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A comprehensive investigation of Bronze Age human dietary strategies from different altitudinal environments in the Inner Asian Mountain Corridor

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Abstract

The early presence of crops from East Asia and Southwest Asia in the Inner Asian Mountain Corridor (IAMC) has drawn attention to the Bronze Age mountain archaeology of Central Asia. Namely, the Bronze Age diffusion and utilization of grains in this region remains unknown as contrasts and extremes characterize the territory in environmental terms, especially elevation. Researchers continue to reflect on how, during the second millennium BC, Bronze Age populations used new crops and local animal resources to adapt to the different elevation environments of the IAMC. In this study, we analyzed the 41 latest stable carbon and nitrogen isotopic results from human and faunal bones from six Bronze Age sites in the IAMC, 261 previously published stable isotopic datasets, and 12 archaeobotanical and four zooarchaeological results to investigate the dietary strategies of populations from different elevation environments in the Bronze Age IAMC. The results show an altitudinal gradient in dietary choices among Bronze Age populations in the IAMC, with mixed C_4 and C_3 consumption at the low-mid elevations and notable C_3 consumption at the high elevations. Archaeobotanical and faunal remains also support these isotopic results. Our study further highlights that the differentiated dietary strategies adopted by the Bronze Age population in IAMC may have been the product of adaptation to local geographic environments. Social interaction may have also played a role in certain types of special dietary consumption.

Keywords: Bronze Age, Inner Asian Mountain Corridor, altitudinal

adaptation, stable isotopes, macroplant remains, faunal remains

1. Introduction

The Bronze Age of Central Asia is a dynamic period in which the East and the West cultural elements spread and diffuse such as bronze metallurgy, chariot, crops, etc. (e.g., Mei, 2003; Sherratt, 2006; Frachetti, 2012; Stevens et al., 2016; An et al., 2017, 2020a; Dong et al., 2017; Liu et al., 2017). Among these elements, novel crops were introduced, including wheat and barley (*Triticum turgidum/aestivum and Hordeum vulgare/nudum*), which spread eastward from Southwest Asia, and broomcorn and foxtail millets (*Panicum miliaceum and Setaria italic*), which expanded westward from East Asia (Jones et al., 2011; Liu et al., 2019); together with domesticated animals including sheep/goats, cattle and horse, they influenced dietary components, subsistence patterns, and societal development of the Central Asia population (Frachetti et al., 2010; Lightfoot et al., 2013; Spengler, 2015). There are notable characteristics of the diverse geographic environment in Central Asia, and the utilization strategy study of crops and animals resources by the Bronze Age population from different environment conditions is significant to understand the relationship between ancient populations and local environments in Central Asia. In recent years, as increasing Bronze Age sites in the Inner Asian Mountain Corridor -- a term coined by Frachetti

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(2012), IAMC thereafter --have been excavated(e.g., Wu, 2005; Frachetti, 2006; Frachetti and Mar'yashev, 2007; Cong et al., 2013; Ruan and Wang, 2017; Yu et al., 2018), and abundant animal and plant remains have been also discovered (Frachetti, 2012; Liu et al., 2016; An et al., 2020a; Zhou et al., 2020), making the IAMC become the key region of human-land relationship study, which also provided great condition to explore the resource utilization strategy in mountainous region of Central Asia during the Bronze Age (e.g., Frachetti, 2012; Xinjiang, 2013; Spengler et al., 2014c, 2015; Wang et al., 2018; Doumani et al., 2015; Hermes et al., 2019; Matuzeviciute et al., 2019, 2020; Zhou et al., 2020).

In the IAMC, the changes in climatic condition and vegetation composition according to altitude constitute one of the main geographic characteristics in mountainous environment. The extreme environmental variation from desert steppes of low elevations to snow belts of high elevations in the IAMC presented challenges for the survival of the local populations (Aldenderfer et al., 2006). Modern populations in the IAMC mainly obtain food resources through animal husbandry based on sheep/goats, cattle, and horses, and crops of wheat, corn, and rice. In the IAMC during the Bronze Age, the crops of millet, wheat, and barley, together with these above mentioned domesticated animals provided a potential source of diet and subsistence for the local community. Previous

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studies also reveal these animal resources and crops especially millet have contributed to the Bronze Age community diet component in the IAMC (e.g., Si et al., 2013; Matuzeviciute et al., 2015; Zhang et al., 2016a, 2016b, 2016c; Wang et al., 2017, 2018). However, questions remain over how Bronze Age mountain communities utilize these crops and livestock to deal with differential elevation environments in the IAMC, and the factors influencing their resource utilization strategy also remain unknown.

Paleodietary analysis provides an excellent way to understand human utilization strategy of crops and animal resources. Among many research methods of ancient human diet, stable isotope technology is widely applied with the advantage of quantitative analysis. Specifically, stable carbon isotope ($\delta^{13}C$) analyses of human remains can provide measurements of staple foods (millet, wheat, barley, and animal resources) and the extent of their consumption (e.g., Zhang et al., 2003; Svyatko et al., 2013; Liu et al., 2014; Miller et al., 2014; Lightfoot et al., 2015; Matuzeviciute et al., 2015, 2016; Zhou et al., 2015; Ma et al., 2016). Generally, groups that subsist on a predominantly C_3 diet (e.g., wheat, barley, and herbivores) typically have more negative $\delta^{13}C$ values, around −22‰ to −18‰ (Miller et al., 2019). In contrast, groups that subsist on a predominantly C_4 diet (e.g., millet crops) typically have $\delta^{13}C$ values between −12‰ to −6‰ (Wang et al., 2017). Stable nitrogen isotope ($\delta^{15}N$) values measured in human bone collagen

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can generally be used to evaluate the amount of animal protein in the diets of ancient humans (DeNiro and Epstein, 1981; Schoeninger et al., 1983; Matuzeviciute et al., 2016). The source of animal protein can also be assessed, based on the standard that δ^{15}N values tend to increase by 3–6% with the enhancement of trophic levels (Bocherens and Drucker, 2003; O'Connell et al., 2012). However, beyond dietary factors, other environmental stressors, such as aridity and salinity, could also elevate the δ^{15}N values of human bones (Sealy et al., 1987; Ambrose, 1991). Besides stable isotopic technology, archaeobotanical and zooarchaeological analyses are also an excellent study method of ancient human diet, which could provide physical evidence of possible dietary sources (Li et al., 2016; Ren et al., 2017; Yang et al., 2019).

In this study, we conducted a stable isotopic analysis of human and animal skeletal remains from six sites during the Bronze Age (the second millennium BC) in the IAMC. We also integrated published contemporaneous human and faunal bone stable isotopic data as well as macroplant and faunal remain results from different altitude sites in the IAMC to discuss comprehensively the Bronze Age human dietary strategies of different environments in the IAMC and their influencing factors.

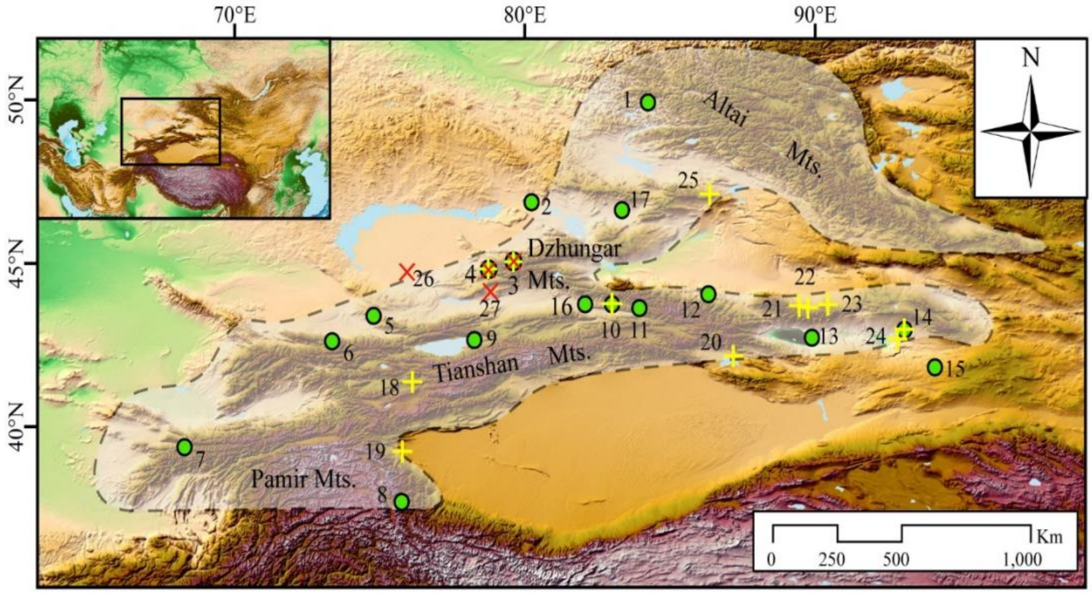

Fig. 1. Map of the Inner Asian Mountain Corridor and study sites discussed in this article. The geographical scope of the Inner Asian Mountain Corridor is defined by the gray shadow with black dotted line (Frachetti, 2012). The green circles represent stable isotopic study sites, the yellow crosses represent archaeobotanical study sites, and the red x's indicate zooarchaeological study sites.

Table 1

The information of sites studied for this research.

Site no.	Sites	Elevation (m a.s.l.)	Groups /elevations	Study types	Data sources
1	Kanai	912	Low elevation	Stable isotope	Narasimhan et al., 2019
2	Kazakh Mys	401	Low elevation	Stable isotope	Narasimhan et al., 2019

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3	Tasbas/Dali	1520	Middle elevation	Stable isotope Archaeobotany Zooarchaeology	Doumani et al., 2015; Spengler et al., 2014c; Hermes et al., 2019; Narasimhan et al., 2019
4	Begash	950	Low elevation	Stable isotope, Archaeobotany Zooarchaeology	Frachetti et al., 2010; Spengler et al., 2014c; Hermes et al., 2019
5	Oi-Dzailau VII	1228	Middle elevation	Stable isotope	Matuzeviciute et al., 2015; Narasimhan et al., 2019
6	Oi-Dzhailau	1200	Middle elevation	Stable isotope	Narasimhan et al., 2019
7	Dashty-Kozy	1454	Middle elevation	Stable isotope	Narasimhan et al., 2019
8	Xiabandi	3000	High elevation	Stable isotope	Zhang et al., 2016
9	Kyzyl Bulak-1	892	Low elevation	Stable isotope	Matuzeviciute et al., 2015; Narasimhan et al., 2019
10	Goukou	1216	Middle elevation	Stable isotope, archaeobotany	Wang et al., 2018, 2019; This study
11	Tangbalesayi	1837	High elevation	Stable isotope	This study
12	Shihuyao	734	Low elevation	Stable isotope	This study
13	Yanghai	-40	Low elevation	Stable isotope	Si et al., 2013
14	Wubu	782	Low elevation	Stable isotope, Archaeobotany	Wang et al., 1983; Yu, 1993; This study
15	Tianshanbeilu	525	Low elevation	Stable isotope	Eng et al., 2009; Zhang et al., 2010; Wang et al., 2017
16	kalasu	1124	Middle elevation	Stable isotope	This study
17	Xiakalangguer	560	Low elevation	Stable isotope	This study
18	Aigyrzhal-2	2005	High elevation	Archaeobotany	Matuzeviciute et al., 2017
19	Wupaer	1411	Middle elevation	Archaeobotany	Donson et al., 2013

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20	Xintala	1075	Middle elevation	Archaeobotany	Zhao et al., 2012
21	Luanzagangzi	1498	Middle elevation	Archaeobotany	Jia et al., 2011
22	Xicaozi	1574	Middle elevation	Archaeobotany	Donson et al., 2013
23	Sidaogou	1267	Middle elevation	Archaeobotany	Donson et al., 2013
24	Aisikexiaer	136	Low elevation	Archaeobotany	Li, 2002
25	Tongtian Cave	1810	High elevation	Archaeobotany	Yu et al., 2018; Zhou et al., 2020
26	Serektas	776	Low elevation	Zooarchaeology	Haruda, 2018
27	Turgen	1900	High elevation	Zooarchaeology	Haruda, 2018

2. Study region

The Inner Asian Mountain Corridor (IAMC), located in Eastern Central Asia, starts in the Hindu Kush Mountains of Afghanistan, and its main body includes Pamir, the Tian Shan, the Dzhungar, and the Altai Mountains of southwestern Siberia (Frachetti, 2012; Figure 1). The previous systematic climate study of the IAMC has been limited, and in arid Central Asia, including the Tian Shan mountain range, paleoclimate studies based on geological archives, including lakes, loess, and peat, indicated a consistently persistent wetting trend during the Holocene (11−0 ka), and the wettest conditions occurred in the late Holocene (4−0 ka; e.g., An et al., 2012; Chen et al., 2008, 2016; Wang et al., 2013; Hong et al., 2014). However, paleoclimate records of the Altai Mountains reveal a different climate variation trend, suggesting that the wettest conditions occurred in the early-middle Holocene (10-6 ka), and the middle-late Holocene was relatively dry (6-0 ka; Zhang and Feng, 2018; An et al., 2020a). The difference in the Holocene climate change trends between the Tian Shan and the Altai Mountains highlights the regional complexity of past climate variations in the IAMC. Despite this, it could be inferred that climate conditions seemed to be relatively stable from the Bronze Age to the present in IAMC. In contrast to modern semi-arid and arid Central Asia, which is dominated by a temperate continental climate, the IAMC is notable for its wet islands, with an annual precipitation of more than 450 mm (Zhang et al., 2016). The annual mean temperature is around 0°C in the IAMC (Huang et al., 2003). In this region, climatic conditions—especially temperature and precipitation—change significantly over altitudes. In the Tian Shan mountain range, the accumulated temperature (≧10 °C), which is closely related to crop growth, decreases by 1.5~2.0°C as the altitude rises by 100m. Conversely, annual precipitation increases by 10~60 mm when the altitude is below 3000 meters above sea level (m a.s.l). The changes in temperature and precipitation over altitudes led to the formation of notable mountain altitudinal belt spectra of vegetation in the IAMC, especially in the Tian Shan and Dzhungar mountain ranges. At the north slope of the Tian Shan, the vegetation of the foothill zone (300–1000 m a.s.l.) is mountainous

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deserts or desert steppes, followed by mountainous steppes (1000–1800 m a.s.l.), mountainous forests (1800–2600 m a.s.l.), alpine meadows (2600–3800 m a.s.l.), and glaciers (>3800 m a.s.l.; Hu, 2004). In the Dzhungar Mountains, the foothills (1000–1200 m a.s.l.) are mountainous steppes, followed by meadow steppe shrublands (1200–1500 m a.s.l), juniper forests (1500–2000 m a.s.l.), and alpine meadows at the peaks (2000–3000 m a.s.l.; Shahgedanova, 2003). In the IAMC, the upper limit of the mountainous steppes can be established at an elevation of 1500 m a.s.l to 1800 m a.s.l. Its low bound may be around 1000 m a.s.l. The region below 1000 m a.s.l. is occupied by mountainous desert steppes or deserts, and the region above 1800 m a.s.l. is primarily dominated by mountainous forests, alpine meadows, and glaciers. Based on site elevation and the mountain altitudinal belt spectra of vegetation of the IAMC where sites are occupied in, these sites in this study can be divided into three groups including low altitudes sites of mountainous desert steppes or deserts zone (<1000 m a.s.l.), middle altitudes of mountainous steppes zone (1000–1600 m a.s.l.), and high altitudes sites of mountainous forests and alpine meadows zone (>1800 m a.s.l.) (Table 1 and Supplementary Table 1–2).

3. Materials and methods

3.1. Samples selection

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Human and faunal bones applied to stable carbon and nitrogen isotope analysis were sampled from six Bronze Age sites in the IAMC. Specifically, there were 28 human skeletal remains from the Shihuyao, Goukou, Wubao, and Tangbalesayi sites and 13 faunal bones from the Goukou, Tangbalesayi, Wubao, Kalasu, and Xiakanglanguer sites. Further, we systematically collected previously published IAMC Bronze Age stable carbon and nitrogen isotope data from 183 human bone samples that were sourced from 14 sites and 78 animal bone samples from six sites. We used these data and 12 archaeobotanical as well as 4 zooarchaeological study sites to explore the dietary strategies of populations living in the different altitudinal environments of the Bronze Age IAMC.

3.2. Collagen extraction

Bone collagen was extracted according to the method described in Bocherens et al. (1991) with several modifications. Using an electric Dremel® grinder, all visible contaminants were mechanically removed from both inner and outer bone surfaces until only fresh surfaces were exposed. Approximately 2 g of dense bone was selected from each bone sample and washed thoroughly with deionized water. Bone samples were demineralized by soaking them in 0.5 molar hydrochloric acid (HCl) at 4°C and refreshing the solution every two days for about three weeks until the bone samples were soft, and no bubbles were produced. Samples were rinsed with deionized water and subsequently soaked in 0.125 molar NaOH at 4°C for 20 h and rinsed with deionized water again. Samples were gelatinized in acidic solution (pH 3) at 75°C for 48 h and filtered. Finally, the liquid samples were freeze-dried.

3.3. Isotopic analyses

Stable carbon and nitrogen isotopic compositions were determined using a Thermo Finnigan DeltaPlus continuous-flow isotope ratio mass spectrometer (IRMS) coupled with a Conflo device at the Key Laboratory of Western China's Environmental Systems, Ministry of Education (MOE), and Lanzhou University. An elemental analyzer (EA) called the vario EL cube (State Key Laboratory of Applied Organic Chemistry, Lanzhou University) was used to determine the atomic C/N ratios. The isotopic results are expressed as delta (δ) values in per mil (‰) notation, $\delta^{13}C = 1000 \times [(R_{sample}/R_{standard}) - 1]$, where R_{sample} and $R_{standard}$ are the $^{13}C/^{12}C$ ratios of the sample and standard, respectively, and the same for $\delta^{15}N$ (Coplen, 2011). Stable carbon and nitrogen isotopic compositions are calibrated relative to the Vienna PeeDee Belemnite limestone (VPDB) and AIR scales using USGS40 and USGS41. Measurement uncertainty was monitored using three inhouse standards with well-characterized isotopic compositions: IRM-1 (GLY, $\delta^{13}C$ = −33.3‰, $\delta^{15}N$ = +10‰), IRM-2

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(PUGE, $\delta^{13}C = -12.6‰$, $\delta^{15}N = +5.6‰$), and IRM-3 (collagen, $\delta^{13}C = -9‰$, $\delta^{15}N = +7.6‰$). Precision was determined to be ± 0.1‰ for both $\delta^{13}C$ and $\delta^{15}N$ based on repeated measurements of calibration standards, check standards, and sample replicates.

3.4. Data analysis

Data visualization and statistical analyses were performed using R, version 3.5.3. R packages used in this study include ggplot2, dplyr, and gridExtra (John and Sanford, 2011; Wickham, 2016). An analysis of variance (ANOVA) was conducted in conjunction with post hoc Tukey's honestly significant difference (HSD) test to identify mean differences among the groups for each measurement and to assess if the differences were statistically significant. The statistical significance level was set to $p < 0.05$.

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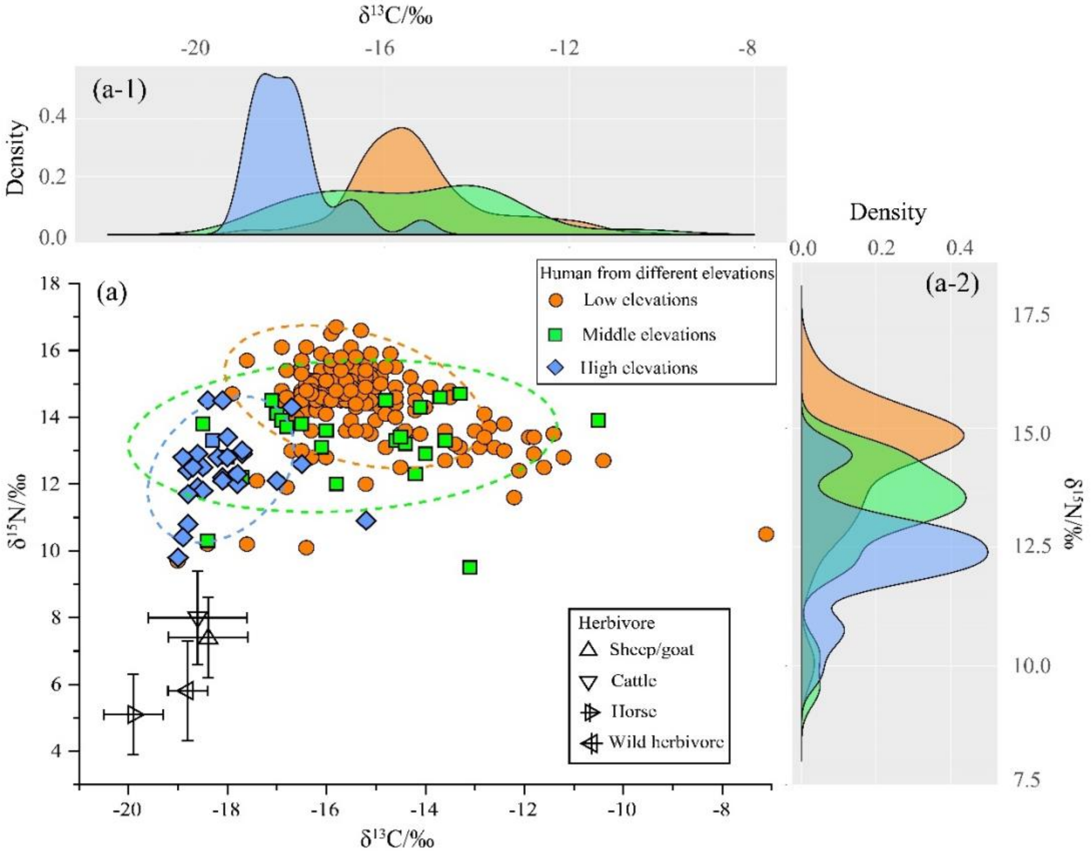

Fig. 2. Stable isotope distribution of human and faunal bones from different elevation sites in the Bronze Age IAMC. Low elevations (<1000 m a.s.l.) are shown in orange, middle elevations (1000–1600 m a.s.l.) are shown in green, and high elevations (>1800 m a.s.l.) are shown in blue. (a) the scatter plot of stable carbon and nitrogen isotope values of human bones from different elevations. They are plotted with ellipses and represent 95% confidence intervals for each elevation and average faunal stable isotope values, including those for sheep/goats, cattle, horses, and wild herbivores in the IAMC (± 1 standard deviation). (a-1) shows the density distribution of stable carbon isotope values of human bones from different elevations, and (a-2) shows the density distribution of the stable nitrogen isotope values of human bones from different elevations.

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Table 2

The δ^{13}C and δ^{15}N results of faunal bones from different altitudes in the IAMC.

Species (n)	$\delta^{13}C_{VPDB}$(‰)				$\delta^{15}N_{NAIR}$ (‰)			
Faunal	Mean	Sd	Max	Min	Mean	Sd	Max	Min
Sheep/goats (51)	−18.4	0.8	−15.9	−20.0	+7.4	1.2	+9.7	+3.3
low elevation (36) (<1000 m a.s.l.)	−18.5	0.7	−16.5	−20.0	+7.6	1.1	+9.7	+5.5
middle elevation (15) (1000-1600 m a.s.l.)	−18.1	0.9	−15.9	−19.4	+7.0	1.5	+9.4	+3.3
Cattle (23)	−18.6	1.0	−16.4	−20.0	+8.0	1.4	+10.4	+5.0
low elevation (21) (<1000 m a.s.l.)	−18.6	1.0	−16.4	−19.9	+8.1	1.3	+10.4	+6.5
middle elevation (2) (1000-1600 m a.s.l.)	−19.0	1.4	-18.0	-20.0	+7.0	2.8	+9.0	+5.0
Horses (5)	−19.9	0.6	−19.1	−20.8	+5.1	1.2	+6.6	+3.2
Wild herbivores (5)	−18.8	0.4	−18.5	−19.4	+5.9	1.5	+7.8	+3.8

Table 3

The δ^{13}C and δ^{15}N results of human bones from different altitudes in the IAMC.

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Species (n)	$\delta^{13}C_{VPDB}$(‰)				$\delta^{15}N_{NAIR}$ (‰)			
Human	Mean	Sd	Max	Min	Mean	Sd	Max	Min
Low elevations (157) (<1000 m a.s.l.)	−15.2	1.6	−7.0	−19.0	+14.4	1.3	+16.7	+9.7
Middle elevations (25) (1000-1600 m a.s.l.)	−15.5	2.0	−10.5	−18.5	+13.2	1.2	+14.7	+9.5
High elevations (27) (>1800 m a.s.l.)	−18.0	0.9	−15.2	−19.0	+12.4	1.1	+14.5	+9.8

Table 4

The mean $\delta^{13}C$ and $\delta^{15}N$ offset values between humans from different elevations and four kinds of herbivores.

	Mean $\delta^{13}C$ offset between human and herbivore (‰)			Mean $\delta^{15}N$ offset between human and herbivore (‰)		
Herbivores	Low elevations	Middle elevations	High elevations	Low elevations	middle elevations	High elevations
Sheep/goats	3.2	2.9	0.4	7.0	5.8	5.0
Cattle	3.4	3.1	0.6	6.4	5.2	4.4
Horse	4.7	4.4	1.9	9.3	8.1	7.3
Wild herbivores	3.6	3.3	0.8	8.6	7.4	6.6

4 Results

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In total, 209 of the 211 human bone samples and 84 of the 91 faunal bone samples from both this study and previously published literature produced collagen with C:N values between 2.9 and 3.5 (Supplementary Table 1 and 2), which is within the acceptable quality range of 2.9–3.6 and suggests these samples are well preserved (DeNiro, 1985; Ambrose, 1990).

4.1. Stable carbon and nitrogen isotope results of faunal bones in the IAMC

The carbon and nitrogen isotope results from faunal bone collagen from the IAMC are shown in Table 2, Figure 2, and Supplementary Table 1 . The range of δ^{13}C value in all of faunal in IAMC including sheep/goats, cattle, horses, and wild herbivores was −20.8‰ to −15.9‰ (n=84), the most positive mean δ^{13}C values of −18.4 ± 0.8‰ (n=51), belonged to the sheep/goat samples, which were followed by cattle (−18.6 ± 1.0‰, n=23), wild herbivores (−18.8 ± 0.4‰, n=5), and horses (−19.9 ± 0.6‰, n=5). The range of δ^{15}N value in all of faunal in IAMC was 3.2‰ to 10.4‰ (n=84). The most positive average, δ^{15}N value of +8.0 ± 1.4‰ (n=23), came from the cattle samples. It was followed by the sheep/goat samples (+7.4 ± 1.2‰, n=51), wild herbivore (+5.8 ± 1.5‰, n=5), and horse (+5.1 ± 1.2‰, n=5). The ANOVA among domesticated faunal including sheep/goats, cattle and horses revealed the significant differences for δ^{13}C values ($F=7.1$, $p<0.002$, $n = 79$), and also for δ^{15}N values ($F =10.1$, $p<0.001$, $n = 79$). Post-hoc tests showed that among domesticated animals, the horse samples had significantly lower $\delta^{13}C$ and $\delta^{15}N$ values than sheep/goats and cattle (Tukey HSD test, $p<0.001$; Table 2).

The mean $\delta^{13}C$ values of −18.4 ± 0.8‰ (n=36) in sheep/goat samples from low elevation is slightly negative than that of middle elevation (−18.1 ± 0.9‰, n=15). Cattle have positive mean $\delta^{13}C$ values of −18.6 ± 1.0‰ (n=21) in low elevation than that of middle elevation (−19.0 ± 1.4‰, n=2). The average $\delta^{15}N$ value in sheep/goat and cattle samples from low elevation are +7.6 ± 1.1‰ (n=36) and +8.1 ± 1.3‰ (n=21), which is more positive than that of middle elevation (sheep/goat: +7.0 ± 1.5‰, n=15; cattle: +7.0 ± 2.8‰, n=2). The ANOVA among sheep/goat and cattle samples from different elevations indicates there is no significant differences for $\delta^{13}C$ values ($F=1.1$, $p=0.36$, $n = 74$) and $\delta^{15}N$ values ($F=2.3$, $p=0.08$, $n = 74$; Table 2).

4.2. The stable carbon and nitrogen isotope results of human bones from the IAMC

The stable carbon and nitrogen isotope results of human bone collagen from the IAMC are shown in Table 3, and Figures 2, and Supplementary Table 2. Among the three groups of samples from different elevations, the human bone samples from the low elevations had the mean $\delta^{13}C$ and $\delta^{15}N$

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values, of −15.2 ± 1.4‰ and +14.4 ± 1.2‰ (n=157) respectively, which were followed by that of the middle elevations (δ^{13}C: −15.5 ± 2.0‰； δ^{15}N: +13.2 ± 1.2‰, n=25) and the high elevations (δ^{13}C: −18.0 ± 0.9‰; δ^{15}N: +12.4 ± 1.1‰, n=27). The ANOVA among humans from different elevations revealed the significant differences for δ^{13}C values (F=40.23, p<0.001, n = 209) and also for δ^{15}N values (F =30.86, p<0.001, n = 209). Post-hoc tests showed that the human bone samples of high elevation had significantly lower δ^{13}C and δ^{15}N values than that of low and middle elevation (Tukey HSD test, p<0.001; Table 3).

In low elevation, the mean δ^{13}C offset between the humans and herbivore range from 3.2 to 4.7, which is higher than that in middle elevation with the range of 2.9 to 4.4 as well as in high elevation with the range of 0.4 to 1.9. From low elevations to high elevation in IAMC, the mean δ^{15}N offset between humans and sheep/goats range from 5.0 to 7.0, and is similar with that between humans and cattle with the range of 4.4 to 6.4. This is very different from that between humans and horses as well as wild herbivores with the range of 6.6. to 9.3 (Table 4).

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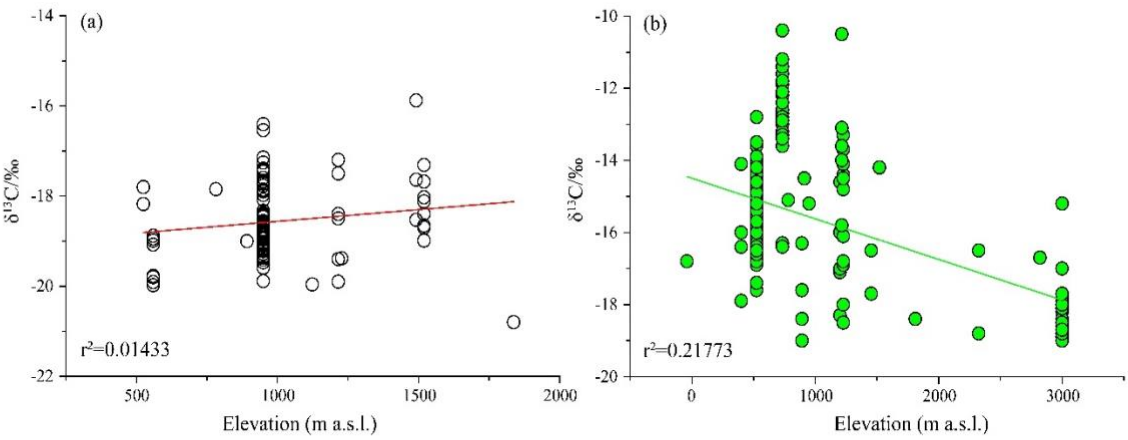

Fig. 3. The relationship between the δ^{13}C value of collagen samples and the elevations in Bronze Age IAMC. (a) faunal bone (b) human bone.

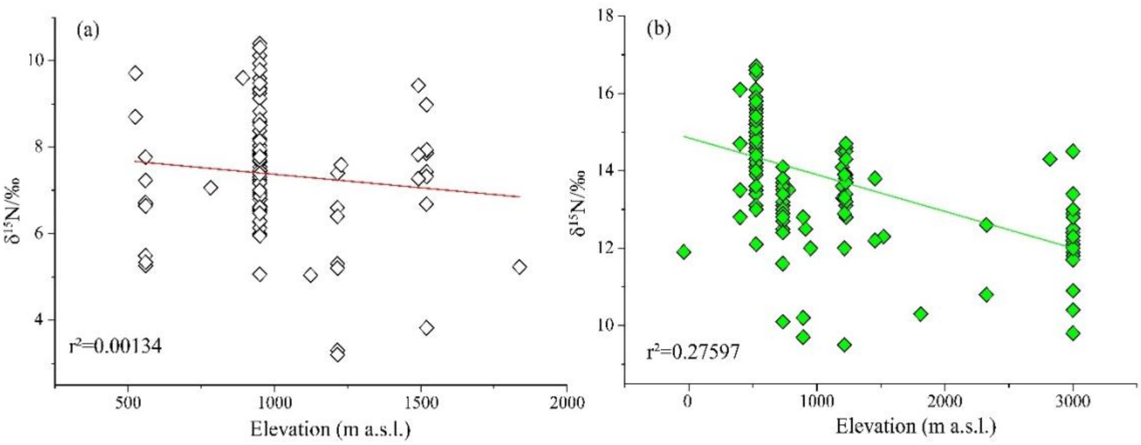

Fig. 4. The relationship between the δ^{15}N values of collagen samples and the elevations in Bronze Age IAMC. (a) faunal bone; (b) human bone.

Table 5

The emergence of major crops including C_4 crops (*Setaria italica* and *Panicum miliaceum*) and C_3 crops (*Triticum aestivum* and *Hordeum*

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vulgare) discovered at different elevation sites in Bronze Age IAMC.

Site	Site No.	Elevation (m a.s.l.)	*Setaria italica*	*Panicum miliaceum*	*Triticum aestivum*	*Hordeum vulgare*	Reference
Aisikexiaer	24	136	+				Li, 2002
Wubao	14	782	+			+	Wang et al., 1983; Yu, 1993
Begash	4	950		+	+	+	Frachetti et al., 2010; Spengler et al., 2014c
Xintala	20	1075		+	+	+	Zhao et al., 2012
Goukou	10	1227	+	+	+	+	Wang et al., 2018, 2019
Sidaogou	23	1267			+		Donson et al., 2013
Wupaer	19	1411			+		Donson et al., 2013
Tasbas	3	1492	+	+	+	+	Spengler et al., 2014c; Doumani et al., 2015
Luanzagangzi	21	1498	+		+	+	Jia et al., 2011
Xicaozi	22	1574			+		Donson et al., 2013
Tongtian Cave	25	1810	+	+	+	+	Yu et al., 2018; Zhou et al., 2020
Aigyrzhal-2	18	2005			+	+	Matuzeviciute et al., 2017

5. Discussion

5.1. Stable isotopic evidence of human dietary strategies at different altitudes in the Bronze Age IAMC

Stable isotopic comparison among the three population groups, from low, middle, and high elevations, respectively, in the IAMC indicate that there are differentiated dietary components along an elevational gradient, in which the population at the low-middle elevations consumed mainly a mixed C_3/C_4 foodstuffs, and the high-elevation population preferred to consume primarily a C_3 foodstuffs (Figure 2).

We discussed some possible foodstuff sources which may contribute to human increasing proportion of a C_4 diet in the low- and middle-elevation populations, such as herbivores fed on C_3 plants with much more positive $\delta^{13}C$ value or higher proportion of wild C_4 plants at the lower altitudes (Sage et al., 1999), wild edible C_4 plants (Miller et al., 2014; Rühl et al., 2015), and the domesticated C_4 crops (Liu et al., 2012). In natural environments of IAMC, wild C_3 plants are dominant, and the $\delta^{13}C$ value of C_3 plants would increase obviously as the altitude decreases under the elevation is below 2500 m in North Tianshan (Zhang, 2010). Meanwhile, in lower elevation, the proportion of wild C_4 plants are much more notably higher than that of high elevation (Li et al., 2009). Both cases may result in the much more positive $\delta^{13}C$ value of herbivores in low elevation that fed on local plants, which further influences human diet component

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through food chain effect. Here, we analyzed the relationship between the $\delta^{13}C$ value of herbivores and altitudes in IAMC to test this possibility. The results show that the $\delta^{13}C$ value of herbivores did not increase significantly with decreasing altitude (Figure 3a), which is different from the relationship between the C_3 plants and elevations in North Tianshan (Zhang, 2010). It suggests that the influence of the altitudinal change in $\delta^{13}C$ value of C_3 plants or higher proportion of wild C_4 plants in lower altitudes on herbivore $\delta^{13}C$ value is very limited. Meanwhile, the $\delta^{13}C$ offset between humans and herbivores in low-middle elevation ranges from 2.9 to 4.7, which is beyond the generally assumed consumer-prey $\delta^{13}C$ offset of 0.5-2‰ (Bocherens and Drucker, 2003; Table 4 and Figure 3b). This suggests that the consumption of herbivores cannot contribute significantly to predominately C_4 diet of humans from the low-middle elevations. Whether wild edible C_4 plants constitute a predominately C_4 human diet also needs to be evaluated. In Bronze Age sites of the IAMC, wild C_4 plants that can be found frequently include mainly *Chenopodaciae*, *Poaceae*, and *Polygonaceae* (Frachetti et al., 2010; Spengler et al., 2014a, 2014b; Doumani et al., 2015; Wang et al., 2018). However, it is noteworthy that these wild C_4 plant seeds are generally obtained from burning animal dung, such as at Begash and Tasbas sites (Spengler et al., 2013, 2014b), which makes it difficult to differentiate whether these plants remains are the food component of animals or humans (Spengler, 2019). Therefore, it is hard to evaluate effectively the contribution of these wild C_4 plants to the human diet in the Bronze Age IAMC. After excluding the above two possibilities, it can be inferred that domesticated C_4 crops are likely predominately C_4 diet sources for humans at the low-middle altitudes. In Bronze Age Central Asia, millet (broomcorn and foxtail millet) is the only visible domesticated C_4 crop (e.g. Wang, 1983; Frachetti, 2010; Zhou et al., 2020), which has been widely discovered at the Bronze Age sites of the IAMC, especially low- and middle-elevation sites (Yu 2012; An et al., 2020b; Li, 2020; Table 5). Meanwhile, millet crops are also very significant crops components in certain Bronze Age sites in the IAMC, such as in Yanghai and Goukou sites (Jiang et al., 2007; Wang et al., 2019). Considering the high frequency and importance of millet crops in Bronze Age sites of the IAMC, it can be inferred that millet crops are very likely to be the main source of C_4 foodstuffs for most of the Bronze Age population at the low-middle elevations of the IAMC.

The C_3 foodstuffs consumed by the Bronze Age population in IAMC, especially high-elevation groups, could likely be from domesticated C_3 crops and herbivores. Here, C_3 crops refer mainly to wheat and barley, which have been discovered widely in the sites of different elevations in the Bronze Age IAMC (e.g., Frachetti, 2010; Zhou et al., 2020; Table 5).

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Animal resources available in the Bronze Age IAMC include mainly sheep/goats, cattle, horses as well as wild herbivore (Bendrey et al., 2011). The preliminary relationship between animal resources and human diet could be observed by the similar trend with altitude between the δ^{15}N value of human and herbivore (Figure 4). For specific animal resource consumption strategy of the ancients human from different elevations in the Bronze Age IAMC, it is necessary to compare the δ^{15}N offset between human and different herbivores. It could be found that from low to high elevation in IAMC, the δ^{15}N offset between humans and sheep/goats and cattle is much closer to the 3-6‰ of the δ^{15}N difference standard between consumers and prey (Bocherens and Drucker, 2003; O'Connell et al., 2012), which differs significantly from the larger δ^{15}N difference between humans and horses as well as wild herbivores. It highlighted the significant role of sheep/goats and cattle in human diet compared to horse and wild herbivore. Through further analysis, it could be found the δ^{15}N difference between humans and sheep/goats is higher than that between humans and cattle from low elevation to high elevation (Table 4), suggesting that for the Bronze Age populations from different elevations in the IAMC, the contribution of sheep/goats (in the form of meat or possible milk) to human diet could be very significant.

It could be concluded that there are different human dietary strategies

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between low-middle and high elevation in the Bronze Age IAMC, indicating the low-middle elevation population mainly consumed a mix of C_3/C_4 foodstuffs probably from the crops of millet, wheat, and barley as well as animal resources of sheep/goats or cattle, and the high-elevation population consumed predominately C_3 foodstuffs from the sheep/goats, cattle as well as the wheat and barley crops. Meanwhile, some exceptions can also be found, for example, at high altitudes, a few individuals consumed probably much more C_4 millet crops than others.

5.2. Zooarchaeological and archaeobotanical evidences relevant with human dietary strategy at different altitudes in the Bronze Age IAMC

Published zooarchaeological and archaeobotanical results from Bronze Age sites of IAMC are synthesized to further the argument of the stable isotopic results. The analysis of faunal remains in the Bronze Age IAMC indicated from low to high elevation, the proportion of domesticated herbivores, including sheep/goats, cattle, and horses, of all the discovered faunal bones is always very high, which is more than 90% (Figure 5a). Sheep/goats are consistently dominant in domesticated herbivores from low to high elevation, which were followed by cattle and horses (Figure 5a). The dominance of sheep/goat in the domesticated faunal composition highlighted the significant role of sheep/goats in population dietary and

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subsistence patterns of different elevations in the IAMC (Frachetti et al., 2009; Doumani et al., 2015; Haruda et al., 2018), which is very consistent with our stable isotopic results that sheep/goats contribute significantly to the human consumption of animal protein.

Archaeobotanical studies show different altitude distribution in the proportion of domesticated crops in the Bronze Age IAMC (Figure 5b). In the low-middle elevations sites of the IAMC, C_4 crops millet was frequently discovered (Table 5), and especially in the Begash (950 m a.s.l.) and Goukou sites (1227 m a.s.l.), millet dominated local agricultural crops (Frachetti, 2010; Spengler et al., 2014c; Wang et al., 2019). Meanwhile, the evidence of processing chaff (rachises) and impressions of culms and grains in Tasbas site (1492 m a.s.l.) highlighted the presence of millet agriculture in middle elevation (Spengler et al., 2014b; Wang et al., 2018; Hermes et al., 2019). It could be found that with the increase of altitude, the proportion of millet to all major crops decreased significantly (Figure 5b). At Aigyrzhal-2, even with an elevation of around 2000 m a.s.l., there is no evidence of millet remains (Matuzeviciute et al., 2017; Figure 5b). There is an obvious difference in the altitudinal distribution between C_3 crops of wheat and barley and C_4 crops of millet. Wheat and barley remains could be discovered in sites from low to high elevations (Table 5), and wheat and/or barley crops dominate agricultural composition in middle-

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high elevations sites of the Bronze Age IAMC (Figure 5b). Besides, the chaff remains of wheat and barley at the Aigyrzhal-2 site (2000 m a.s.l.) provide clear evidence of human involvement in wheat/barley agriculture in high elevations of the IAMC (Matuzeviciute et al., 2017). The elevation differences of agricultural composition in the Bronze Age IAMC corresponded well to our stable isotopic results that populations at low-middle elevations consumed much more C_4 foodstuffs from millets, and populations at high elevations obtained more C_3 foodstuffs, which was partly from wheat/barley crops.

5.3. Husbandry practices along the altitude gradient

In different elevation sites of the Bronze Age IAMC, there is a significant difference in human dietary strategy. Whether there are also differentiated husbandry practices in the Bronze Age IACM can be explored preliminarily based on stable isotopic data. The faunal remains in this article are mainly from low-middle elevation sites, and the ANOVA analysis indicates there are no significant differences in dietary component of sheep/goats (and cattle) between low and middle elevations. This result corresponded well to human homogeneous dietary composition between low and middle elevation in the IAMC. In low-middle elevation sites of IAMC, C_4 crops millet contributed significantly to the Bronze Age population diet (Figure 3b). In contrast to human, the $\delta^{13}C$ value of the

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majority of herbivore is not more than −18‰, indicating the contribution of C_4 plants including millet crops to herbivores diet in major low-middle elevation sites of IAMC are very limited (Figure 3a), and only in a few sites such as Goukou and Begash, can it be observed that a small number of herbivores—for example sheep/goat and cattle—consumed some C_4 plants which may well be millet (Wang et al., 2018; Hermes et al., 2019). This is obviously different from how the Neolithic population in North China fed domesticated cattle with a number of millet fodder (Chen et al., 2016). The difference in the diet pattern of domesticated animals between the IAMC and North China indicate their different husbandry practices, that is, extensive herded raising strategy (receiving less millet fodder) in the IAMC and intensive foddering strategy in North China. In addition, the lack of stable isotopic data of faunal bone in high elevation sites limited the comparison of husbandry practices between high and middle-low elevations in the Bronze Age IAMC, which remains to be further studied.

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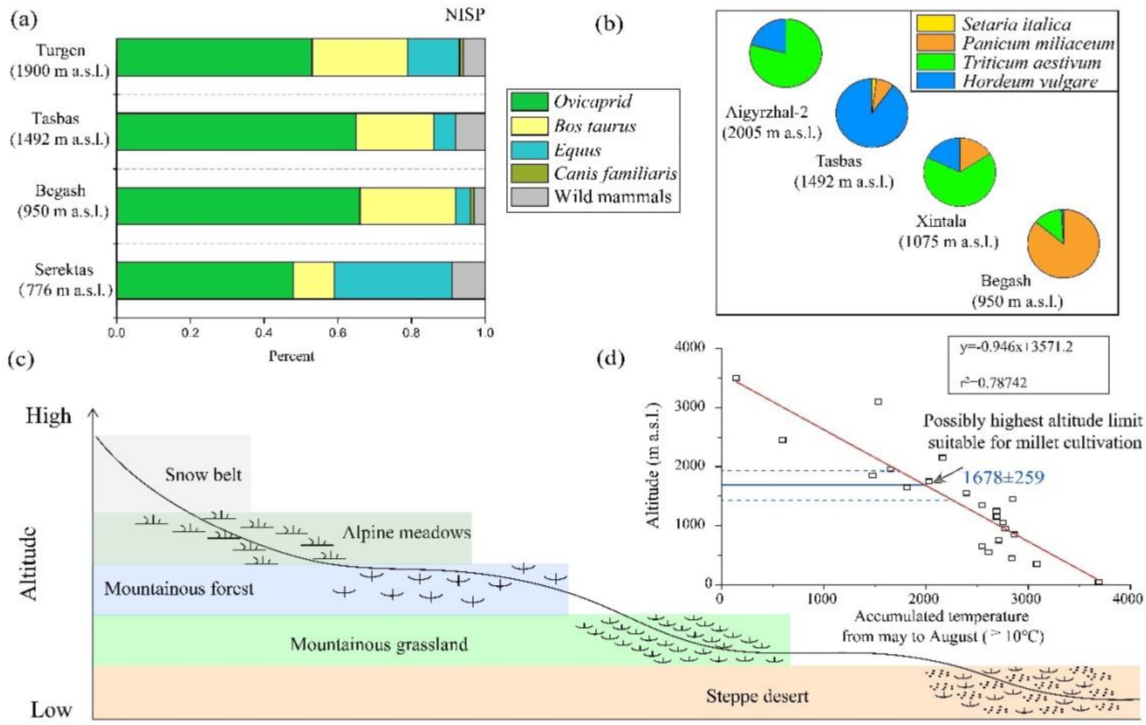

Fig. 5. The altitudinal change in faunal composition, macroplant composition, vegetation belt spectra, and accumulated temperature in the Bronze Age IAMC. (a) The comparative percentages of main faunal remains from different altitudes sites in the Bronze Age IAMC; (b) The comparative percentages of the major domesticated agricultural crop remains from different altitudes sites in the Bronze Age IAMC; (c) The concept model of the mountain altitudinal belt spectra of vegetation in the IAMC; (d) The linear relationship between altitudes and modern accumulated temperature (≧10 °C) during the millet growing period (from May to August) in the Tian Shan mountain range of the IAMC (red line). The blue line represents the highest elevations region in the Tian Shan mountain range that is suitable for millet agriculture, and the blue dashed line refers to the error range of elevation.

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5.4. Dietary diversities among the IAMC populations along altitude gradient: environmental factors and social interactions

Dietary patterns of the Bronze Age populations from different elevations in the IAMC mainly reflected the dietary difference in millet crops between low-middle and high elevations in the Bronze Age IAMC. Meanwhile, it also included internal dietary differences among population at high altitudes. Here, we discuss the possible factors influencing the dietary patterns of the Bronze Age populations from different elevations in the IAMC from two aspects including geographic environments condition and social interactions.

Generally, there are close relationships between human diet components and local subsistence patterns; for this reason, agriculture should be granted much more attention. For agricultural crops, there are certain growth characteristics, which make crops cultivation susceptible to influence by geographic environment such as elevation or vegetational zone (Figure 5c). Millet, as a drought-tolerant thermophilic crop, is more suitable for planting and growing in an environment with an accumulated temperature (≧10 °C) that is not less than 2000 °C during the whole millet growth period (Liu, 1998). In contrast to millet, cold-tolerant crops such as wheat and barley can be cultivated in an environment with an accumulated

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temperature (≧10 ℃) that is less than 2000 ℃ during the whole wheat/barley growth period (Liu, 1998). We calculated the accumulated temperature (≧10 ℃) from May to August (millet growth period) recorded by the modern weather stations from different altitudes of the Tian Shan Mountains, and then fit linearly the relationship between the accumulated temperature and the elevation of the meteorological station. Based on the linear relationship, we found that the accumulated temperature condition (≧10 ℃) of 2000 ℃, which was the lower limit of temperature suitable for millet cultivation, corresponded to the altitude of around 1678±259 m a.s.l. (Figure 5d). That is, when the location of sites is above this altitude, that is 1937 m a.s.l. in the Tian Shan, local accumulated temperature conditions could be unsuitable for millet cultivation, which is consistent with our study result that the millet remains and the consumption of millet rarely occurs in Bronze Age sites at an elevation of more than 2000 m a.s.l.. In contrast to millet crops, wheat and barley can be well planted at an elevation of more than 2000 m a.s.l. Barley, a cold-resistant crop, facilitated human settlement at altitudes between 2500 and 3500 m a.s.l during the Bronze Age in the Tibet Plateau (Chen et al., 2015; Zhang et al., 2016; Zhang and Dong, 2017). And barley can even be planted in modern Pamir with an average elevation of more than 3000 m a.s.l. and the Tibet Plateau at around 4750 m a.s.l. (Xinjiang, 2012; Qinghai, 2001).

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Compared to the significant role of geographic environments in human dietary components of different elevations in the Bronze Age IAMC, social interaction could play a role in special dietary selection among the high-elevation population of the Bronze Age IAMC. It could be found that a few individuals from the high-elevation sites of the IAMC for example Xiabandi (3000 m a.s.l.) appear to have consumed much more C_4 foodstuffs than the rest of the population (Zhang et al., 2016). It has been known that millet cultivation can be restricted in areas with altitudes of 2000 m a.s.l. or higher, which prompts the question: how did those few members of the high-elevation population access millet? Notably, the IAMC became a crossroads of cultural exchange from the third to second millennium BC. There is increasing archaeological evidence of the appearance of commodities, technologies, and domesticated grains from distant regions during this period (e.g., Frachetti and Benecke, 2009; Frachetti et al., 2010, 2012; Spengler et al., 2015; Liu et al. 2016, 2019; Stevens et al., 2016). In this context, there are two possible explanations for the high-elevation outliers. One possibility is that they could have migrated in the late stages of their lives from low-middle altitude regions—where they could have accessed C_4 foodstuffs—to the high-elevation regions. This theory should receive more attention, due to the regions' similarities in geographic and cultural factors (e.g., certain similar dietary components between middle and high elevations; Figure 2). Another possibility is that there could have been a grain exchange network between the high and low elevations, through the key middle-elevation mountainous grassland, which would have allowed some members of the high-elevation population to access millet. In the latter scenario, the millet supply at high-elevation sites was unlikely to have been large, because it was accessed and consumed by a few individuals, not the entire population.

6. Conclusion

In this study, we investigated the dietary strategies of Bronze Age communities from different elevation environments in the IAMC and their access to dietary resources. We gained a better understanding of the utilization of crops and animal resources by humans in the Bronze Age IAMC. We conducted stable isotope analyses of human and animal skeletal remains from six Bronze Age sites in the IAMC and collected published human and faunal stable isotopic data as well as zooarchaeological and archaeobotanical results from this region. We found that:

(1) Dietary strategies can be differentiated among the Bronze Age populations in the IAMC based on their different elevation environments;

(2) Dietary choices of Bronze Age population in the IAMC varied along an elevational gradient, with a decrease in access to C_4 food resources (for example, millet) and an increase in C_3 food resources (for example, wheat and barley) from lower to higher elevations. Faunal and archaeobotanical remains reinforced the stable isotopic results.

(3) The differentiated dietary strategies may have been the product of adopting to local geographic environments. Meanwhile, social interaction could have also played a role in the special dietary consumption of a few high-elevation populations.

Data availability

All data analyzed during this study are included in supplementary information.

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