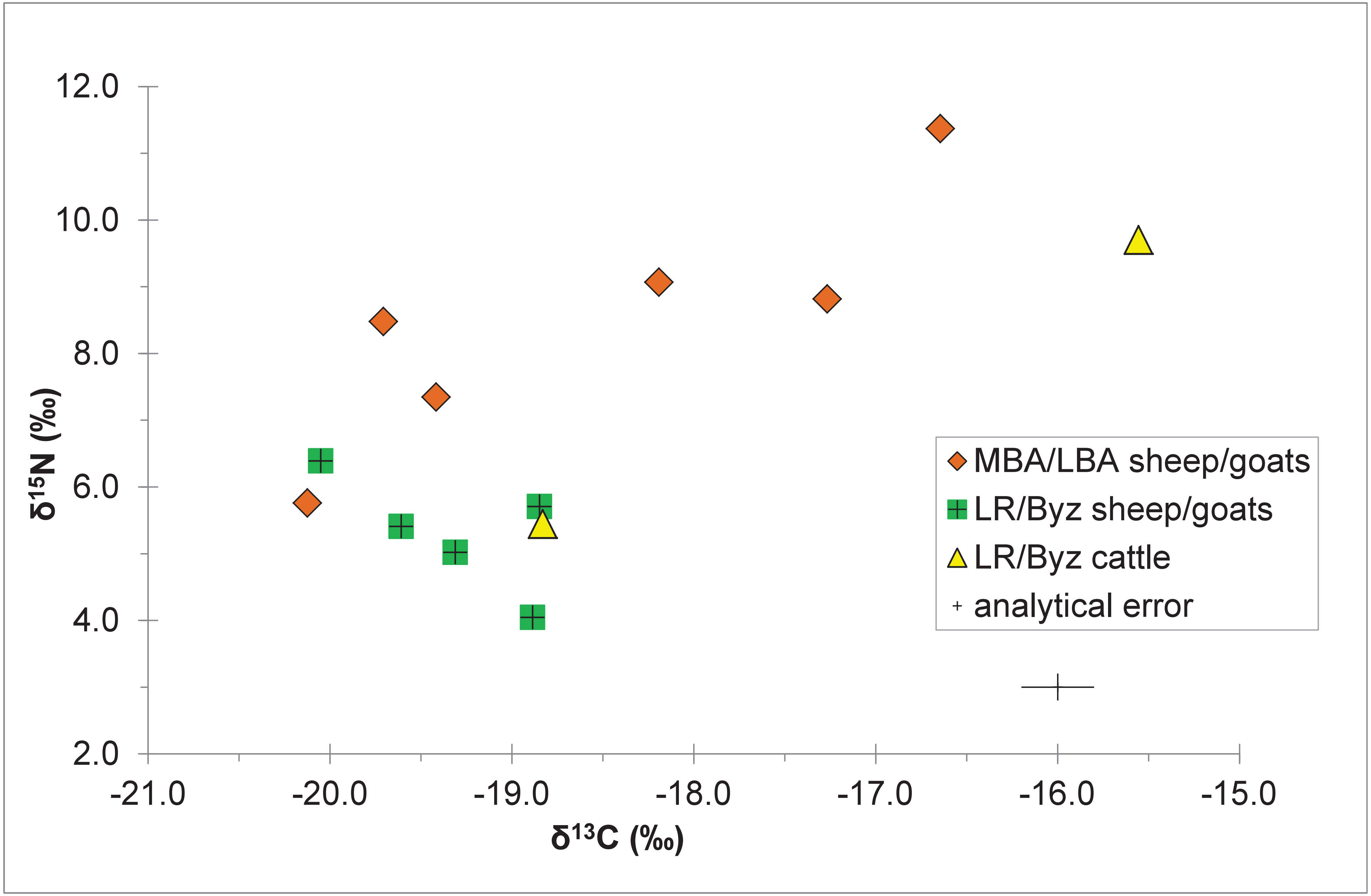
Figure


a
Mediterranean Sea
Lake
Tiberias
SYRIA
ISRAEL
Irbid
Yasilieh
Tell Al-Husn
Pella
Tell al-Hayyat
Sa'ad
Ya'amun
Sa'idiyeh
Jerash
Jordan Valley
Amman
Dead Sea
JORDAN
ISRAEL
Wadi Araba
Basta
EGYPT
0
100km
Mediterranean
Irano-Turanian
Saharo-Arabian
Sudanian

Figure

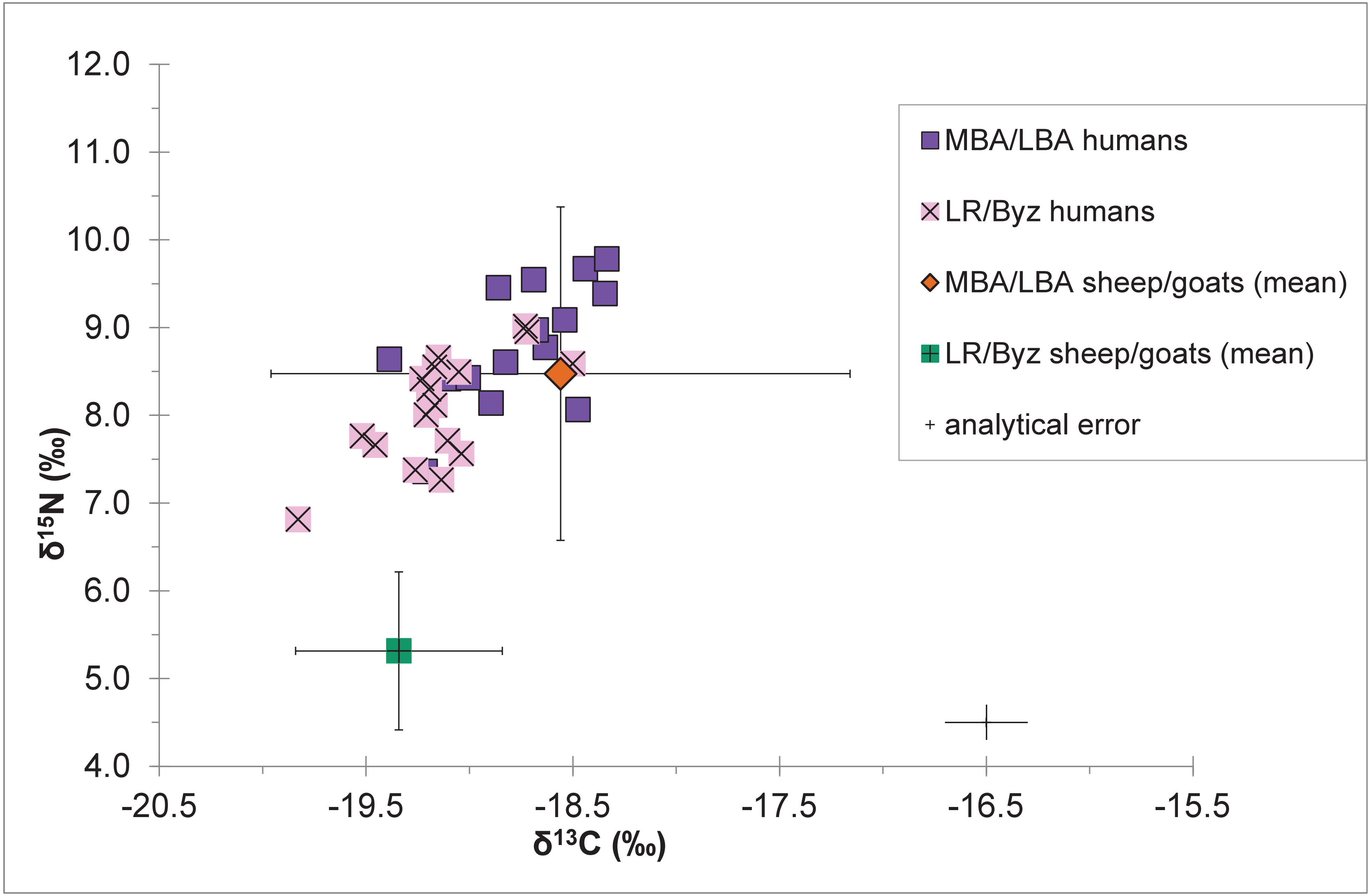

b
Mediterranean Sea
Lake
Tiberias
SYRIA
ISRAEL
Irbid
Yasilieh
Pella
Tell Al-Husn
Tell al-Hayyat
Ya'amun
Sa'ad
Sa'idiyeh
Jerash
Jordan Valley
Amman
Dead Sea
JORDAN
Average Annual
Rainfall (mm)
≥600
≥500
≥400
≥300
≥200
≥100
<100
ISRAEL
Wadi Araba
Basta
0
100km
EGYPT

Figure



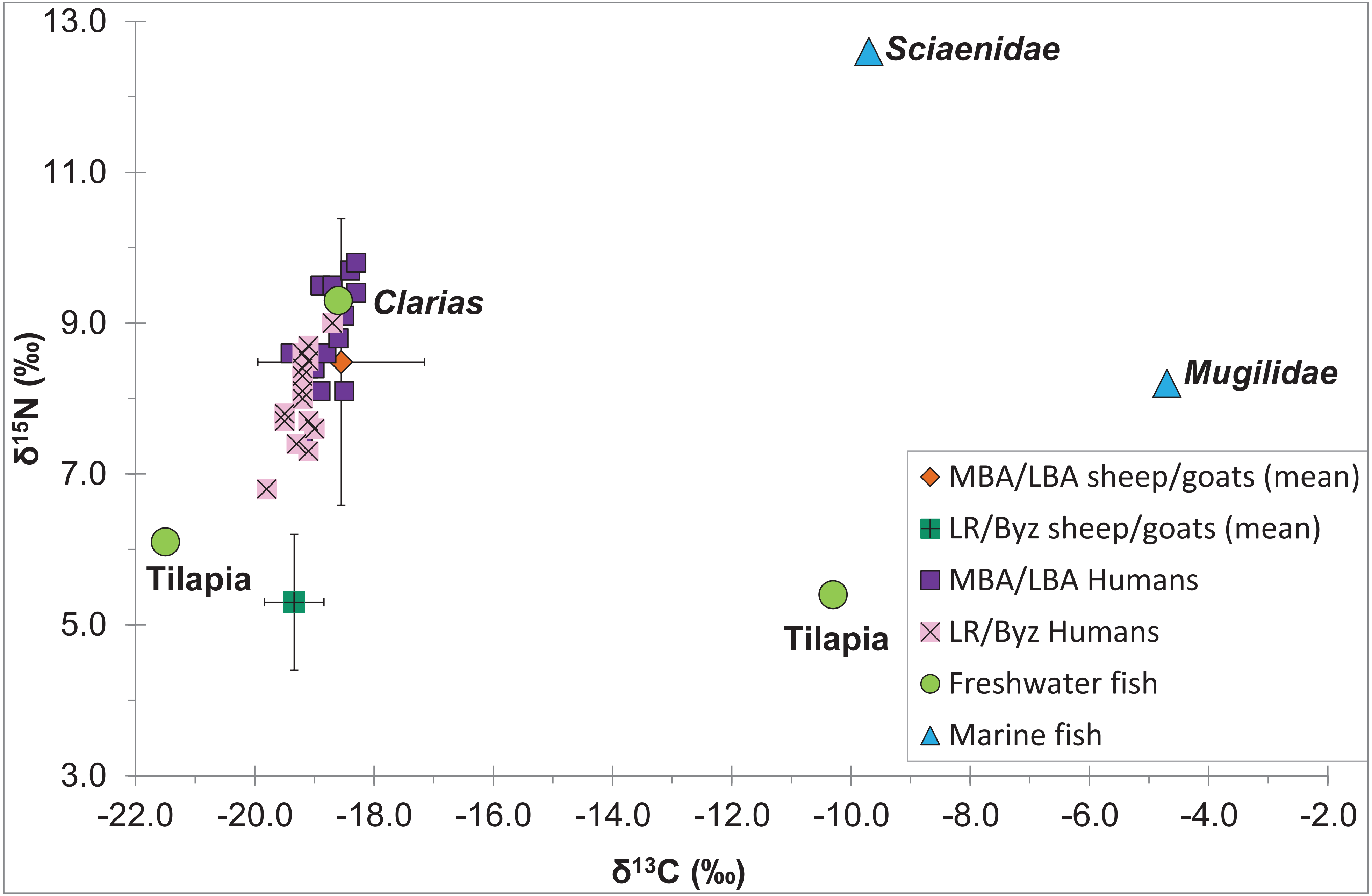
12.0
10.0
8.0
6.0
4.0
2.0
δ15N (‰)
-21.0
-20.0
-19.0
-18.0
-17.0
-16.0
-15.0
δ13C (‰)
MBA/LBA sheep/goats
LR/Byz sheep/goats
LR/Byz cattle
analytical error

Figure



12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
δ15N (‰)
-20.5
-19.5
-18.5
-17.5
-16.5
-15.5
δ13C (‰)
MBA/LBA humans
LR/Byz humans
MBA/LBA sheep/goats (mean)
LR/Byz sheep/goats (mean)
analytical error

Figure



Sciaenidae
Clarias
Mugilidae
Tilapia
Tilapia
MBA/LBA sheep/goats (mean)
LR/Byz sheep/goats (mean)
MBA/LBA Humans
LR/Byz Humans
Freshwater fish
Marine fish
δ15N (‰)
δ13C (‰)
13.0
11.0
9.0
7.0
5.0
3.0
-22.0
-20.0
-18.0
-16.0
-14.0
-12.0
-10.0
-8.0
-6.0
-4.0
-2.0

Supplementary Information

Diet and herding strategies in a changing environment: stable isotope analysis of Bronze Age and Late Antique skeletal remains from Ya‘amūn, Jordan

Sample Preparation and Analytical Methods

Cortical bone from the diaphysis of long bones, taken from areas devoid of any pathological lesions, was the preferred sampling material. Samples consisted of bone chunks weighing between 200 and 300 mg. All outer surfaces were abraded with the aid of a drill before collagen extraction was carried out following the Longin ((1971) method modified according to recommendations by Collins and Galley (1998). . Briefly, bone chunks were demineralised in 0.5 M in the fridge for several days, after which they were rinsed to neutrality with ultrapure water (Milli-Q®). The samples were then placed in a pH3 HCl solution and gelatinised in a heater-block at 70 degrees C for 48 hours. Acid insoluble residues where removed with the aid of an Ezee®-filter (60-90µm, Elkay) and the remaining solutions was frozen and then freeze-dried for 48h. Aliquots of between 0.9 and 1.1 mg of freeze-dried ‘collagen’ were weighed in duplicates into ultraclean tin capsules.

Carbon and nitrogen stable isotope compositions of samples were determined by analysis on a Europa Geo 20-20 Continuous Flow Isotope Ratio Mass Spectrometer (CF-IRMS) interfaced with Sercon® elemental analyser (EA) in the School of Human and Environmental Sciences, University of Reading, UK. All $\delta^{13}C$ values are expressed relative to Pee Dee Belemnite (V-PDB) and while the $\delta^{15}N$ values are referred to atmospheric nitrogen (AIR). The analytical error was calculated from repeat analysis of internal collagen standards included in each run and was determined at ±0.2‰ (1sd) or better for $\delta^{13}C$, and $\delta^{15}N$ measurements. Internal working standards which were calibrated to internationally certified reference materials included the amino acid methionine (Elemental Microanalysis/MethR), powdered Bovine Liver Standard (NIST1577a/BLS) and a batch of pork gelatine prepared at the Reading stable isotope laboratory (“Reading Pork Gelatine”/RPG).

Collagen samples were considered of acceptable quality when having an atomic C:N ratio between 2.9 and 3.6, %C ≥ 13% and %N ≥ 4.8% (Ambrose, 1990, DeNiro, 1985). Samples that yielded less than 1% collagen were still regarded as acceptable if they fulfilled these criteria and if their $\delta^{13}C$ and $\delta^{15}N$ ratios were not unusual within the population context (van Klinken 1999). Inferential statistics were computed with SPSS v.19.

References

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Table S1. Carbon and nitrogen stable isotope data and collagen quality indicators of faunal bone samples from Ya‘amūn. Archaeological dates are abbreviated as follows: MBA=Middle Bronze Age; LBA=Late Bronze Age; LR/Byz=Late Roman/Byzantine. Nil refers to samples which yielded no collagen for analysis.

Species	**Sample Code**	**Date**	**δ^{13}C**	**δ^{15}N**	**%C**	**%N**	**C:N**	**%Coll**
Bos	YMN fb 084	MBA						Nil
Sheep/Goat	YMN fb 085	MBA						Nil
Sheep/Goat	YMN fb 086	MBA	-19.7	8.5	40.3	14.0	3.4	1.3
Sheep/Goat	YMN fb 087	MBA	-16.6	11.4	19.5	6.8	3.4	2.6
Fish (*Sciaenidae).*	YMN fb 088	MBA	-9.7	12.6	40.0	14.3	3.3	6.6
Sheep/Goat	YMN fb 089	MBA	-19.4	7.3	41.1	13.8	3.5	0.8
Sheep/Goat	YMN fb 090	MBA						Nil
Sheep/Goat	YMN fb 074	LBA						Nil
Sheep/Goat	YMN fb 075	LBA	-20.1	5.8	42.8	15.0	3.3	3.1
Sheep/Goat	YMN fb 076	LBA	-17.3	8.8	42.8	15.2	3.3	2.7
Sheep/Goat	YMN fb 077	LBA	-18.2	9.1	42.6	15.1	3.3	7.2
Sheep/Goat	YMN fb 078	LBA						Nil
Sheep/Goat	YMN fb 092	LR/Byz	-19.3	5.0	41.6	15.0	3.2	9.0
Sheep/Goat	YMN T fb 093	LR/Byz	-18.8	5.7	39.0	14.2	3.2	12.0
Bos	YMN T fb 094	LR/Byz	-18.8	5.4	42.3	15.2	3.3	3.4
Bos	YMN T fb 095	LR/Byz	-15.6	9.7	44.1	16.0	3.2	16.0
Sheep/Goat	YMN T fb 096	LR/Byz	-20.1	6.4	38.0	13.3	3.3	4.1
Sheep/Goat	YMN T fb 097*	LR/Byz	-18.9	4.0	43.6	16.0	3.2	18.2
Sheep/Goat	YMN T fb 098	LR/Byz	-19.6	5.4	41.1	14.7	3.3	9.2
Fish (*Mugilidae)*	YMN T fb 099	LR/Byz	-4.7	8.2	43.1	15.8	3.2	12.0
Fish (Tilapia sp.)	YMN T fb 100	LR/Byz	-21.5	6.1	43.2	15.7	3.2	10.0
Fish (Tilapia sp.)	YMN T fb 101	LR/Byz	-10.3	5.4	42.4	15.5	3.2	9.4
Fish (*Claridae)*	YMN T fb 102	LR/Byz	-18.6	9.3	41.2	14.9	3.2	6.0

Table S2. Carbon and nitrogen stable isotope data and collagen quality indicators of human bone samples from Ya‘amūn. Archaeological dates are abbreviated as follows: MBA=Middle Bronze Age; LBA=Late Bronze Age; LR=Late Roman; Byz= Byzantine. Nil refers to samples which yielded no collagen for analysis.

Sample Code	Date	$\delta^{13}C$	$\delta^{15}N$	%C	%N	C:N	%Coll
YMN hb 001	MBA	-19.4	8.6	40.4	14.0	3.4	0.9
YMN hb 002	MBA	-19.1	8.4	42.2	14.8	3.3	4.0
YMN hb 003	MBA	-18.9	9.5	42.2	14.7	3.3	2.0
YMN hb 004	MBA	-19.2	7.4	41.5	13.9	3.5	0.6
YMN hb 005	MBA						Nil
YMN hb 006	MBA	-19.0	8.4	41.6	13.5	3.6	1.3
YMN hb 007	MBA						Nil
YMN hb 008	MBA						Nil
YMN hb 009	MBA	-18.5	9.1	41.0	14.6	3.3	4.3
YMN hb 010	MBA	-18.3	9.4	43.4	15.6	3.2	9.3
YMN hb 011	MBA	-18.4	9.7	43.8	15.7	3.3	7.5
YMN hb 012	MBA						Nil
YMN hb 013	MBA	-18.6	8.8	42.9	15.4	3.3	9.0
YMN hb 014	MBA	-18.9	8.1	43.3	15.7	3.2	10.0
YMN hb 015	MBA	-18.3	9.8	42.4	15.3	3.2	5.1
YMN hb 016	MBA	-18.8	8.6	43.0	15.7	3.2	14.5
YMN hb 017	LBA						Nil
YMN hb 018	LBA						Nil
YMN hb 019	LBA	-18.7	9.0	42.8	15.4	3.2	6.0
YMN hb 020	LBA						Nil
YMN hb 021	LBA	-18.7	9.5	42.0	15.1	3.2	2.8
YMN hb 022	LBA	-18.5	8.1	39.0	13.8	3.3	4.0
YMN hb 023	LR						Nil
YMN hb 024	LR	-19.1	8.5	41.4	15.1	3.2	10.0
YMN hb 025	LR	-18.7	9.0	42.8	15.3	3.3	10.0
YMN hb 026	LR	-19.5	7.7	40.9	14.1	3.4	1.3
YMN hb 027*	Byz	-18.5	8.6	43.0	15.5	3.2	17.0
YMN hb 028	Byz	-19.1	7.3	38.5	13.5	3.3	3.5
YMN hb 029	Byz	-19.3	7.4	39.1	13.6	3.4	3.6
YMN hb 030	Byz	-19.2	8.0	35.9	12.5	3.3	2.6
YMN hb 031	Byz	-19.8	6.8	42.0	14.9	3.3	3.6
YMN hb 032	Byz	-19.1	7.7	43.4	15.3	3.3	3.3
YMN hb 033	Byz	-19.5	7.8	28.9	9.9	3.4	3.7
YMN hb 034	LR/Byz	-19.0	7.6	33.0	11.7	3.3	5.8
YMN hb 035	LR/Byz	-19.2	8.6	38.3	13.5	3.3	7.2
YMN hb 036	LR/Byz						Nil
YMN hb 037	LR/Byz						Nil
YMN hb 038	LR/Byz	-19.2	8.3	43.0	15.0	3.4	6.0
YMN hb 039	LR/Byz	-19.2	8.1	41.6	14.3	3.4	4.2
YMN hb 040	LR/Byz						Nil
YMN hb 041	LR/Byz						Nil
YMN hb 042	LR/Byz						Nil
YMN hb 043	LR/Byz	-18.7	9.0	43.4	15.6	3.2	6.8
YMN hb 044*	LR/Byz	-19.2	8.4	43.7	15.7	3.2	19.5
YMN hb 045	LR/Byz	-19.1	8.7	42.8	15.1	3.3	11.5