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Dietary transition in the western inner Asian mountain corridor: preliminary stable isotope perspective from early iron age Fergana populations

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ABSTRACT

The Fergana Valley has been a crucial passage for cultural exchange since the Middle Holocene. Despite numerous archaeological discoveries, research on the subsistence patterns of its populations remains limited. In this study, carbon and nitrogen stable isotope analysis was applied to human skeletal remains from the Iron Age Khanabad-1 cemetery in the eastern Fergana Valley. This provides the first small subset reconstruction of dietary patterns for the local population around 2000 BP. The preliminary results indicate an average $\delta^{13}C$ value of −17.9‰, confirming a C_3 dominated mixed plant intake. The average $\delta^{15}N$ value of 10.0‰ is approximately 3.0‰ higher than that of contemporaneous livestock in the surrounding area, suggesting a modest level of animal protein consumption. Considering the local environment of the Khanabad-1 cemetery and the artifacts recovered from the graves, we infer that agriculture formed the important part in the local population subsistence system. The diet was mainly composed of C_3 plants, supplemented by C_4 plants and animal resources. This dietary structure represents a transitional pattern between the mountain agropastoral populations and the oasis agricultural populations during the Bronze to Iron Age in the region. Notably, it closely resembles the isotopic records of the medieval agricultural populations in the Fergana Valley. This similarity may demonstrate both the connections between local agricultural groups, the agropastoral populations of the IAMC, and the oasis agricultural societies, as well as the continuity of local dietary traditions over time.

1. Introduction

The Middle Holocene constituted a crucial stage for the emergence and development of civilizations and early food globalization processes across Eurasia. During this period, the establishment of ancient exchange channels, as represented by the Eurasian Steppe and the Inner Asian Mountain Corridor (IAMC), significantly facilitated interactions and development among different early civilizations. New foods and technologies also disseminated rapidly along these corridors to different regions (Frachetti, et al., 2012, Ventresca Miller and Makarewicz, 2019, Zhou, et al., 2020). Furthermore, sustained *trans*-Eurasian exchanges, included population migrations, the spread of agropastoral

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technologies, and the intensified exploitation of plant and animal secondary products, gradually transformed the subsistence strategies of regions along these inland exchange corridors, particularly in Central Asia (Allentoft, et al., 2015, Dong, et al., 2017, Spengler, et al., 2014).

During the Bronze and Iron Ages, intensified interactions between early agricultural and pastoralist populations in Central Asia fostered a complex pattern of subsistence strategies. Early archaeological scholarship maintained that early agricultural populations in Central Asia were primarily distributed in river valleys, such as the Surkhan Darya, Zarafshan, and Fergana Valleys, while foothill and mountainous zones were dominated by pastoralism (Askarov, 1981, Dani and Masson, 1992) However, recent archaeological research from numerous settlements within the IAMC reveals a landscape characterized by a mixed agropastoral economy (Chang, et al., 2003, Lyonnet and Dubova, 2020, Spengler, et al., 2013, Ventresca Miller, et al., 2014), this finding challenges the earlier opinion. Therefore, comprehensive analysis of archaeological sites in agro-pastoral transition zones is significant for improve our understanding of prehistoric economic practices in Central Asia and for reconstructing the region's civilizational history.

Stable isotope analysis of human skeletal remains constitutes an important method for reconstructing ancient dietary patterns and has been extensively applied in international archaeological research in recent decades (Hu, 2018, Richards, 2020). Its principle is based on the ratios of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopes in biological tissues record an individual's food sources and environmental context via trophic level effect: $\delta^{13}C$ values primarily distinguish the consumption ratios of C_3 (e.g. wheat, rice) and C_4 (e.g. millet) crops; while $\delta^{15}N$ values reflect trophic level position and the degree of animal protein intake. This approach can not only determine individual dietary composition and trophic level with precision but also facilitate further analysis of population-level subsistence economies and social complexity (Lightfoot, et al., 2015, Makarewicz and Sealy, 2015, Shishlina, et al., 2018). However, current research on human skeletal stable isotopes in South Central Asia remains limited, with published data scattered across southeastern Kazakhstan, the mountainous regions of Kyrgyzstan, and south-central Uzbekistan (Ananyevskaya, et al., 2020, Smithers, et al., 2024, Zhu, et al., 2025). Related records are exceptionally scarce for key agricultural region within the IAMC, such as the Fergana Valley, a gap that significantly constrains our understanding of subsistence pattern change and civilizational adaptations strategies within the context of *trans*-Eurasian exchange.

In this research, we present an archaeological investigation of the Khanabad-1 cemetery in the Fergana Valley of eastern Uzbekistan. A chronological framework was established using AMS ^{14}C dating, and stable isotopic analysis was conducted, for the first time, on Iron Age human remains from the Fergana region. The $\delta^{13}C$ and $\delta^{15}N$ compositions of bone collagen were utilized to reconstruct and assess the dietary structure and trophic level of the cemetery population. A comparative analysis was further undertaken using published isotopic data from human remains from the Bronze Age to the Medieval period in surrounding areas, which provides crucial bioarchaeological evidence for understanding the dietary composition, agricultural subsistence practices, and adaptive strategies of early populations along the Silk Road in this pivotal region.

2. Materials and methods

2.1. Archaeological background of Khanabad-1 cemetery

The Khanabad-1 cemetery (40°48′54.89″N, 73°0′32.29″E) is situated on a hillside east of Khanabad city, in the Qo'rg'ontepa district of Andijan province, within the eastern Fergana Valley of Uzbekistan. The site lies at an elevation of 697 m asl (Fig. 1). It is located approximately 3.5 km from the northern shore of the Kara Darya River, with the western foothills of the Tian Shan Mountains to the east and the Uzbekistan-Kyrgyzstan border about 2 km to the south.

The site is located on a slope of the Western Tianshan Mountains, with numerous gravels of varying sizes scattered across the surface. The northeastern side is a cliff, while the southwestern side is an irrigation canal connected to the Andijan Reservoir, which was constructed during

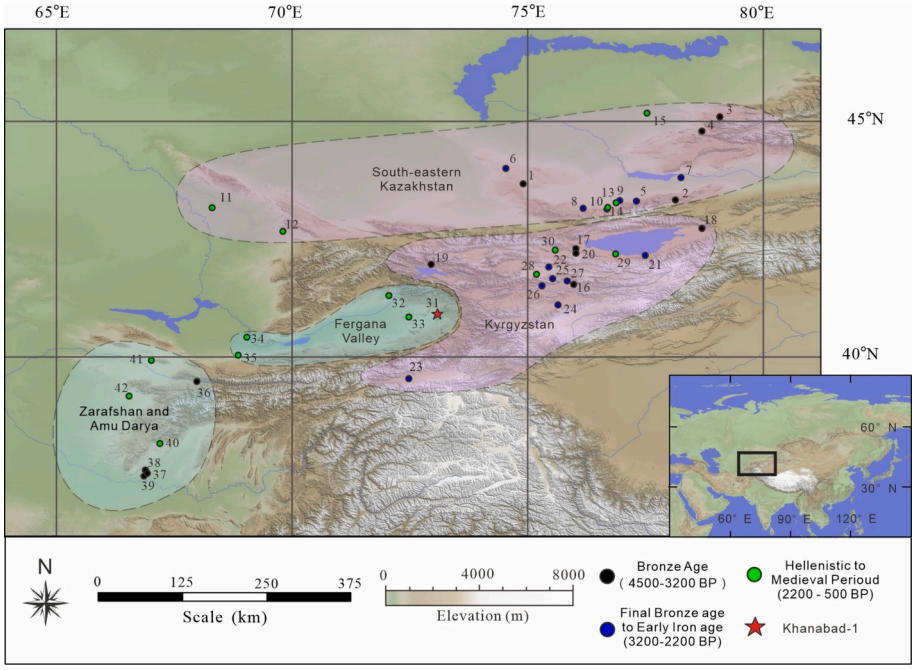


Fig. 1. The research area, location of the Khanabad-1 cemetery, and the site with stable isotope record discussed in the research. 1. Oi-Dzailau VII; 2. Kyzyl Bulak-1; 3. Dali; 4. Begash; 5. Turgen-2; 6. Shatyrkul; 7. Karatuma; 8. Kargaly-I; 9. Alatau-1; 10. Kamenka; 11. Konyr-Tobe I; 12. Temirlanovka; 13. Turgen II; 14. Butakty I; 15. Karatal; 16. Aigyrzhal 1–3; 17. Kara-Tumshuk; 18. Kyrk-Sheyit; 19. Shyldyrak; 20. Chap I-II; 21. Uch-Kurbu; 22. Chechen- Bulak; 23. Chon-Alai; 24. Mechet at-Bashi; 25. Zhapyryk; 26. Keden; 27. Baskya 1–2; 28. Boz-Adyr; 29. Kyzyl-Too; 30. Kok-Tash; 31. Khanabad-1; 32. Chartok; 33. Chor Dona; 34. Uturlik Tepe; 35. Tshbulak; 36. Dashty-Kozy; 37. Bustan; 38. Djarkutan; 39. Sapali Tepe; 40. Rabat; 41. Frinkent; 42. Altyntepe.

the 1970s and 80s. During the construction, substantial amount of sediment ranging from 0.5 to 2.3 m thickness accumulated over the northeastern part of this site. This resulted in better preservation of the graves in the northern area, whereas those in the southwest were relatively poorly preserved. Additionally, surface stones were damaged due to machinery use during the canal construction.

The graves within the cemetery are constructed by stones and sediment. The main stone piles are generally situated beneath a humus layer approximately 12–50 cm thick. The stones are typically irregular in both arrangement and size. Graves are close to each other, spaced anywhere from 1-2 m to 3–4 m apart. They are primarily simple vertical pit graves, with the predominant burial style being supine and extended. Some graves were found to be superimposed, primarily filled with a mixture stones and sediment. The number of burial goods varied, but overall, they were relatively sparse, suggesting the graves were likely inhabited by civilian.

The site was discovered in 2020 by Bakhtiyor Abdullayev, Samarkand Archaeological Institute and Nasibilo Kambarov, Fergana State University during an archaeological survey in the Khanabad region. Multiple excavations were conducted between 2020 and 2023. A total of 21 graves were excavated, yielding artifacts including pottery, bronze, iron artifact and bone, stone tools. Detailed archaeological background of the materials used in this study can be found in EMS 1.

2.2. Stable isotope analysis methods

All human skeletal samples analyzed in this research were obtained from distinct graves. To avoid interfering with subsequent osteological observations and measurements, sampling avoided critical anatomical regions such as the skull and major limb bones, prioritizing instead smaller elements from the hands and feet. All bone samples were preliminarily identified in the field during excavation before being transported to the laboratory for further anatomical curation. Bone collagen preparation and isotope analysis were conducted at the Paleoenvironment Laboratory, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences; Shanxi University and Northwest University.

Bone Collagen extraction was performed as follows: Approximately 0.5 g of bone was selected as a sample. Surface contaminants were mechanically removed from both the inner and outer surfaces of each fragment until fresh bone was exposed. Using the electronic balance to recorded the weight. The cleaned sample was weighed using an electronic balance. Then ultrasonically cleaned in deionized water until the supernatant appeared clear. Subsequently, the sample was demineralized by soaking in 0.5 mol/L hydrochloric acid (HCl) solution at room temperature, with the HCl solution changed every 3 to 4 days until the bone sample was soft and without bubbles, the duration of this step varied by sample. Following demineralization, the sample was rinsed with deionized water to neutrality. To remove humic acids, it was immersed in a 0.1 mol/L sodium hydroxide (NaOH) solution at room temperature for 1 day, then rinsed again to neutrality. After that, the purified sample was then gelatinized in a weak HCl solution (PH = 3) at 80 °C for ~ 48 h. The resulting solution was filtered, transferred to centrifuge tubes, and frozen at −40 °C. Once completely solidified, the tubes were removed, their seals were punctured, and they were placed in a freeze-dryer for approximately 48 h. The resulting solid collagen was weighed to determine the collagen yield (% Yield), then sealed and stored for subsequent isotopic determination.

Total organic carbon (TOC) and total organic nitrogen (TN) content of the samples were analyzed using a Costtech Instruments Elemental Combustion System 4024 elemental analyzer with He as the carrier gas, redox reaction was carried out at 980°C. Calibration was performed with the Methionine standard (C content 40.25%, N content 9.39%), RSD ≤ 5%.

TOC stable isotope $\delta^{13}C$ values were measured using Thermo Scientific Flash2000 elemental analyzer connected to a 253 Plus gas phase stable isotope mass spectrometer. Calibration was performed using standard samples U1 ($\delta^{13}C = -34.1‰$ VPDB), U2 ($\delta^{13}C = -8.0‰$ VPDB), U3 ($\delta^{13}C = 11.7‰$ VPDB), and the international standard IAEA-CH3 ($\delta^{13}C = -24.7‰$ VPDB). Total organic nitrogen isotope ($\delta^{15}N$) values were determined using a Thermo Scientific Flash 2000 elemental analyzer as the reaction front end. A redox reaction was performed at 980 °C to convert TN in the samples into nitrogen gas. Results were analyzed using a 253 Plus gas-phase stable isotope mass spectrometer. Standard samples U1 ($\delta^{15}N = 0.3‰$ air N_2), U2 ($\delta^{15}N = 20.2‰$ air N_2), U3 ($\delta^{15}N = 40.6‰$ air N_2), the international standard IAEA-NO_3 ($\delta^{15}N = 4.7‰$ air N_2), and USGS-25 ($\delta^{15}N = -30.4‰$ air N_2) were used for calibration.

The relative deviation of carbon stable isotope values in the standard samples was less than 0.2‰ for effective organic carbon isotope data. The relative deviation of carbon stable isotope values in the sediment samples was less than 0.3‰ for effective organic nitrogen isotope data.

2.3. Radiocarbon dating

Samples for radiocarbon dating were selected from plant remains in different graves. 2 dates were obtained from charred plant remains. The pretreatment protocol followed by acid-base-acid (ABA) method. First, the samples were cleaned of any adhering sediment and other materials, and then they were crushed. The process involved washing them in hot HCl (5%), rinsing, treating them with 1% NaOH, rinsing again, followed by treatment with hot HCl (5%), rinsing, and drying. After the pretreatment, the samples were combusted to CO_2 by oxidation at 800 °C using CuO. The CO_2 was purified in the presence of silver wire to absorb any SO_x and NO_x produced, and then it was reduced to graphite with H_2 at 550 °C using an iron catalyst. The pressed graphite targets were sent to the Radiocarbon Dating Laboratory of Beta Analytic for accelerator mass spectrometry measurements. The radiocarbon ages were subsequently calibrated using OxCal v4.4 software with the IntCal20 database (Ramsey, 2009, Reimer, et al., 2020).

3. Result

3.1. Chronological results

Due to the severe degradation of human bones, the collagen recovery rate was relatively low and no short-lived plants carbonized plants remains were found in the Khanabad-1 cemetery. Therefore, Charcoal and uncarbonized wood remains were selected from different graves as AMS^{14}C dating materials, yielding 2 AMS^{14}C dating results. These results indicate that the Khanabad-1 cemetery dates to approximately 2406–2099 cal. yr BP, belonging to the Iron Age.

Due to the inherent properties of wood and charcoal, the result may be affected by the “old carbon effect”. However, considering that the 2 wood samples obtained from Khanabad-1 have relatively close dating result, the results of both fall within the currently recognized chronological range of the Iron Age (around 8–7 Century to 3 Century BC) in the Ferghana (Dani, et al., 1994). Moreover, the burial customs of the two tombs and the artifacts found within them are also relatively similar, and dating result is generally consistent with the results determined during excavation based on artifacts such as pottery. Therefore, we infer that these two ^{14}C dating results are generally reliable. However, here we still need to point out the possibility that it may be affected by the “old carbon effect” base on the limitations of the materials. High-resolution chronology work may require further development in the future.

The specific dating results are shown as follows (Table 1).

3.2. $\delta^{13}C$, $\delta^{15}N$ stable isotope analysis results

Due to severe degradation of the samples, the collagen extraction yield was relatively low. Current stable isotope research ($\delta^{13}C$, $\delta^{15}N$) on

Table 1
Chronological results in Khanabad-1 cemetery.

Lab NO.	Sample NO.	Marital	Age BP	σ	Calibrate age cal. yr BP
Beta-686162	Xonobod 22 M4	Wood	2180 ± 30	2	2313—2099
Beta-758804	Honobod M9 2	Wood	2320 ± 30	2	2406—2180

bone collagen indicates that samples are generally considered reliable and free from severe contamination when they exhibit a total organic carbon (TOC) content of 15.3% to 47%, a total nitrogen (TN) content of 5.5% to 17.3%, and a C/N molar ratio of 2.9 to 3.6 (Ambrose, 1990, DeNiro, 1985, Van Klinken, 1999). Among the 16 samples from the Khanabad-1 cemetery, only 5 yielded collagen data conforming these quality control requirements. For these 5 samples, the TOC content ranged from 25.0% to 42.0%, the TN content from 9.3% to 15.5%, and the C/N molar ratio from 3.1 to 3.5. The $\delta^{13}C$ values ranged from −20.7‰ to −16.6‰, averaging −17.9‰, while the $\delta^{15}N$ values ranged from 9.1‰ to 12.9‰, with a mean of 10.6‰.

The $\delta^{13}C$ and $\delta^{15}N$ results for human bones from the Khanabad-1 cemetery are shown as follows (Table 2).

4. Discussion

4.1. Dietary estimation based on isotopic analysis of Khanabad-1 collagen

$\delta^{13}C$ and $\delta^{15}N$ isotope can effectively reflect the dietary composition of humans and animals (Kohn, 1999, Lee-Thorp, 2008, Van der Merwe and Vogel, 1978). In paleodietary studies, individuals with $\delta^{13}C$ values more negative than −18‰ in collagen samples are typically classified as having a diet primarily based on C_3 plants, represented by crops such as barley (*Hordeum vulgare*) and wheat (*Triticum aestivum*). Conversely, individuals with $\delta^{13}C$ values more positive than −11‰ in collagen samples are classified as consuming a diet dominated by C_4 plants, such as common millet (*Panicum miliaceum*) and foxtail millet (*Setaria italica*). Values between −18‰ and −11‰ indicate a mixed C_3/C_4 diet (Yang, et al., 2019). However, as there are no relevant studies on regional isotope thresholds in this research area currently, so we still use the thresholds from the East Asia here to make a preliminary judgment on the diet of the population. Further work is needed to determine whether the local thresholds differ from data from inland East Asia.

The average $\delta^{13}C$ values from the Khanabad-1 cemetery ranged from −20.7‰ to −16.6‰, with a mean of −17.9‰ and a standard deviation of 1.62. Individual records indicate the presence of populations following both C_3 diet and C_3/C_4 mixed diet. However, considering potential inter-individual dietary differences, some individuals with $\delta^{13}C$ values below −18‰ were also observed at the site. Therefore, based on the current $\delta^{13}C$ isotopic evidence, the diet of the Khanabad-1 population included both C_3 and C_4 crops. Nevertheless, C_4 plants constituted a relatively minor component compared to C_3 resources, indicating a dietary pattern distinct from that of populations relying solely on C_3 plants.

The $\delta^{15}N$ values from human bones at the Khanabad-1 cemetery (9.1‰-12.9‰, average 10.6‰) are approximately 3‰ higher than those from typical livestock, represented by sheep, goats, and cattle recorded in the Kyrgyzstan and southeastern Kazakhstan mountains (sheep/goats: ~7.5‰; cattle: ~7.5‰) (Hermes, et al., 2019, Itahashi, et al., 2020, Wang, et al., 2020) (Fig. 2).

Table 2
Human bones $\delta^{13}C$ and $\delta^{15}N$ results in Khanabad-1 cemetery.

Sample ID	Age	Sex	$\delta^{13}C$	$\delta^{15}N$	TN%	TOC%	C/N
M13	Adult	Male	−20.7	12.9	14.0%	37.6%	3.10
M14	Unknow	Unknow	−17.1	11.3	14.3%	39.3%	3.21
M15	Adult	Female	−16.6	10.3	15.5%	42.0%	3.17
M18	Adult	Female	−17.6	9.1	9.3%	25.0%	3.10
M19-3	Adult	Female	−17.3	9.1	11.7%	35.2%	3.51

Current research indicates that $\delta^{15}N$ enriches by approximately 3‰ to 5‰ per trophic level and also increases with higher dietary protein intake (Hedges and Reynard, 2007). The human $\delta^{15}N$ values from Khanabad-1 are about 3‰ higher than those of contemporaneous local livestock, consistent with a one-step trophic level elevation and suggesting livestock consumption. However, given that this 3‰ enrichment is at the lower end of the expected trophic shift range, the diet of the Khanabad-1 population may have contained a relatively modest proportion of animal protein.

However, due to the lack of systematic stable isotopic records of regional Iron Age fauna in the Fergana Valley, the faunal data from the surrounding mountains may differ from those of the valley due to the different of climate and environment. Limited by the available data, only the above preliminary results can be obtained at present, it must be pointed out that the lack of local faunal data, the number limited of comparative data, and potential environmental differences may affect our preliminary conclusions regarding current population trophic levels and animal protein intake, further high-resolution research is needed in the future.

4.2. Dietary changes from the Bronze age to the medieval period in the IAMC population

The subsistence patterns of a population are shaped by multiple factors, such as the regional natural environment, technological traditions, and cultural exchanges. Current research indicates that climatic conditions (Hartman, 2011), elevation (Hart, et al., 2013, Wang, et al., 2020) dietary and technological traditions(Li, et al., 2020) and the frequency of population interactions (Dong, 2021) can all influence the carbon and nitrogen stable isotope values of regional flora, fauna, and humans. Therefore, research based on $\delta^{13}C$ and $\delta^{15}N$ values from human bones must consider these surrounding natural conditions and the archaeological cultural context. However, the lack of high-resolution local climate records and stable isotope data from early regional civilizations in the study area hinders more in-depth comparative research.

The stable isotope results from the Khanabad-1 cemetery represent the earliest human bone isotope record in the Fergana Valley. To compare the spatiotemporal variation in human diet between Fergana and surrounding populations, we selected published data from the western IAMC, including the Surkhan and Zarafshan regions (Hermes, et al., 2018, Kroll, 2021, Liu, et al., 2020, Narasimhan, et al., 2019), Kyrgyzstan (Motuzaite, et al., 2022) and southeastern Kazakhstan (Ananyevskaya, et al., 2018, de Barros Damgaard, et al., 2018, Hermes, et al., 2019, Itahashi, et al., 2020, Matuzeviciute, et al., 2015). A comparison was conducted between human bone $\delta^{13}C$ and $\delta^{15}N$ records from the Bronze Age to the Medieval period (Table 3) and the data from the Khanabad-1 cemetery in Fergana (Figs. 3 and 4).

The results show that during the Bronze Age, the $\delta^{13}C$ values of oasis agricultural populations in southern Central Asia, represented by those from the Surkhan and Zarafshan Darya regions, centered around −18.0‰, while the average $\delta^{15}N$ value was 12.8‰, indicating a predominant C_3 plant diet. Farther to the north in Kyrgyzstan, the average $\delta^{13}C$ value was approximately −18.16‰, and the average $\delta^{15}N$ was 11.7‰, showing a pattern similar to the southern oasis agricultural populations (t test, $p \geq 0.05$). In southeastern Kazakhstan, located further north, the $\delta^{13}C$ values during this period were significantly more positive than those in the southern regions, with an average of approximately −16.1‰, reflecting a mixed C_3/C_4 diet. The average $\delta^{15}N$ value there was about 13.0‰, similar to the values recorded in the south (t test, $p \geq 0.05$).

According to current research, the earliest evidence of C_4 Crops cultivation like millet in the northern foothills of the western Tianshan Mountains dates to the Bronze Age, around 4400 yr BP, as represented by the site of Begash (Frachetti, et al., 2010). Although millet has also been identified in the Surkhan Darya during a later period (Miller, et al.,

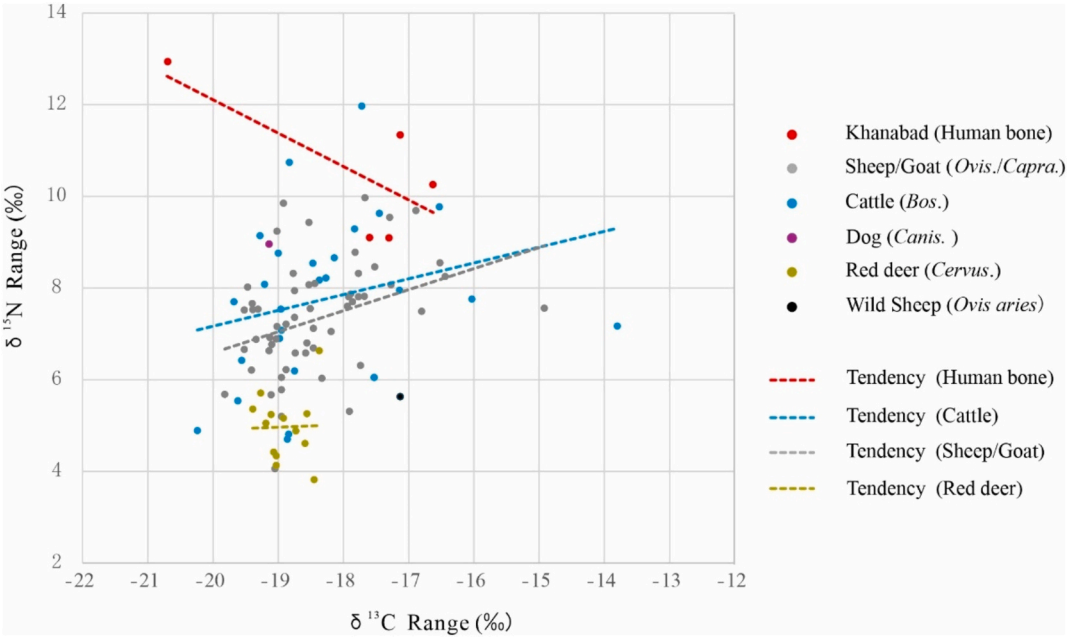


Fig. 2. $\delta^{13}C$ and $\delta^{15}N$ stable isotopic records of human bones from the Khanabad-1 cemetery and records of Iron Age mammal in the surrounding Kyrgyzstan and southeast Kazakhstan mountainous (References in ESM2).

Table 3
The $\delta^{13}C$ and $\delta^{15}N$ records from human bones in different regions in western IAMC, from Bronze Age to Medieval period (References in ESM2).

Period	Region	Average elevation /m	Site Num.	Sample Num.	Average $\delta^{13}C$	Sd (σ)	Average $\delta^{15}N$	Sd (σ)
Bronze Age	South-eastern Kazakhstan	1146	4	18	−16.1	1.9	13.0	1.9
5500–3200 BP	Kyrgyzstan	1878	5	13	−18.2	0.8	11.7	0.8
	Zarafshan and Amu Darya	596	3	17	−18.0	0.8	12.8	0.8
Final Bronze age –	South-eastern Kazakhstan	1142	7	77	−15.3	1.1	12.6	1.5
Early Iron age	Kyrgyzstan	2342	9	25	−17.4	1.2	12.2	1.2
3200–2200 BP	Fergana	755	1	5	−17.9	1.6	10.6	1.6
	Zarafshan and Amu Darya	370	1	1	−17.7	/	13.1	/
Hellenistic–	South-eastern Kazakhstan	873	5	29	−15.4	2.5	12.0	2.5
Medieval	Kyrgyzstan	2285	8	42	−17.0	1.3	12.5	1.3
2200–500 BP	Fergana	874	4	28	−16.9	1.1	11.3	1.1
	Zarafshan and Amu Darya	713	3	15	−18.5	0.6	10.9	0.6

2016), the isotopic values from human bones at these southern sites generally cluster around −18‰, which marks the boundary for a C_3/C_4 mixed range. During this period, compare the $\delta^{13}C$ record for domesticated herbivore animals in the southern oasis and northern mountains, the result shows the C_3 result (Average $\delta^{13}C = -18.5‰$, $\delta^{15}N = 7.7‰$, n = 58) in northern mountains and the C_3/C_4 mixed result (Average $\delta^{13}C = -16.5‰$, $\delta^{15}N = 10.0‰$, n = 18) in the southern oasis (Kroll, 2021, Motuzaite, et al., 2022). This means that compared to people in the northern mountainous who consume more C_4 plants, C_4 plants in Oasis more like to consume by livestock during the Bronze age. However, due to the lack of wild animal isotope records in Bronze Age oasis, it is currently impossible to determine whether this difference is due to human activity or not.

Therefore, during the Bronze Age, C_4 plants had become an important plant food source for populations in the northern foothills of the western Tianshan Mountains (Wang et al., 2019). In contrast, in the more southerly oasis agricultural zones, C_4 plants did not become a dominant food source like C_3 plants. Furthermore, the more dispersed distribution of both $\delta^{13}C$ and $\delta^{15}N$ values from the northern population in western Tianshan Mountains, compared to the oasis agricultural populations, possibly indicates more frequent population movement in that region.

Also noteworthy is the difference between the $\delta^{13}C$ records in Kyrgyzstan, although some data falls within the C_3/C_4 mixed dietary pattern, a considerable number of individuals still exhibit purely C_3 characteristics, resulting in a significantly negative mean value. This is markedly different from the situation in southeastern Kazakhstan, where the region as a whole fall within the C_3/C_4 mixed range.

Paleoenvironmental records from Kyrgyz Mountains like Son Kol Lake (Mathis, et al., 2014), Issyk-Kul Lake (Ferronskii, et al., 2003, Leroy and Giralt, 2020), and Talisman Cave (Tan, et al., 2024) indicate that the climate in the western Tianshan region during the Bronze Age was generally relatively humid, but gradually became drier after around 4000 yr BP. This is consistent with paleoenvironmental records observed at the piedmont alluvial fan (Chen, et al., 2024, Zhang, et al., 2025), confirming the overall consistency of regional paleoenvironmental trends. Therefore, we speculate that during this period, local environmental differences may not have been the main factor causing isotopic differences among populations in different regions. Current research suggests that this difference in $\delta^{13}C$ may be due to the influence of altitude. Since C_4 crops such as millet require higher accumulated temperatures than C_3 crops, they cannot be cultivated above approximately 2000 m in the western Tianshan Mountains (Wang, et al., 2020). In contrast, the average elevation of Bronze Age human stable isotope records in Kyrgyzstan is 1878 m, approaching the upper limit for C_4 crop cultivation. Current human stable isotope studies in the Tianshan region

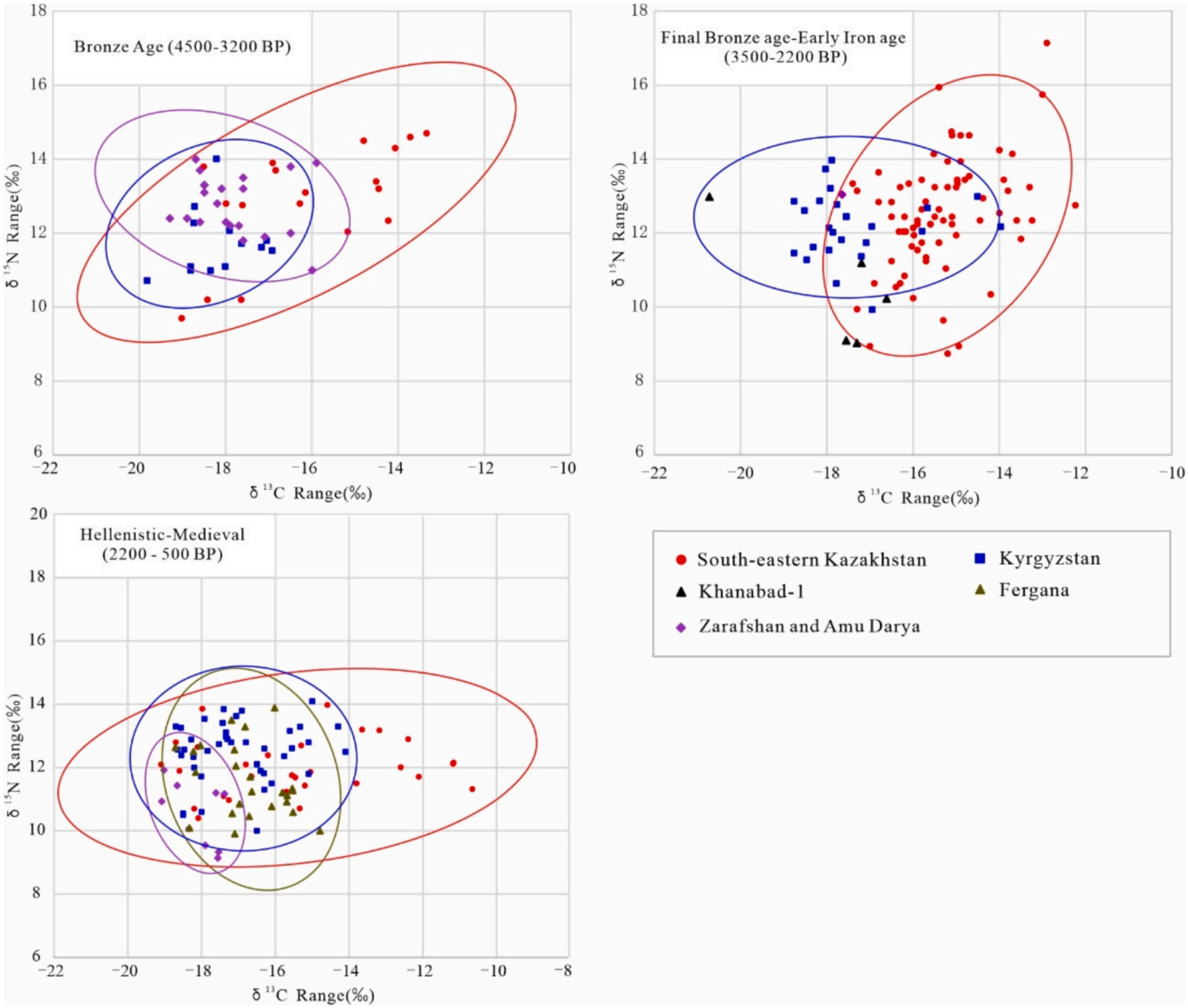


Fig. 3. Huma $\delta^{13}C$ and $\delta^{15}N$ stable isotopes record distribution from the Western IAMC during Bronze Age to Medieval period (References in ESM2).

have also observed a gradual decrease in $\delta^{13}C$ values with increasing altitude, indicating a transition from a C_3/C_4 mixed diet in lower altitude areas to a C_3 diet in higher altitude areas (Wang, et al., 2020). This altitudinal discrepancy may have influenced the isotopic values of the population in the region. However, due to the limited number of isotopic records from the area, further discussion of this issue is not feasible at present.

In the Iron Age, $\delta^{13}C$ records from different regions in the western part of the IAMC showed varying degrees of positive biased then Bronze age. Human $\delta^{13}C$ records from southern Kazakhstan, represented by Tersakan, Zheken, and Aktogai (Itahashi, et al., 2020) show a further positive shift, reflecting an increased proportion of C_4 plants in their diet, while $\delta^{15}N$ values remained largely unchanged from the Bronze Age. The $\delta^{13}C$ records from domesticated and wild herbivore animals from Begash during this period is largely consistent with that of the Bronze Age, remaining C_3 type (Average $\delta^{13}C = -18.5‰$, $\delta^{15}N = 7.1‰$, $n = 81$) (Motuzaite, et al., 2022), which indicates an increased consumption of C_4 crops by the regional population.

In the Zerafshan and Surkhan Darya, the $\delta^{13}C$ records of agricultural populations, represented by the later remains at Djarkutan, also exhibited this positive trend. The human bone $\delta^{13}C$ value of −17.7‰ falls within the range of a C_3/C_4 mixed range, while the corresponding $\delta^{15}N$ value increased slightly to 13.1‰, which no significant changes then Bronze Age. However, considering that only one isotopic record from human bone exists for the Amu Darya region during this period, and that this record originates from the final occupation phase at Djarkutan (Kroll, 2021), which is in the end of final Bronze age, the current missing in more relevant Iron age data may have influenced our analytical conclusions.

Based on the paleoenvironmental records within the Western Tianshan Mountains, represented by Talisman Cave (Tan, et al., 2024) and Fazilman Lake (Dugerdil, et al., 2026), the region during the Iron Age was generally undergoing a fluctuating drying trend. This is consistent with the positive bias observed in the $\delta^{13}C$ of human bones and the record of increased C_4 crop remains in river valley agricultural site (Wu, et al., 2015) during this period. Considering potential drought events during this period and the southward expansion of nomadic populations associated with the Andronovo horizon in archaeological context (Cattani, 2008, Narasimhan, et al., 2019), the increased intake of C_4 plants in agricultural population may have been influenced by a combination of environmental and migratory factors.

The Khanabad-1 cemetery, as a representative record of Iron Age

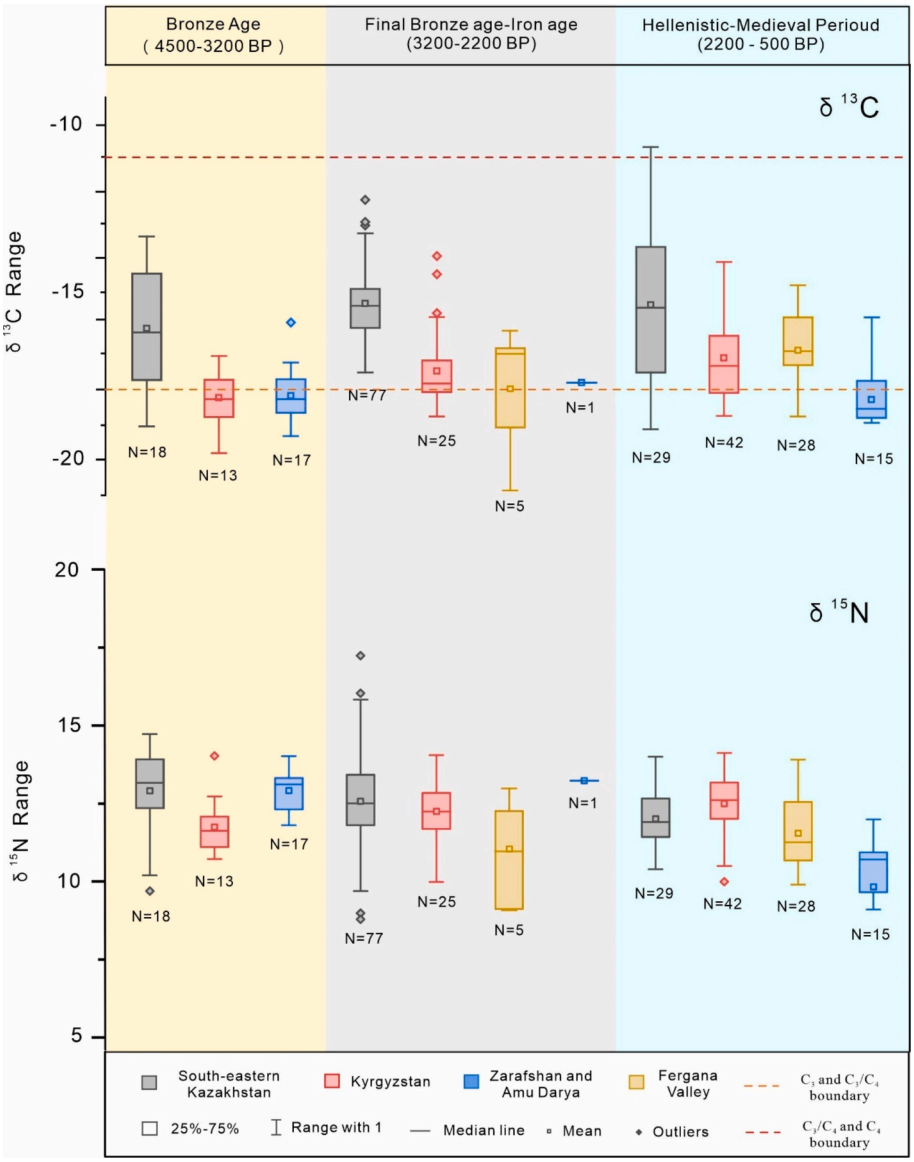


Fig. 4. The spatiotemporal differences and changing trends of δ^{13}Cand δ^{15}N records of human bones in western IAMC during the Bronze Age to the Medieval period (References in ESM2).

human activity in the Fergana Valley, is situated in a transitional zone between the agricultural populations in the oasis and the agropastoral populations in the mountain. A comparison of its δ^{13}C and δ^{15}N values with contemporaneous surrounding regions reveals that the δ^{13}C value at Khanabad-1 is −17.9‰, characteristic of a C_3-dominated mixed diet. This is similar to records from Kyrgyzstan and the southern oasis agricultural populations (t test, $p \geq 0.05$), but significantly more negative than the −15.3‰ recorded in the northern foothills of the western Tian Shan Mountains. Based on the current archaeobotanical records around Fergana Valley like Surungur (Boxleitner, et al., 2026) in this period, the C_3 crops consumed by the local population were likely barley and wheat. The average δ^{15}N value in Khanabad-1 is 10.6‰, which is notably lower than the 12.6‰ observed in southwestern Kazakhstan, 12.24‰ in Kyrgyzstan, and 13.1‰ in the Amu Darya region, show significant differences (t test, $p < 0.05$).

Khanabad-1 is dated to 2406–2099 cal. yr BP. High-resolution stalagmite oxygen isotope records from Talisman Cave, approximately 73 km southwest of the site, indicate that the Fergana region was experiencing a relatively humid phase during this period, with two distinct humid peaks between 2500–2360 yr BP and 2250–2100 yr BP (Tan, et al., 2024). Considering that some studies suggest that drier climates may lead to a positive bias in the δ^{15}N isotope record of populations (Bocinsky and Kohler, 2014, Tieszen, 1991), we combining the Khanabad-1 dating result with the relatively humid trend shown in high-resolution paleoenvironmental records in Fergana during this period, we infer that the relatively negative δ^{15}N record of the Khanabad-1 population more likely reflects the regional population animal protein intake rather than environmental stress caused by aridification. However, we must also note that the lack of enough systematic, continuous chronological human isotope records in the study area may affect our preliminary correlation results.

Overall, This modest animal protein consumption dietary structure contrasts sharply with that of the agropastoral populations in the surrounding Kyrgyzstan mountains. In conjunction with stone farming tools such as millstones and sickles found in graves, it is highly likely that plant foods obtained through agriculture constituted an important part of the diet for the Khanabad-1 population.

Comparing the δ^{13}C and δ^{15}N values obtained from Khanabad-1 with those from medieval agricultural populations in the Fergana Valley, represented by Chor Dona and Chartok (Hermes, et al., 2018), reveals a

slight increase in C_4 plant and animal protein intake among the medieval populations ($\delta^{13}C = -16.9‰$ and $\delta^{15}N = 11.3‰$) compared to the Iron Age records from Khanabad-1 ($\delta^{13}C = -17.9‰$ and $\delta^{15}N = 10.6‰$). However, the overall change is relatively small, which may indicate a close connection between the dietary traditions of medieval and Iron Age agricultural populations in the Fergana Valley, Meanwhile, the $\delta^{13}C$ records of domesticated herbivores animals around the southeastern Kazakhstan and Kyrgyzstan Mountains during this period were still of the C_3 type (Average $\delta^{13}C = -19.4‰$, $\delta^{15}N = 7.2‰$, n = 7) (Motuzaite, et al., 2022), showing no significant changes compared to the Bronze and Iron Ages in west Tianshan mountains region.

From the regional climate perspective, compared to the extremely arid periods around 5500 yr BP and the Late Bronze Age, the western IAMC did not experience extreme drought events during the Medieval Warm Period. The regional climate was relatively stable during this period, with a distinct wet phase occurring between 970 and 1030 yr BP. Therefore, the slightly positive $\delta^{13}C$ and $\delta^{15}N$ deviations in human bones from the Fergana region during this period are more likely to reflect changes in the regional population's dietary structure.

Further comparison with contemporary surrounding populations shows that the medieval Fergana $\delta^{13}C$ and $\delta^{15}N$ values are significantly more positive than those of the agricultural populations in the Zarafshan and Surkhan Darya regions to the south ($\delta^{13}C = -18.5‰$ and $\delta^{15}N = 10.9‰$). This contrasts with the diet of the southern oasis agricultural populations, which was predominantly based on C_3 plants with relatively low animal protein intake. Compared to records from southwestern Kazakhstan and Kyrgyzstan, which are generally consistent with the Iron Age, the Fergana Valley occupy a transitional position between the mixed agropastoral populations of the western Tian Shan Mountains and the oasis agricultural populations of the Amu Darya. This could be the further demonstrates the dietary connection between local agricultural populations and the mixed agropastoral groups within the IAMC.

5. Conclusion

In this research, we conducted chronological and isotopic analyses based on remains from the Khanabad-1 cemetery, and compared these findings with published human isotopic records from the Bronze Age to the Medieval period in the western IAMC. For the first time, preliminary reveals the diet of the Iron Age population of Fergana with a small subset. The principal conclusions are as follows:

The Iron Age population in the Fergana Valley preliminary exhibited a C_3-dominated mixed diet with a modest level of animal protein consumption. Although no crop remains were found in the cemetery, but given the numerous stone tools associated with agricultural production found at the Khanabad-1 site, farming likely constituted a main component of local subsistence strategies.

The preliminary dietary pattern of a small subset from the Khanabad-1 population differs from that of the Bronze to Iron Age agropastoral populations within the IAMC, as well as from the agricultural populations of the southern Central Asian oases during the Iron age, primarily in its lower proportion of animal protein. This structure is closely aligned with the isotopic records of medieval agricultural populations in the Fergana Valley. It may represent an important facet of regional agricultural dietary history, reflecting connections between local Fergana populations, the agropastoral groups of the IAMC mountains, and the agricultural communities of the southern oases.

CRediT authorship contribution statement

Nasibilo Kambarov: Writing – original draft, Resources, Investigation, Funding acquisition, Conceptualization. **Guanhan Chen:** Writing – original draft, Visualization, Methodology, Funding acquisition, Formal analysis, Data curation. **Xinying Zhou:** Writing – review & editing, Supervision, Resources, Project administration. **Junchi Liu:** Writing – review & editing, Validation, Methodology, Formal analysis. **Junjie Zhang:** Methodology, Formal analysis. **Keliang Zhao:** Writing – review & editing, Supervision. **Jiacheng Ma:** Validation, Investigation. **Bakhtiyor Abdullayev:** Investigation. **Jianxin Wang:** Supervision. **Xue Ling:** Methodology, Data curation. **Liangliang Hou:** Methodology, Data curation. **Dongyue Zhao:** Supervision. **Jian Ma:** Supervision, Funding acquisition. **Xiaoqiang Li:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2026.105914.

Data availability

Data will be made available on request.

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