



Subsistence and the isotopic signature of herding in the Bronze Age Hexi Corridor, NW Gansu, China

Pia Atahan^{a,*}, John Dodson^a, Xiaoqiang Li^b, Xinying Zhou^c, Songmei Hu^d, Fiona Bertuch^a, Nan Sun^c

^a Institute for Environmental Research, Australian Nuclear Science and Technology Organisation, Locked Bag 2001, Kirrawee DC NSW 2232, Australia

^b Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Science, 142 Xizhimenwai Street, Beijing 100044, China

^c Institute for Earth Environments, Chinese Academy of Science, High Tech Zone, Xi'an, 710075 Shaanxi, China

^d Shaanxi Archaeological Institute, Leyou Lu, Xi'an, Shaanxi 710054, China

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ABSTRACT

Dietary patterns at two Bronze Age sites in the Hexi Corridor are investigated by the analysis of stable carbon and nitrogen isotopes in faunal bone collagen. The findings are compared with archaeobotanical remains from one of the sites which include high proportions of millet (*Panicum miliaceum* and *Setaria italica*) as well as the western derived cereals wheat (*Triticum aestivum*), barley (*Hordeum vulgare*) and oat (*Avena sativa*). The isotopic data indicate domestic omnivores (*Canis* and *Sus*) had diets dominated by millet. Minimally offset $\delta^{15}\text{N}$ values between herbivore and omnivore fauna suggest low consumption of animal protein by omnivores. Diets of herded animal (*Bos* and *Caprinae*) included only low proportions of C4 foods, suggesting that these animals were not regularly foddered with millet plants, and that their grazing areas were mostly beyond the agricultural zone. The wide range in $\delta^{15}\text{N}$ values amongst herbivore fauna (4.1‰–11.8‰) suggests grazing occurred in a variety of ecological zones, and this would be consistent with the occurrence of long-distance transport of livestock in the region.

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1. Introduction

Systematic study of Bronze Age archaeological sites in the Hexi Corridor has barely commenced, but a picture is emerging of agro-pastoralist economies centred on cultivating millet and keeping livestock including pig, sheep, cattle and horse, while also producing bronze objects of alloyed copper, arsenic and tin (Dodson et al., 2009, in press; Flad et al., 2007; Mei, 2004; Thorp, 2006). The comparatively low-lying Hexi Corridor has been a favoured route for exchange between eastern and western Eurasia in the past, and archaeological remains from Bronze Age sites there include a suite of eastern and western derived domesticates. Seed assemblages are dominated by the Asian millets (*Panicum miliaceum* and *Setaria italica*); also reported are the western derived cereals including; wheat (*Triticum aestivum*), barley (*Hordeum vulgare*) and oat (*Avena sativa*) (Dodson et al., in press; Flad et al., 2010). Stable isotope analysis of bone collagen provides a means to gain direct information about the importance of certain foods at

a site, and when compared with archaeobotanical information, to allow for a better understanding of subsistence practices.

Several methods have been used to reconstruct prehistoric diets at sites across northern China, and the accumulating evidence shows subsistence strategies to vary between regions, particularly in the use of wild foods (e.g. Barton et al., 2009; Li et al., 2010; Liu et al., 2010; Pechenkina et al., 2002, 2005). Palaeodietary work using stable isotopes shows millet to feature heavily in the diets of humans and domestic fauna in the Yellow and Wei River valleys of Gansu and Shaanxi Provinces, during the late Neolithic and Bronze Age (Barton et al., 2009; Pechenkina et al., 2005). In the south, a broader subsistence base is apparent: at Gouwan site (Xichuan County, Henan Province), C3 plant foods feature equally with millet in diets according to isotope analysis (Fu et al., 2010); and at Chenqimogou site (Lintan County, Gansu Province), diets were focused on at least 3 cereals (wheat, barley and millet) as well as other plant foods such as acorn, ginkgo, bean, root and tubers, according to starch grain inclusions in dental calculus (Li et al., 2010). The limited amount of information on Bronze Age diets in Xinjiang Province provides a contrasting picture of subsistence practices. There, human tooth wear patterns at three sites suggest foods were rougher in texture and lower in carbohydrates,

* Corresponding author. Tel.: +61 2 9717 7261.

E-mail address: pia.atahan@ansto.gov.au (P. Atahan).

compared with sites to the east where foods were softer and more extensively processed (Liu et al., 2010; Pechenkina et al., 2002).

Diet reconstructions using isotope analysis have tended to focus on early agricultural centres in the Yellow and Wei River valleys (e.g. Barton et al., 2009; Hu et al., 2006, 2008; Pechenkina et al., 2005). The present study extends this work further west, to the Hexi Corridor region of Gansu Province, and expands on isotopic information from Huoshiliang previously provided by Dodson et al. (in press), by presenting bone collagen $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values for a suite of associated fauna.

1.1. Stable isotopes and diet reconstruction

Isotopic measurements of carbon and nitrogen in bone collagen allow for direct assessment of importance of certain food groups in diets (see recent reviews by Hedges and Reynard (2007) and Lee-Thorp (2008)). This technique stems from the principle that stable isotope ratios in consumer body tissue reflect those of the diet, after a trophic fractionation effect is accounted for. Dietary protein, however, has been shown to disproportionately influence bone collagen $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, due to the high proportion of amino acids that are directly routed to collagen (Ambrose and Norr, 1993; Corr et al., 2005; Fogel and Tuross, 2003; Jim et al., 2004, 2006). As a result, low protein foods, such as cereals, will be under represented in bone collagen isotope values if high protein foods are also being consumed. Carbonate in the mineral portion of bone (bioapatite) derives from the total metabolic carbon pool and therefore, unlike collagen, has an isotopic composition that is unbiased towards dietary protein (see Froehle et al., 2010; Jim et al., 2004; Schwarcz and Schoeninger, 1991). Assessing diagenetic alteration of bioapatite is difficult however, and for this reason collagen (which is more easily assessed) and enamel apatite (which is relatively resistant to diagenetic change) are preferentially used (Kohn and Cerling, 2002; Lee-Thorp, 2008). The emerging technique involving compound specific isotope analysis of the individual amino acids composing bone collagen is providing a new means to assess the isotopic signature of both protein and non-protein components of diets (see Evershed, 2007; Fogel and Tuross, 2003; Howland et al., 2003; Jim et al., 2004, 2006).

Plants utilising the two main photosynthetic pathways, C3 and C4, have marked differences in carbon isotope composition. Strong net discrimination against ^{13}C occurs during C3 photosynthesis, as dissolved mesophyll CO_2 is converted to ribulose biphosphate carboxylase/oxygenase (RUBISCO). Less net discrimination against ^{13}C occurs during C4 photosynthesis, due to CO_2 being concentrated in bundle-sheath cells prior to release into the RUBISCO cycle (O'Leary, 1981; Farquhar et al., 1989). As a result, C3 plants have $\delta^{13}\text{C}$ values that are markedly lower than C4 plants. C3 plant $\delta^{13}\text{C}$ values range between -24 and -36‰ (mean = -26.5‰), while C4 plant $\delta^{13}\text{C}$ values range between -9 and -17‰ (mean = -12.5‰) (Deines, 1980; Smith and Epstein, 1971; Tieszen, 1991). In North China, the Asian millets – early C4 cultigens – are isotopically distinct from the C3 plant dominated natural vegetation and other early cultigens. In archaeological settings, bone collagen $\delta^{13}\text{C}$ is a useful method for inferring presence of an isotopically distinct cultigen (e.g. Finucane et al., 2008; Gil et al., 2009; Vogel and van der Merwe, 1977).

The large $\delta^{15}\text{N}$ offset between diet and bone collagen of around $3\text{--}5\text{‰}$ (Bocherens and Drucker, 2003) is commonly used to infer animal or aquatic food consumption in prehistoric populations (e.g. Bocherens et al., 2007; Richards et al., 2006; Schulting et al., 2008). However $\delta^{15}\text{N}$ is affected by a number of other factors in plants and animals, including: aridity (Murphy and Bowman, 2006; Schwarcz et al., 1999); salinity (Britton et al., 2008; Heaton, 1987); and

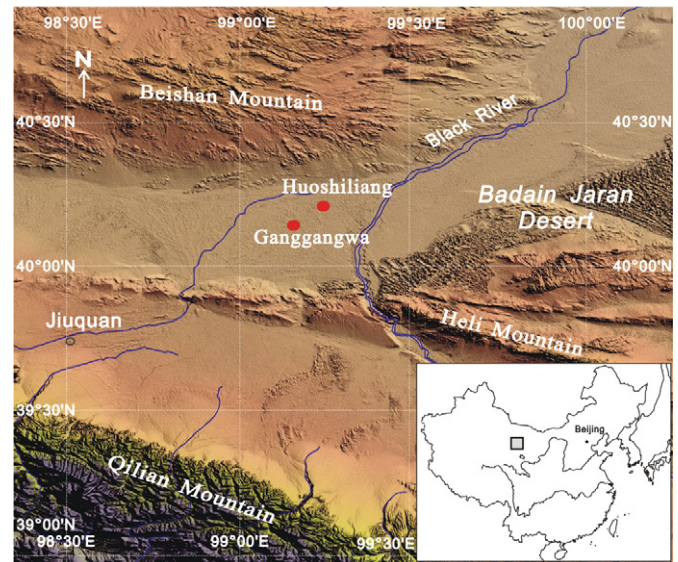


Fig. 1. Map showing the locations of Huoshiliang and Ganggangwa sites in the Hexi Corridor.

manuring (Bogaard et al., 2007). And these other influences have the potential to provide additional information about a study site.

2. Study sites

Huoshiliang and Ganggangwa are located in the Hexi Corridor region of northwest Gansu Province (Fig. 1). The sites are approximately 11 km apart, and are composed of surface scatters of cultural remains, each of which cover several thousand square metres and appear as probable lag deposits between mobile sand dunes (Dodson et al., 2009). Previous work at the sites has focused on early copper metal work remains (Dodson et al., 2009), on human skeletal and cereal seed remains (Dodson et al., in press), and on charcoal fossils of fire wood (Sun et al., 2010).

The Hexi Corridor landscape is arid and sparsely vegetated, mostly with low shrubs and perennial herbs. Available water is limited to desert rivers and oases fed by water flowing northwards from the Qilian Mountains. Historically, human activity in the region has been restricted to areas of available water, and settlement sites have shifted in response to changing hydrological regimes and water management practices (Hou, 1985; Wang et al., 2005; Zhang, 2006).

Radiocarbon dates on material collected from Huoshiliang and Ganggangwa sites (Table 1) shows calibrated ages from Huoshiliang range from ca. 2135–1692 BC, and this narrow age range (which includes dates taken from a trench section through the cultural remains to 1.6 m depth) suggests the sediments accumulated quickly, and/or could have been exposed to a degree of mixing.

Calibrated ages at Ganggangwa fall within two different phases, an earlier phase that corresponds with the cultural remains at Huoshiliang, ca. 2292–1758 BC, and a later phase from ca. AD 237–666. The later phase is based on two charcoal samples that were collected near to remains of smelting pits, some hundreds of metres from the main surface scatter area. This clear separation of radiocarbon ages suggests at least two periods of occupation at Ganggangwa.

3. Methods

Thirty mammal bone specimens collected from Huoshiliang and Ganggangwa sites were prepared for $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ measurement

Table 1
AMS ¹⁴C dates for samples taken from Huoshiliang and Gangangwa sites.

Lab code	Site	Depth (cm)	Sample type	AMS ¹⁴ C age (BP)	Calibrated age range (2σ)
OZK596 ^a	Huoshiliang	0–5	Charcoal	3516 ± 52	2009–1693 BC
OZK597 ^a	Huoshiliang	40–45	Charcoal	3538 ± 47	2015–1745 BC
OZK598 ^a	Huoshiliang	80–85	Charcoal	3566 ± 49	2032–1757 BC
OZK599 ^a	Huoshiliang	140–145	Charcoal	3509 ± 50	1957–1692 BC
OZK600 ^a	Huoshiliang	163	Charcoal	3601 ± 57	2135–1775 BC
OZK603 ^a	Huoshiliang	80–100	Seed	3636 ± 44	2135–1895 BC
OZM248	Huoshiliang	Surface	Charcoal	3555 ± 40	2020–1769 BC
OZM249	Huoshiliang	Surface	Charcoal	3579 ± 38	2032–1777 BC
OZL292 ^b	Huoshiliang	Surface	Bone collagen	3515 ± 45	1892–1859 BC
OZL293 ^b	Huoshiliang	Surface	Bone collagen	3590 ± 45	2016–1996 BC
OZL294 ^b	Huoshiliang	Surface	Bone collagen	3515 ± 40	1896–1862 BC
OZK657 ^a	Gangangwa	Surface	Charcoal	3737 ± 50	2292–1979 BC
OZK658 ^a	Gangangwa	Surface	Seed	3558 ± 47	2026–1758 BC
OZK659 ^a	Gangangwa	Surface	Charcoal	1565 ± 113	AD 237–666
OZM245	Gangangwa	Surface	Charcoal	3652 ± 40	2140–1915 BC
OZM246	Gangangwa	Surface	Charcoal	3744 ± 383	2283–2033 BC
OZM247	Gangangwa	Surface	Charcoal	1908 ± 34	AD 21–213

^a Dates previously published by Dodson et al. (2009).^b Dates previously published by Dodson et al. (in press).

using the ultra-filtration method (Brock et al., 2007; Bronk Ramsey et al., 2004; Brown et al., 1988; Higham et al., 2006) (see Tables 2 and 3 for a list of samples). The specimens were selected from the surface scatters. Samples were wrapped in aluminium foil and placed in separate labelled sample bags at the time of collection. The preparation of collagen used about 1 g of clean ground bone. Compact bone, rather than trabecular, was used whenever possible. The procedure involved removal of the outer bone surface by abrasion; acid–alkali–acid treatment (0.5 M HCl, 0.1 M NaOH, 0.5 M HCl); gelatinization (pH 3, 75 °C, 20 h); Ezee-filtration (5–8 μm); ultra-filtration (30 kDa); and freeze-drying.

Isotopic analysis was carried out in the AMS chemistry laboratories at the Australian Nuclear Science and Technology Organisation (ANSTO). $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, C%, N% and atomic C/N ratio were measured on an Elemental Analyser (EuroVector EA3000) and an Isotope Ratio Mass Spectrometer (GV Instruments IsoPrime). The

Table 2
Isotope and quality indicator measurements of bone collagen from Huoshiliang site.

Lab code	Taxon	% collagen (>30 kDa)	Carbon content (%)	Nitrogen content (%)	Atomic C/N	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$
SI1555	Cervinae	3.3	44	15	3.2	–18.9	5.8
SI1556	Rattus	2.8	44	15	3.3	–8.1	8.7
SI1557	Rattus	2.6	44	15	3.2	–8.8	8.2
SI1558	Cervus	5.6	45	16	3.2	–18.9	5.0
SI1559	Cervus	4.7	44	15	3.3	–18.5	5.9
SI1560	Canis	5.0	43	15	3.2	–11.7	8.4
SI1561	Canis	6.5	44	15	3.2	–11.6	8.3
SI1562	Canis	5.2	42	15	3.2	–15.8	6.8
SI1563	Sus	3.5	43	15	3.2	–19.3	7.1
SI1564 ^a	Bos	0.2	43	14	3.3	–16.4	7.3
SI1565	Cervus	4.6	43	15	3.2	–19.4	4.9
SI1566	Sus	3.0	44	15	3.2	–7.7	8.0
SI1567 ^a	Cervinae	0	–	–	–	–	–
SI1568	Caprinae	3.7	43	15	3.3	–18.1	6.3
SI1569	Caprinae	3.1	43	15	3.2	–18.4	7.9
SI1570	Cervinae	5.5	44	15	3.2	–19.0	5.4
SI1571	Cervinae	5.5	43	15	3.2	–15.2	6.5
SI1572	Bos	3.0	43	15	3.2	–19.0	4.1
OZL292 ^b	Human	6.5	–	–	3.2	–8.71	6.10
OZL293 ^b	Human	4.1	–	–	3.2	–8.86	9.76
OZL294 ^b	Caprinae	6.5	–	–	3.2	–18.5	11.83

^a Samples excluded from further analyses due to their having less than 0.5% collagen yield.^b Samples previously published in Dodson et al. (in press).**Table 3**
Isotope and quality indicator measurements of bone collagen from Gangangwa site.

Lab code	Taxon	% collagen (>30 kDa)	Carbon content (%)	Nitrogen content (%)	Atomic C/N	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$
SI1576 ^a	Rattus	0.2	40	14	3.3	–16.5	8.6
SI1577	Bos	3.3	44	15	3.2	–18.6	5.3
SI1578	Bos	3.4	44	15	3.2	–18.2	8.5
SI1579	Felidae	1.5	44	15	3.2	–10.9	9.8
SI1580	Sus	1.7	43	15	3.2	–16.0	12.2
SI1581	Caprinae	1.7	46 ± 3	16	3.3	–15.6	10.0
SI1583	Bos	2.0	45	15	3.2	–18.3	9.3
SI1584	Cervinae	0.9	45 ± 2	15	3.2	–17.9	9.4
SI1585	Sus	0.7	45	16	3.2	–7.9	9.2
SI1586	Cervinae	4.0	44	15	3.2	–14.8	7.2
SI1587	Rattus	0.7	41	14	3.3	–10.4	11.3
SI1588	Bos	4.4	43	15	3.2	–18.4	7.3

^a Sample excluded from further analyses due to it having less than 0.5% collagen yield.

reference materials used were: $\delta^{13}\text{C}$ – IAEA C8 oxalic acid with a consensus value of -18.31‰ VPDB (Gonfiantini et al., 1995; Le Clercq et al., 2006); $\delta^{15}\text{N}$ – IAEA N-3 with a consensus value of $\delta^{15}\text{N}_{\text{AIR}} = +4.7\text{‰}$ and IAEA N-2 with a consensus value of $\delta^{15}\text{N}_{\text{AIR}} = +20.3\text{‰}$ (Bohlke and Coplen, 1995); 3:1 atomic ratio standard – Internal standard of 2-isopropylimidazole; ‘Chitin Organic Analytical Standard’ with respective carbon and nitrogen values of 44.71% and 6.79% (Elemental Microanalysis Catalogue No. B2160); and an internal standard of undenatured bovine achilles tendon collagen. Samples were run in duplicate and the analytical precision was 0.1‰ for $\delta^{13}\text{C}$ values and 0.2‰ for $\delta^{15}\text{N}$ values.

4. Results

4.1. Collagen preservation

Collagen is well preserved in most of the bone samples (see Tables 2 and 3). Atomic C/N ratios range from 3.2 to 3.3 (mean = 3.2, s.d. = 0), carbon values range from 40% to 46% (mean = 4.3%, s.d. = 1.1) and nitrogen from 14% to 16% (mean = 15%, s.d. = 0.5). Collagen yields were low in all samples (mean = 3.1%, s.d. = 1.8), and this is likely to be due to the use of ultra-filters to remove material with a molecular weight below 30 kDa. Low collagen yields have previously been attributed to this preparation step (see Jørkov et al., 2007; Thompson et al., 2005). Three samples yielding less than 0.5% of collagen (SI1564, SI1567 and SI1576) were excluded from further analyses. Three samples yielding between 0.5% and 1% collagen (SI1584, SI1585 and SI1587) were included, as the other quality measures (nitrogen and carbon percent and C/N ratio) indicated that the collagen was sufficiently preserved. The low collagen yield of these samples is most likely due to the loss of material during sample processing.

4.2. Carbon isotopes

The faunal samples had a wide range in $\delta^{13}\text{C}$ values, from -19.4‰ to -7.7‰ , indicating that both C3 and C4 plants contributed to their diets. $\delta^{13}\text{C}$ values of the fauna clearly fall into three groups with $\delta^{13}\text{C}$ values falling between: -19.4‰ and -17.9‰ ; -16.0‰ and -14.8‰ ; and -11.7‰ and -7.7‰ (see Fig. 2). Only omnivore and carnivore fauna compose the group with the most positive $\delta^{13}\text{C}$ values and their $\delta^{13}\text{C}$ values are within the range expected for diets dominated by C4 plants, or protein from animals fed C4 plants.

A two-end member linear mixing model used by Schwarcz et al. (1985) estimates proportions of C4 plant foods in herbivore diets. The equation follows:

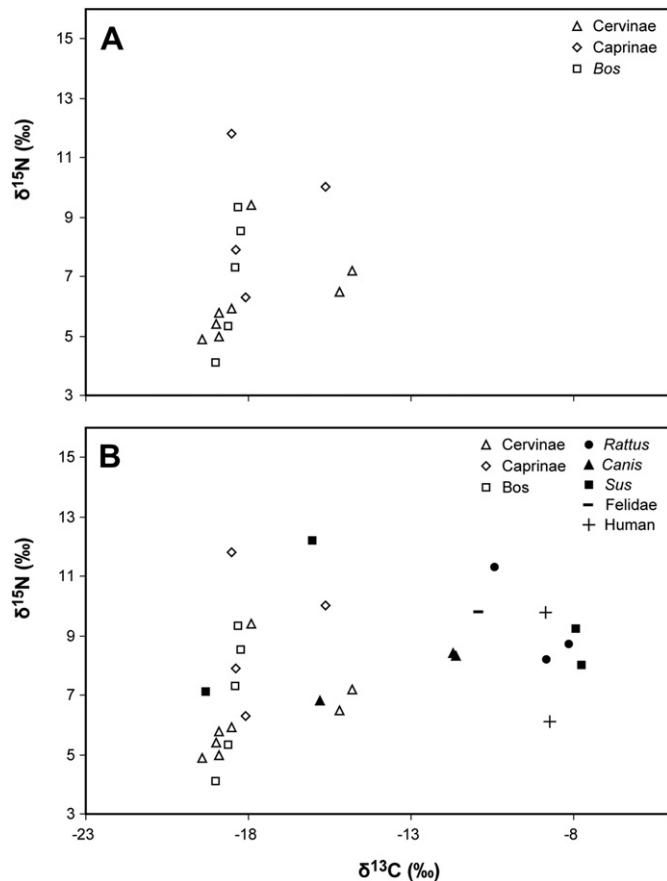


Fig. 2. Plot of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ data measured from herbivore (A & B) and omnivore and carnivore (B) bone collagen samples from Huoshiliang and Gangangwa sites. Isotope values are listed in Tables 2 and 3.

$$\%C4 = \frac{\delta_c - \delta_3 + \Delta_{dc}}{\delta_4 - \delta_3} \times 100$$

where δ_c is the measured $\delta^{13}\text{C}$ of bone collagen, δ_3 is a mean $\delta^{13}\text{C}$ value for C3 plants taking into account a 1.5‰ offset due to the effects of fossil fuel combustion (−25‰) (Marino and McElroy, 1991; Tieszen and Fagre, 1993; White and Schwarz, 1994), δ_4 is the mean $\delta^{13}\text{C}$ value for 14 prehistoric millet seeds measured at various sites in north China (−11.9‰; data to be presented in a forthcoming paper) and Δ_{dc} is the fractionation factor between diet and bone collagen (−5‰) (van der Merwe and Vogel, 1978). The model estimates that C4 plant consumption in herbivore diets at Huoshiliang and Gangangwa ranged from 4.6% to 39.7%. This model has not been applied to omnivore or carnivore samples, as it does not account for bias towards dietary animal protein in bone collagen $\delta^{13}\text{C}$ values (Thompson et al., 2008).

4.3. Nitrogen isotopes

Herbivore $\delta^{15}\text{N}$ values range from 4.1‰ to 10.0‰ and omnivore/carnivore $\delta^{15}\text{N}$ values range from 6.8‰ to 12.2‰. The difference in mean $\delta^{15}\text{N}$ of the omnivore/carnivore and herbivore samples across both the sites is 1.6‰, and this is less than the generally stated trophic level offset of 3–5‰ (Bocherens and Drucker, 2003; Schoeninger and DeNiro, 1984).

Comparison of $\delta^{15}\text{N}$ values from each of the study sites shows a general tendency for higher $\delta^{15}\text{N}$ values at Gangangwa compared with those at Huoshiliang (see Fig. 3). A significant difference exists

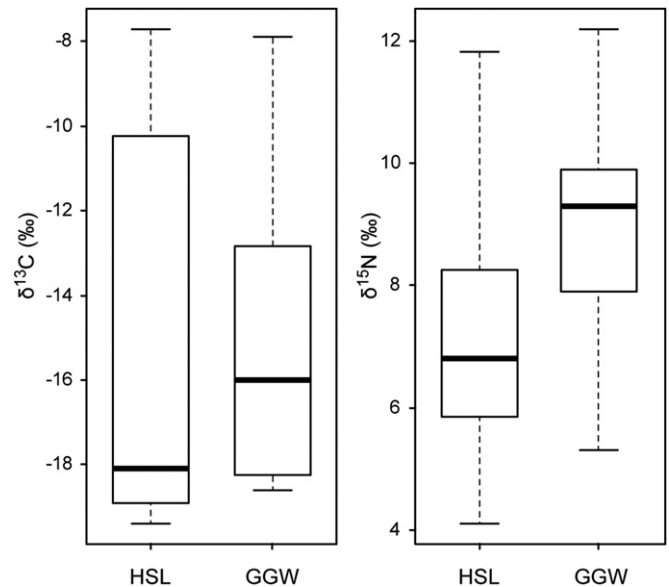


Fig. 3. Box plots comparing $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values for Huoshiliang (HSL) and Gangangwa (GGW) sites.

between mean $\delta^{15}\text{N}$ values of the two sites according to a two-sample *t*-test ($t = -2.67$, d.f. = 20.57, *P*-value = 0.01; including values from Huoshiliang previously published by Dodson et al. (in press)). No significant difference exists between mean $\delta^{13}\text{C}$ values of the two sites ($t = 0.13$, d.f. = 24.57, *P*-value = 0.89).

5. Discussion

5.1. Cereal and animal protein consumption

Omnivore fauna $\delta^{13}\text{C}$ values are between −11.7‰ and −7.7‰ in all but three samples, and these values reflect diets dominated by millet, or millet-fed animals. The two humans from Huoshiliang also have bone collagen $\delta^{13}\text{C}$ values within this range (Dodson et al., in press), and this high consumption of millet is consistent with the current understanding of diets in late Neolithic and early Bronze Age north China (Barton et al., 2009; Pechenkina et al., 2002, 2005). The millet variety likely to have been mostly consumed at the study sites is *P. miliaceum* (broomcorn millet), as this cereal dominates the seed remains recovered from Huoshiliang (Dodson et al., in press). Dietary difference inferred from bone collagen isotope analysis has been used to distinguish between wild and domestic animals at other archaeological sites in North China (e.g. Barton et al., 2009; Guan et al., 2007) and a similar distinction can be applied to the *Sus* and *Canis* presented here. Whereby the pigs and dogs with $\delta^{13}\text{C}$ values higher than −12‰ are likely to have been domestic, consuming millet-rich human waste and scraps, while the other pigs and dog, with lower $\delta^{13}\text{C}$ values, are likely to have been living beyond human settlements and consuming wild foods.

The 1.6‰ difference between mean herbivore and mean omnivore $\delta^{15}\text{N}$ values suggests the inclusion of some animal protein in omnivore diets, and/or the application of manure fertilizer on millet fields that were subsequently harvested and consumed by omnivores. It is unlikely that the isotopic offset between herbivores and omnivores in this study was produced by the effects of differing $\delta^{15}\text{N}$ in the grain and chaff of millet (as discussed by Pechenkina et al. (2005)), as herbivore diets appear to have contained only minimal amounts of C4 foods. The distinctly different $\delta^{13}\text{C}$ values of herbivore and most omnivore fauna suggest that neither domestic nor wild herbivore protein (flesh, milk or blood products)

contributed heavily to human or domestic omnivore diets. Animal protein in omnivore diets appears to have predominantly been that of high millet consumers, which in this sample set comprise *Sus*, *Canis*, *Rattus* and the predatory taxon Felidae.

The isotopic evidence for low consumption of herbivore protein by omnivores at Huoshiliang and Gangangwa is surprising, given that herbivore bone, stone arrow heads and other hunting tools are abundant at the sites, and that Bronze Age societies in the Hexi Corridor are considered to have been agro-pastoral in nature. Similar findings for low herbivore protein consumption based on bone collagen isotope data have been reported at another agro-pastoral society in southern Turkmenistan (Bocherens et al., 2006). This discordance, between palaeodiet reconstructions using isotopic evidence and those using a complete archaeological assemblage, could arise from the potentially longer periods of time and larger human populations relating to a site's archaeological remains, compared with isotopic information which reflects individual diets over the last 10–30 years of life (Bocherens et al., 2006). A better understanding of this discordance will be gained as isotopic methods are applied to more agro-pastoralist sites in Asia.

Wheat, barley and oat remains have been recovered in low proportion from Huoshiliang (Dodson et al., in press) as well as other Bronze Age sites in the Hexi Corridor and Yellow River valley (Flad et al., 2010; Lee et al., 2007; Li et al., 2007). The isotope results presented here, however, indicate that the dietary importance of these cereals at Huoshiliang and Gangangwa was minimal at most.

5.2. Herding practices

Isotope data from Huoshiliang and Gangangwa indicate that the key agricultural crop of the region (millet) featured minimally in the diets of Caprinae and *Bos*, and probably composed no more than 4.6%–39.7% of their diets, according to the linear mixing model. It is unlikely that the natural vegetation of the Hexi Corridor included high proportions of C4 plants, due to its location in high northern latitudes, beyond the influence of the East Asian Monsoon. Current estimates of C4 plant proportions in the Hexi Corridor are not available, however estimates of C4 plant abundance in the steppe grasslands of Inner Mongolian range from 10% to 20% of above-ground biomass (see Auerswald et al., 2009; Wang, 2003; Wittmer et al., 2010). At Huoshiliang and Gangangwa, millet may have been available to domestic and wild herbivores in the form of stubble in untended fields following harvest, or as wild millet colonizing disturbed areas near human settlements. The low proportions of C4 plants in herbivore diets suggest that herding tended towards mobile or transhumant pastoralism, where herds were taken beyond the agricultural zone to graze. This low dependence on millet may have been an important aspect of the subsistence economy at Huoshiliang and Gangangwa, as survival of the herds would have been largely independent of annual variability in millet production, and presumably on seasonal or river side vegetation abundance.

The range in herbivore $\delta^{15}\text{N}$ values at Huoshiliang and Gangangwa (4.1‰ to 11.8‰) is wide and generally elevated when compared with previously reported herbivore values at sites in North China. $\delta^{15}\text{N}$ values for herbivores at sites in the Yellow and Wei River valleys provided by Pechenkina et al. (2005) range from 6.6‰ to 8.0‰, and at Dadiwan site, values range from 4.6‰ to 8.1‰ (Barton et al., 2009). Wide variation in herbivore $\delta^{15}\text{N}$ values in other regions has been attributed to grazing in multiple and distinct ecological contexts (e.g. Pearson et al., 2007; Thompson et al., 2005, 2008). The Hexi Corridor includes distinct ecological zones that vary markedly in terms of water availability and salinity (e.g. river valleys, oases, desert grasslands, dry lake beds and mountain slopes) and these may be important factors affecting herbivore $\delta^{15}\text{N}$

values and leading to the more ^{15}N enriched values at Gangangwa. Higher $\delta^{15}\text{N}$ values of some individuals in the Hexi Corridor may reflect grazing further into arid desert or salt affected regions. Diverse grazing ranges amongst *Bos* and Caprinae at the study sites is suggested by the wide range in $\delta^{15}\text{N}$ values, and this would be consistent with the occurrence of trade or transport of livestock in the region.

5.3. Broader implications

More water must have been present at Huoshiliang and Gangangwa in order for agro-pastoralist activities to have existed there ca. 2292–1692 BC. Existing palaeoecological work indicates that bodies of water were more expansive in the Hexi Corridor region during the Bronze Age (An et al., 2006; Hartmann and Wünnemann, 2009; Yang et al., 2010) and charcoal fragments collected from the study sites belong to the woodland taxa *Tamarix*, *Populus*, *Salix* and Polygonaceae, which are no longer present in the area (Sun et al., 2010). Large changes in hydrological regimes have occurred in the Hexi Corridor through the Holocene, and this has led to periods of settlement abandonment and reclamation (Lu et al., 1997; Wang et al., 2005). During periods when water or arable land was more scarce, societies may have relied more heavily on pastoral activities (Madsen and Elston, 2007; Zhang et al., 2008).

Whether the high consumption of millet by human and domestic omnivores at Huoshiliang and Gangangwa was due to a general focus on cultivation in a period when water or arable land was more prevalent, or was forced by a scarcity of other food types, leading to dependence on a plant that is tolerant of agriculturally marginal conditions (Baltensperger, 1996), is not known. However, the lack of regular foddering of herded animals with millet, as indicated by the isotope data, suggests the latter may have been the case. The heavy reliance on a single cereal, and low consumption of animal protein, however, conforms with the general picture of early agricultural societies elsewhere (Larsen, 2006; Pechenkina et al., 2002) and some of the characteristic health indicators associated with early agricultural societies are noted on human remains at Huoshiliang site (Dodson et al., in press).

A limitation of this study is the minimal temporal constraint on isotopic data to no more than about a 600-year period from ca. 2292 to 1692 BC. The argument for no association between the fauna remains and the two later dates at Gangangwa site, which fall around AD 237–666, is based only on spatial separation of the surface remains of a few hundred metres. More direct dates on fauna remains would improve the temporal certainty of the palaeodietary information presented here. This work, however, provides new insight into herd management and subsistence strategies in the Bronze Age Hexi Corridor.

6. Conclusion

The isotope results from Huoshiliang and Gangangwa reveal a Bronze Age subsistence strategy in the arid Hexi Corridor that relied heavily on cultivated millet. Human and most domestic omnivore fauna appear to have shared diets dominated by millet. The finding for low importance of C3 cereals in omnivore diets supports the notion that wheat was not yet an established crop at Huoshiliang and Gangangwa around 2000 BC.

A suite of domestic and wild fauna was present at the study sites, but do not appear to have been heavily utilized as a food source. This finding contrasts with the archaeological assemblages, which include abundant faunal bones and hunting tools, and highlights potential temporal differences in palaeodietary information obtained through different methods. The isotope data indicate herded animals were predominantly grazed beyond the

agricultural zone, in multiple and ecologically distinct areas. This wide grazing range would be consistent with the occurrence of long-distance transport of livestock in the region, and the dietary separation of herded animals from cultivated millet may have been advantageous, as survival of the herds would have been largely independent of annual variability in millet production.

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