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Transformation of animal utilization strategies from the late Neolithic to the Han Dynasty in the Hexi Corridor, northwest China: Zooarchaeological and stable isotopic evidence

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The trajectory and influencing factors for changes to ancient human livelihoods in the Hexi Corridor of northwest China have been intensively discussed. The Hexi Corridor is a key crossroads for trans-Eurasian exchange in both the prehistoric and historical periods. Although most studies have focused on the reconstruction of human paleodiet and plant subsistence, the diachronic change of animal utilization strategies spanning the prehistoric and historical periods remains unclear, due to the absence of zooarchaeological and isotopic studies, especially in Han Dynasty (202 BCE–220 CE). Here we report new zooarchaeological, stable isotope, and radiocarbon dating data from the Heishuiguo Cemetery of the Han Dynasty in the Hexi Corridor, indicating that humans mainly used domestic chickens, pigs and sheep as funerary objects, with other buried livestock including cattle, horses and dogs. Stable carbon and nitrogen isotope data suggest humans might have fed chickens, pigs and dogs more C_4 foods (likely millets or their byproducts) than herbivorous livestock in the Heishuiguo during the Han Dynasty. Compared to other prehistoric zooarchaeological and isotopic studies in the Hexi Corridor, we detected an increasing significance of herbivorous livestock in animal utilization strategies compared with omnivorous livestock, and a basic declining weight of C_4 foods in fodders from ~2,300 to 200 BCE, which was probably induced by long-distance exchange and climate fluctuation. However, the trend was reversed during the Han Dynasty in the Hexi Corridor, primarily due to the control of the area by the Han Empire and the subsequent massive immigration from the Yellow River valley of north China.

KEYWORDS

zooarchaeology, isotopic analysis, animal exploitation, Han dynasty, the late Neolithic, Hexi corridor

1 Introduction

With the rapid development of bioarchaeological research in recent decades, the spatio-temporal variation of human subsistence strategies in different corners of the planet since the Neolithic has been increasingly concerned (Piperno and Dillehay, 2008; Hu, 2018, 2021; Chen et al., 2020; Fernández-Crespo et al., 2020). This has been especially true of the area around the ancient Silk Road and Eurasian Steppes (Wang et al., 2019; Zhou et al., 2020; Li et al., 2021a; Librado et al., 2021), where there were major passageways for the dispersal of farming and herding groups across Eurasia during both the prehistoric and historical periods (Dong et al., 2017; Frachetti et al., 2017; Liu et al., 2019). Trans-Eurasian exchange emerged and intensified mainly through these two passageways after the third Millennium BCE (Spengler et al., 2014; Wang et al., 2019; Zhang et al., 2021), profoundly influencing human livelihoods across the Old World (Jeong et al., 2018; Ning et al., 2020; Dong et al., 2022), especially in the crossroads areas for long-distance exchange, such as the Hexi Corridor in northwest China.

The earliest human settlement in the Hexi Corridor can be traced back to ~2,800 BCE (Dong et al., 2018), thereafter human subsistence strategies in the area varied evidently before Han Dynasty. Archaeobotanical and isotopic studies reveal that humans in the Hexi Corridor mainly cultivated foxtail and broomcorn millet and consumed C_4 foods during ~2,800–2,000 BCE. They then cultivated millets, wheat and barley, consumed both C_3 and C_4 foods during ~2,000–1,300 BCE, while the significance of barley and wheat in plant subsistence far exceeded foxtail and broomcorn millet during ~900–200 BCE (Zhou et al., 2016; Yang et al., 2019a; Dong G et al., 2020). According to isotopic evidence and historical records, the weight of millet crops in human subsistence strategies was evidently improved in the Hexi Corridor during the Han Dynasty as compared to the early Iron Age (Gao, 2014; Li, 2021).

In contrast to the rapid accumulation of archaeobotanical data, zooarchaeological studies have been conducted at just a few prehistoric sites in the Hexi Corridor (Figure 1). Current studies suggest that the primary livestock shifted from indigenous pigs and dogs to introduced sheep, cattle, and horses between ~2,800 and 2,000 BCE and ~2,000–1,300 BCE, respectively, while herbivorous livestock became the dominant subsistence animal during ~900–200 BCE in the Hexi Corridor (Yang et al., 2019a; Dong G et al., 2020; Dong G. H. et al., 2020; Ren et al., 2022). No zooarchaeological data from the Han Dynasty sites in the area has been reported, and therefore the diachronic change of animal utilization strategies spanning the late prehistoric and historical periods remains enigmatic. Recently, abundant animal bones were unearthed from the Heishuiguo (HSG) Cemetery of the Han Dynasty in the Hexi Corridor. Here we try to further the research on these issues, based on the identification assemblage, as well as carbon and nitrogen isotope analysis of buried animal remains in the Heishuiguo Cemetery, compared to published data from elsewhere in the Hexi Corridor. Moreover, we compare zooarchaeological and stable isotopic data with historical and paleoclimate studies, in order to explore the influencing factors

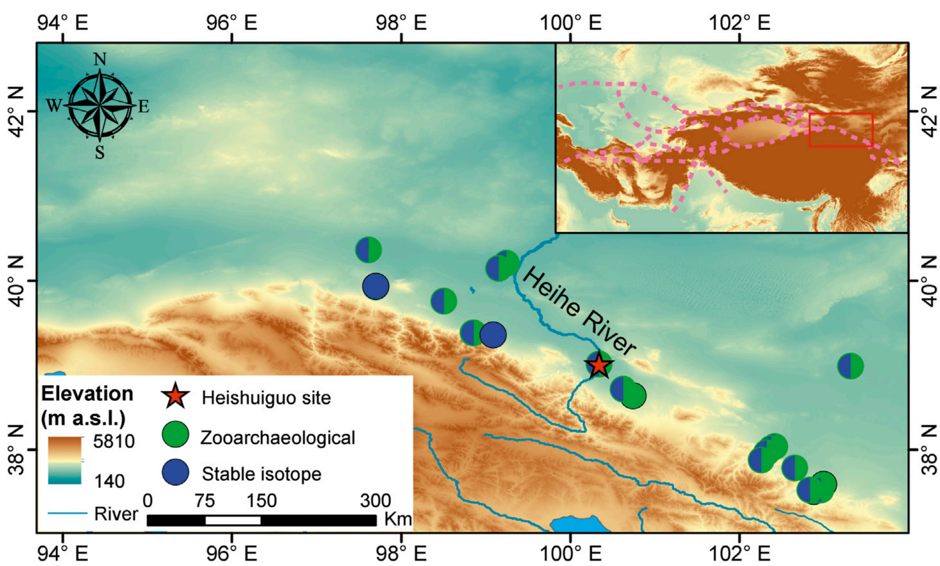

FIGURE 1
Location of sites in the study area referred to in this paper.

behind the transformation of animal utilization strategies in the Hexi Corridor.

2 Study areas

2.1 Geographical background

The Hexi Corridor (37.28°–42.80°N, 92.38°–102.20°E) is located in northwestern China (Figure 1). It is a long narrow corridor, spanning about 1,000 km from the Wushaoling Mountains in the east to the Yumenguan Pass in the west, which bordering the Tibetan Plateau in the southwest, the Mongolian Plateau in the north, the Loess Plateau in the east, and the Tarim Basin and Tianshan Mountains in the west. The study area is characterized by a semi-arid and arid climate, with mean annual temperatures varying from 4°C to 9°C and annual average precipitation of 178 mm (see http://data.cma.cn). From east to west, the precipitation decreases gradually. The Shule, Shiyang, and Heihe Rivers are the three largest inland rivers in the region. The natural vegetation in the study area is dominated by C_3 vegetation (Su et al., 2011) and the sedimentary $\delta^{13}C$ values demonstrate the predominance of C_3 plants during the Holocene (Jiang et al., 2019). The Hexi Corridor is the essential route from China to the Central Asia, West Asia and even Europe, and the region has been an important route for human migration and cultural diffusion from prehistoric to historical times. The study area is located at a key location on the Silk Road and has played an important role in prehistoric trans-Eurasian exchange, especially since the Han Dynasty (202 BCE–220 CE).

Heishuiguo Cemetery (36.92°N, 100.34°E) is located in the middle of the Hexi Corridor (Figure 1), in Ganzhou, Zhangye, and it is near to the Heihe River. The river valley provides a critical connection between the Hexi Corridor and the Eurasian Steppe, making these sites a hub for prehistoric and historical cultural exchange in northwestern China. In 2018, the Gansu Provincial Institute of Cultural Relics and Archaeology conducted rescue excavation of the Heishuiguo Cemetery and excavated 118 Han Dynasty tombs. Based on the cultural relics and funeral objects found, it shows that the Heishuiguo Cemetery was mainly used from the middle Western Han Dynasty to the middle Eastern Han Dynasty (GPICRA, 2019).

2.2 Archaeological background

The archeological framework of cultural evolution in the study area has been established according to previous studies (Wang, 2003; Li, 2011; Yang et al., 2019b). In the Hexi Corridor, the chronological order of archeological culture is: the Machang types of the Majiayao culture (2,300–2,000 BCE), the Qijia/Xichengyi culture (2,000–1,600 BCE), the Siba culture (1,600–1,300 BCE), the Shanma culture (900–200 BCE), the Shajing culture (800–200 BCE), the Western Zhou Dynasty (1,046–771 BCE), the Eastern Zhou Dynasty (770–256 BCE), and the Han Dynasty (202 BCE–220 CE).

According to cultural phases and the radiocarbon dates, we divided the data into four periods: 2,300–2,000 BCE, 2,000–1,300 BCE, 900–200 BCE, and the Han Dynasty (202 BCE–220 CE).

3 Materials and methods

A total of 1,020 pieces of animal bones were unearthed from 27 Han Dynasty tombs in Heishuiguo Cemetery during the excavation in 2018, all of which could be identified to the species level. All animal remains were collected carefully by hand, any attachments on the bone surface were washed away, and then they were left to dry in the shade. Taxon identification and measurement were carried out in the MOE Key Laboratory of Western China's Environmental Systems (Ministry of Education) in Lanzhou University on the basis of the morphological characteristics of the bones. In the course of the zooarchaeological analysis, we compared the Heishuiguo Cemetery remains to ancient animal specimens kept in our lab and some atlases of modern animal bones (Schmid, 1992; France, 2008).

Thirty-three animal bones were selected for isotopic analysis. Bone collagen was extracted by the acid-alkali-acid method, which has been described in other papers (e.g. Ma et al., 2016; Hu, 2018; Li, 2021). The percentages of C and N, the atomic C/N ratios, and the isotopic values of all collagen samples were processed in an isotope mass spectrometer (IsoPrime-100 IRMS) combined with an element analyzer (Vario Pyro Cube). Carbon and nitrogen isotopic ratios were measured relative to VPDB and AIR standard samples, respectively. The analytical precision of isotopic ratios was better than 0.2‰. We used SPSS 25.0 for statistical analysis. The Mann-Whitney and Kruskal–Wallis tests were used to detect differences between different groups of samples.

In addition, two animal collagen samples were radiocarbon dated at Lanzhou University, China. All ^{14}C dates were calibrated in OxCal 4.4.4 (Ramsey, 2021) with the IntCal 20 calibration curve (Reimer et al., 2020) and reported as 'BCE or CE'.

4 Results

The number of animal remains identified to the species level is defined as NISP (the number of identified specimens) and the minimum number of individuals (MNI) of each species can be estimated based on their NISP. All the buried animal remains at Heishuiguo were identified as domestic animals, including chickens (*Gallus gallus domestica*), pigs (*Sus scrofa domesticus*), cattle (*Bos taurus*), sheep (*Ovis aries*), and dogs (*Canis lupus familiaris*) (GPICRA, 2019). All animal identification data are listed in

TABLE 1 Proportion of identified animal remains from the excavation of the HSG Cemetery in 2018.

Period	Species	NISP	NISP (%)	MNI	MNI (%)
Phase 1	Gallus gallus domestica	147	35.34	8	38.10
	Sus scrofa domesticus	132	31.73	9	42.86
	Bos taurus	93	22.36	2	9.52
	Ovis aries	35	8.41	1	4.76
	Canis lupus familiaris	9	2.16	1	4.76
Total		416	100.00	21	100.00
Phase 2	Gallus gallus domestica	328	58.89	15	68.18
	Sus scrofa domesticus	125	22.44	4	18.18
	Ovis aries	103	18.49	2	9.09
	Aves	1	0.18	1	4.55
Total		592	100.00	22	100.00
undefined	Gallus gallus domestica	47	93.33	1	50.00
	Equus ferus caballus	1	6.67	1	50.00
Total		48	100.00	2	100.00

NISP: number of identified specimens; MNI: minimum number of individuals.

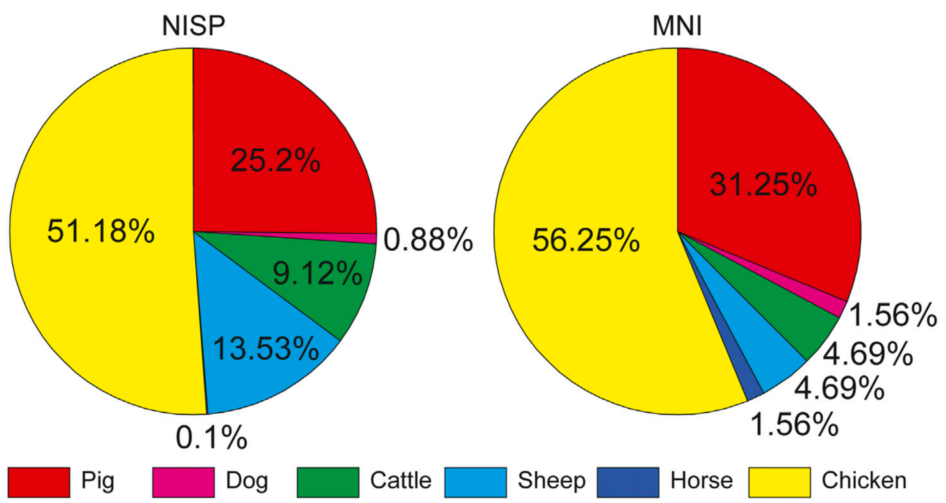

FIGURE 2
Assemblages of domesticated animals from the HSG Cemetery. (NISP: the number of identified specimens, MNI: the minimum number of individuals)

Table 1 and plotted in Figure 2. Based on the characteristics of the cemetery (GPICRA, 2019) and the results of the absolute dating, the animal samples in this study were divided into two periods: 190–50 BCE (phase 1, the middle Western Han) and 50 BCE–200 CE (phase 2, late Western Han to Eastern Han). During phase 1, both the NISP and MNI data for animal bones indicate that chickens account for more than 35 percent of the total animal remains, with 147 fragments representing 8 individuals. The number of pig bones is similar to chicken bones, with 132 by NISP vs. 9 by MNI. The number of cattle bones is less than chickens and pigs during this phase, making up approximately one-fifth of the total animal remains by NISP and one-tenth of the total animal remains by MNI. The remaining samples contained the bones of sheep and dogs, which make up a small proportion of the total

TABLE 2 Summary of carbon and nitrogen isotope results for animal samples.

Phase	Species	Number	$\delta^{13}C$(‰)			$\delta^{15}N$(‰)		
			Mean	SD	Range	Mean	SD	Range
1	Chicken	5	−16.0	2.3	−19.3 ~ -14.0	6.9	1.3	5.2 ~ 8.1
	Pig and dog	6	−13.9	1.5	−15.7 ~ -11.9	8.8	1.2	7.5 ~ 10.0
	Sheep and cattle	2	−19.3	0.2	−19.4 ~ -19.2	7.0	2.0	5.6 ~8.5
	Total	13	−15.5	2.5	−19.4 ~ -11.9	7.8	1.6	5.2 ~ 10.0
2	Chicken	11	−17.6	1.5	−19.2 ~ -14.1	8.6	1.8	6.6 ~ 13.2
	Pig and dog	7	−14.2	1.8	−16.6 ~ -12.3	9.3	1.1	8.2 ~ 11.2
	Sheep and cattle	1	−19.9	–	–	4.7	–	–
	Total	19	−16.5	2.4	−19.9 ~ -12.3	8.6	1.8	4.7 ~ 13.2
Undefined	Chicken	1	−17.0	–	–	8.2	–	–

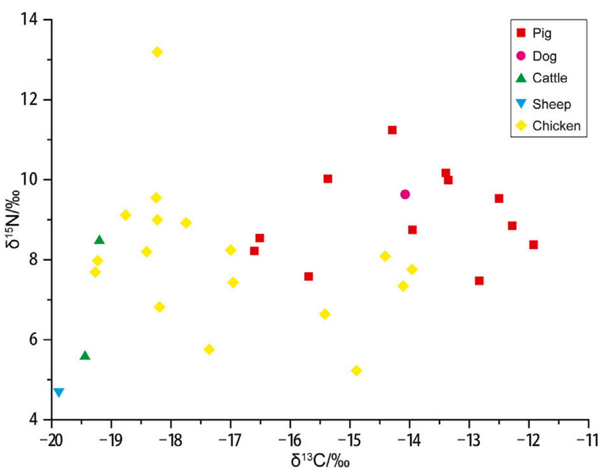

FIGURE 3
Scatter plots of bone collagen $\delta^{13}C$ and $\delta^{15}N$ values of animal samples from the HSG Cemetery.

animal bones of the phase. During phase 2, except for one large bird bone, the samples found are domestic animal remains including chickens, pigs, and sheep. The number of chicken bones is dominant among all animal bones in phase 2, with 328 fragments representing 15 individuals (58.89% by NISP, 68.18% by MNI). Although pigs and sheep account for about 20% (NISP) of all the animal remains, the number of pigs is twice that of sheep, according to the MNI data. In addition, there were 47 chicken bone fragments and one horse (*Equus ferus caballus*) bone excavated from Heishuiguo, which cannot be classified into definite cultural stages without cultural relics and funeral objects.

Animal isotopic data (Table 2 and Supplementary Figure S1; Figure 3) are usually used to reflect the strategies of ancestors to feed and manage animals. The $\delta^{13}C$ value for chickens, pigs, and dogs implies that their diets (mixed C_3 and C_4 foods) did not notably change during either phase (mean $\delta^{13}C$ for chickens: −16.0 vs. −17.6, p=0.189; for pigs and dogs: −13.9 vs. −14.2; p=0.721). However, pigs and dogs ate more C_4 foods than chickens in both phases. In addition, the diet of domesticated herbivores showed heavy reliance on C_3 plants and did not change in either phase (mean $\delta^{13}C$: -19.3 vs. −19.9). The $\delta^{15}N$ value for pigs and dogs during the two phases is highest, which suggests they may eat a significant amount of animal protein included in the leftovers or feces of ancestors. The $\delta^{15}N$ value for chickens is similar to that of sheep and cattle in phase 1, while the $\delta^{15}N$ value for chickens is far higher than that of sheep and cattle in phase 2 (Table 2). The reason for this phenomenon may be that the chickens in phase 2 took a certain amount of animal protein, such as worms. All analyzed domesticated herbivore individuals exhibited $\delta^{13}C$ and $\delta^{15}N$ values consistent with a diet based heavily on C_3 terrestrial sources.

The ^{14}C dating results of two animal bone collagen samples from the Heishuiguo Cemetery are shown in Table 3. The direct dating result of one piece of sheep bone is 25 cal CE~203 cal CE, approximately corresponding to the Eastern Han Dynasty. Another date from one piece of pig bone ranges from 165 cal BCE to 2 cal BCE, falling within the scope of the Western Han Dynasty.

5 Discussion

5.1 Animal utilization strategy during the Han Dynasty in the Hexi Corridor

The identification results of animal remains in the Heishuiguo Cemetery show that domestic chickens, pigs and

TABLE 3 Calibrated radiocarbon dates for animals from the HSG Cemetery.

Lab number	Sample Name	Dating material	^{14}C age BP	Calibrated age BCE/CE (95.4% prob.)
LZU19244	2018ZHM10	Sheep bone	1930 ± 20	25 cal CE~203 cal CE
LZU19245	2018ZHM16	Pig bone	2080 ± 20	165 cal BCE~2 cal BCE

sheep were the dominant species in the funerary animals of these Han Dynasty tombs according to both the NISP and MNI data (Table 1 and Figure 2). This suggests that feeding chickens, pigs, and sheep might play an import role in human livelihoods in the Hexi Corridor during the Han Dynasty, which can also be verified from writing records in historical documents, such as "*Shiji·Huozhiliezhuan*" (《史记·货殖列传》) and "*Jichurubo*" (《鸡出入薄》) written on Xuanquan bamboo slips (悬泉汉简) (Wang, 2017).

Carbon isotopic evidence suggests that pigs and dogs consumed mixed C_4 and C_3 foods (Figure 3), basically corresponding to human diets in the Heishuiguo (Li, 2021). According to historical records, both C_4 crops (e.g. foxtail millet and broomcorn millet) and C_3 crops (e.g. barley, wheat, and beans) were important plant subsistence in the Hexi Corridor (Gao, 2014), suggesting humans might have fed pigs and dogs with byproducts of these crops. Carbon isotopes of chicken bones are generally lighter than omnivorous livestock, but heavier than herbivorous livestock (Figure 3), suggesting chickens were also fed with a certain amount of C_4 foods, though most of them mainly consumed C_3 foods. Carbon isotopes of sheep and cattle bones are lighter than those of pigs, dogs, and chickens, suggesting those herbivorous livestock were likely free grazing in the Hexi Corridor area during the Han Dynasty. Nitrogen isotopes of different animal remains in the Heishuiguo Cemetery mostly overlap, although the values from omnivorous livestock exceed other buried animal remains to some extent (Figure 3), probably implying that some pigs and dogs consumed more animal protein. One sample from chicken showed a significantly higher $\delta^{15}N$ value than other individuals, probably because it ate more worms in the wild. As recorded in the historical document "Jiazhengfa" (《家政法》), chickens like to dig into soil with their claws to find and eat invertebrates such as earthworms and grubs.

In addition to chicken, pig, and sheep remains, a few bones of cattle, dogs, and horses were identified from the Heishuiguo Cemetery (Figure 2). While the low proportion of them in buried animal assemblage may not indicate these livestock were insignificant in human livelihoods in the Hexi Corridor during the Han Dynasty. Here we only take the record of horses in historical documents as an example. The Hexi Corridor is the main traffic route connecting the Central Plains and the Western Regions from east to west. There is no doubt that horses were one of the most common domesticated animals used for animal power on the Silk Road. In more than 60,000 Hexi Han bamboo slips, including Dunhuang Han bamboo slips (敦煌汉简), Juyan Han bamboo slips (居延汉简), Jianshui Jinguan Han bamboo slips (肩水金关汉简), Diwan Han bamboo slips (地湾汉简), and Xuanquan Han bamboo slips (悬泉汉简), there are a large number related to horses (Chen, 2006; Zhou, 2013; Xu, 2016). These bamboo slips records involve the introduction of horses, the setting of hurdles, the distribution of feed, the management of post horses, the registration of passing horses, the treatment of sick horses, and the consumption or treatment of bone and meat after the death of sick horses. Evidence from the slips enables us to better understand not only the policies concerning horses at the time, but also the development of transportation, the postal service and the social economy in Hexi Corridor.

The buried animals can reflect the regional characteristics of the domesticated animals themselves. The animal remains assemblage of the Heishuiguo Cemetery is evidently different to that of contemporaneous cemeteries in other areas of China. Pigs, dogs, and chickens are the most common animals buried in Han Dynasty tombs in Central China, followed by sheep, cattle, deer, and rabbits. For example, the unearthed animal bones in Luozhuang Han Dynasty tomb in Jinan, Shandong Province, are mainly pigs, dogs, sheep, and rabbits (Fang, 2003; Liu, 2015). The nomadic people living in grasslands and plateaus mostly choose sheep, horses, and cattle as burial animals, while aquatic products, livestock, and poultry are more common in coastal areas (Wang et al., 1988; Dodson et al., 2013). Although the humans of the Heishuiguo are most likely to move from the Central Plains or to be descendants of the Han farmers, the Heishuiguo Cemetery does not share the same animal burial customs as the Central Plains. Chickens, pigs, and sheep are the dominant species at the Heishuiguo Cemetery, which indicates that this site may have integrated influences from the Central Plains and plateau areas. This is because pigs, dogs, and chickens are the most common animals buried in the Central Plains, while sheep is the dominant specie in plateau areas. This shows that the custom of sacrificing animals was diversified in different regions of China during the Han Dynasty. The Heishuiguo Cemetery had their own uniqueness, which may imply the fusion of cultures from different regions. It also corresponds with the characteristics that males in the Heishuiguo mainly came from the Yellow River basin and females mainly came from local areas (Xiong et al., 2022).

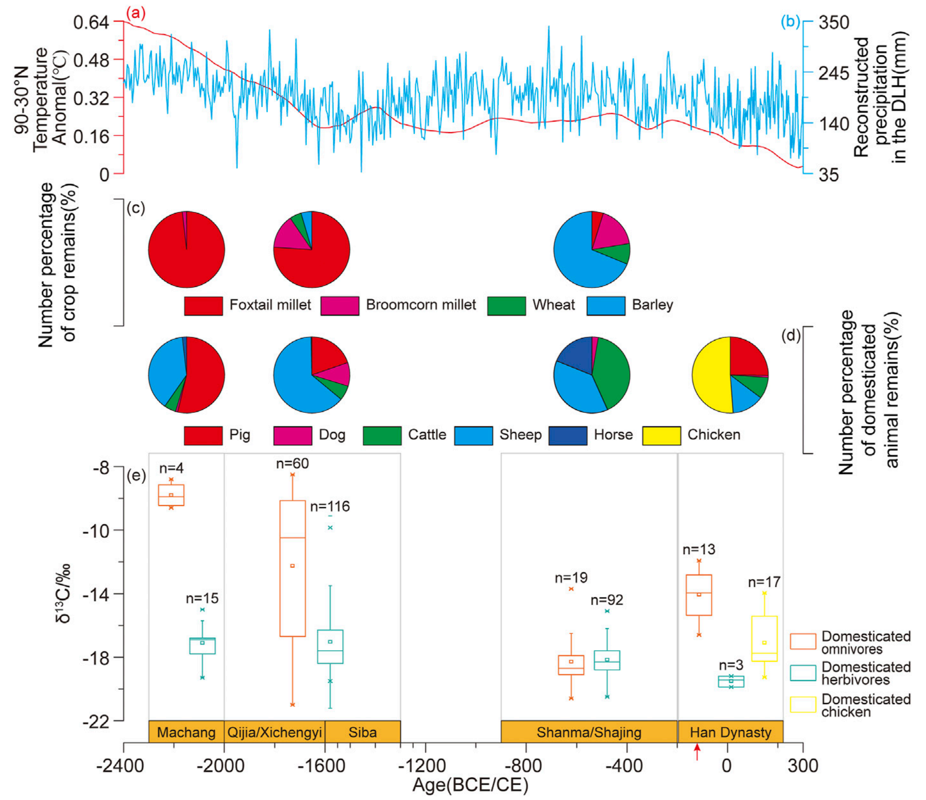

FIGURE 4
Transformation of animal utilization strategies during 2,300 BCE–220 BCE in the Hexi Corridor, compared with climate records, crop remains, domesticated animal remains and $\delta^{13}C$ values of animal samples from sites in the study area. **(A)** Northern Hemisphere (30°–90°) temperature record compared to 1961–1990 instrumental mean temperature (Marcott et al., 2013). **(B)** Reconstructed precipitation from DLH (Delingha, Yang et al., 2021). **(C)** Assemblages of crop remains from sites in the Hexi Corridor. **(D)** Assemblages of domesticated animal remains from sites in the Hexi Corridor. **(E)** $\delta^{13}C$ values of animal samples from sites in the Hexi Corridor. n: the number of isotopic data. Red arrow: the Han Empire controlled the Hexi corridor (121 BCE).

5.2 Diachronic change of animal utilization strategies from the late Neolithic to the Han Dynasty in the Hexi Corridor

From the late Neolithic Age to the Han Dynasty (~2,300 BCE–220 CE), the species of livestock raised by human being in the Hexi Corridor gradually diversified (Figure 4D). During the period of the Machang culture (~2,300–2,000 BCE), Qijia/Xichengyi culture and Siba cultures (~2,000–1,300 BCE), the ancestors raised only pigs, dogs, cattle, and sheep. During the Shanma/Shajing culture (~900–200 BCE), ancestors began to raise horses. In Han Dynasty (202 BCE–220 CE), domestic chickens were also added to the large family of livestock in the Hexi Corridor. Thus, it was also not until the Han Dynasty that the Hexi Corridor really saw the prosperity of the six animals (六畜兴旺) in *Guanzi · Mumin* (《管子·牧民》). Pigs and dogs originated from the Central Plains of China, together with cattle and sheep domesticated in the West Asia, first appeared at the same time in the Mozuizi site of Machang culture in the east of the Hexi Corridor (Lv and Yuan, 2018). Their remains were unearthed in large numbers at the Lijiageleng site of the Qijia culture, the Huoshiliang and Ganggangwa sites of the Xichengyi culture, and the Xichengyi site, the Donghuishan cemetery, the Ganguya cemetery and the Sanbadongzi site of the Siba culture in the middle and west of the Hexi Corridor (Qi, 1998; Fu, 2016; Song et al., 2016; Yang et al., 2019a; Ren et al., 2022). The number of horse remains unearthed in the Hexi Corridor is small, and they were found during the archaeological investigation of the Gudongtan and Zhaojiashuimo sites of Shanma culture (Yang et al., 2019a). The results of zooarchaeological identification show that the Han tombs of the Heishuiguo Cemetery contained the remains of pigs, dogs, cattle, sheep, horses, and chickens. In addition, according to the records of preserved documents and Han bamboo slips (e.g. Juyan Han bamboo slips), camels and donkeys were also important domestic animals used by the ancestors of the

Hexi Corridor in Han Dynasty (Wang, 2017; Ge, 2018; Zhang, 2020).

From the Machang culture period to the Shajing/Shanma culture period, the proportion of pigs in the livestock combination in the Hexi Corridor gradually decreased, and the importance of cattle, sheep, and horses obviously increased (Figure 4D). However, to the Han Dynasty, the number of chickens and pigs increased rapidly, surpassing that of cattle and sheep (Figure 4D). During the Machang culture period, pigs were the main livestock, followed by sheep and cattle (Lv and Yuan, 2018). During the Qijia/Xichengyi, Siba, and Shanma/Shajing culture periods, the proportion of cattle and sheep of domestic animals gradually increased, while the proportion of pigs declined rapidly until it disappeared (Qi, 1998; Fu, 2016; Song et al., 2016; Yang et al., 2019a; Ren et al., 2022). To the Han Dynasty, the proportion of cattle and sheep in domestic animals decreased sharply, while the proportion of chickens and pigs increased. Notably, chickens and pigs accounted for more than three-quarters of the total livestock assembly. The evolution history of animal resource utilization strategies in the Hexi Corridor before the Han Dynasty reflects a process of raising pigs related to agriculture from prosperity to extinction, and the grazing of cattle and sheep from weak to strong. After the Han Dynasty, due to the strategy of the imperial government of the Han Dynasty, the utilization of animal resources was influenced by the Central Plains, and pigs reappeared and chickens dominate the whole livestock assemblage.

The research results of carbon and nitrogen stable isotopes of animal remains from the late Neolithic to the Iron Age (~2,300–202 BCE) in the Hexi Corridor show that the carbon isotope values of domestic omnivores were gradually decrease (Figure 4E). This suggests that they changed from a nearly pure C_4 diet to a mixed C_3/C_4 diet (Atahan et al., 2011; Yang e al. 2019; Ma et al., 2021; Vaiglova et al., 2021; Qiu et al., 2022), and that the consumption of C_3 crops (e.g., barley, wheat) by omnivores was gradually increasing (Dong G et al., 2020). It shows that the breeding strategies of the ancestors of Hexi Corridor for pigs and dogs have changed significantly in different periods. In addition, domestic herbivores gradually changed from a mixed C_3/C_4 diet to a primarily C_3 diet during this period (Atahan et al., 2011; Yang et al., 2019a; Ma et al., 2021; Vaiglova et al., 2021; Qiu et al., 2022), indicating that the feeding and management strategies of cattle and sheep may also have changed. To the Han Dynasty, the relatively enriched $\delta^{13}C$ values of chickens, pigs, and dogs suggested that they had a mixed C_3 and C_4 diet, so these animals may have increased consumption of C_4 crops (i.e., foxtail millet and broomcorn millet) and/or their byproducts again.

5.3 Influencing factors for the transformation of animal utilization strategies from the late Neolithic to the Han Dynasty in the Hexi Corridor

5.3.1 The impact of climate change

The increased cattle and sheep in the Hexi Corridor during the Qijia/Xichengyi, Siba (~2,000–1,300 BCE), and Shanma/Shajing (~900–200 BCE) culture periods compared to the Machang culture period (~2,300–2,000 BCE) broadly coincided with the forest degradation and grassland expansion. The tree ring-based precipitation evidence from Qilian Mountain and the oxygen isotope record of stalagmites clearly indicate a weakened Asian summer monsoon and reduced monsoonal precipitation during this period (Figure 4B, Yang et al., 2021). Furthermore, the temperature records from the Northern Hemisphere imply a cooling trend at the same time (Figure 4A, Marcott et al., 2013). The cooling and drier climate resulted in the forest degradation and grassland expansion, as suggested by pollen records (Zhao and Yu, 2012), thereby facilitating the expansion of pastoralism in this region. In addition, the southward migration of Eurasian steppe nomads (e.g., Scythians) may also have promoted the development of pastoralism in the Hexi Corridor during this period (Shao and Yang, 2006; Han, 2008; Frachetti, 2012; Han, 2012; Yang et al., 2016; Dong G et al., 2020). The increased C_3-crops consumption by domesticated omnivores, as suggested by the depleted $\delta^{13}C$ values, coincides with the increased proportion of barley and wheat unearthed from the archaeological sites in the Hexi Corridor (Flad et al., 2010; Fan, 2016; Zhou et al., 2016; Jiang et al., 2017; Yang et al., 2019a). The expanded planting scale of barley and wheat probably happened because these crops were more tolerant to the cooling climate than millets (Chen et al., 2015; Dong G et al., 2020).

5.3.2 The impact of geopolitical change

In Han Dynasty, animal utilization strategies of people in the Hexi Corridor were significantly different from those of prehistoric times. The diverse livestock reflects that both raising domesticated omnivores (e.g., chickens and pigs) and grazing domesticated herbivores (e.g., sheep, cattle, horses) played important roles in the economic system. The increased raising of chickens and pigs in the region most likely resulted from geopolitical changes. The Han Empire governed the Hexi Corridor from ~100 BCE, and fought frequently with the Huns (GPICRA, 2019). In order to consolidate the border area of the Han Empire, the government implemented a military reclamation system and a large number of males migrated to the Hexi Corridor (Yang, 2010; GPICRA, 2019). These immigrants also brought the customs of the Central Plains into the Hexi Corridor, i.e., the raising and burial of chickens and pigs (Gao, 2010; Liu, 2010). The abundant cattle and sheep remains show that pastoralism was still a crucial economic strategy (GPICRA, 2019). This may be related to the wide distribution of grasslands and deserts in the region. The diverse animal utilization strategies clearly reflect the integration of the farming culture from Central China and nomadic culture from Eurasian grassland into the Hexi Corridor. In addition, geological records and historical documents suggest a relatively warm and humid climate during the Han Dynasty (Ljungqvist, 2010; Ge et al., 2013; Li et al., 2021b), which was conducive to the development of agriculture and animal husbandry.

Our results suggest that changes in animal utilization were mainly passive adaptations to climate change in the Hexi Corridor during the prehistoric period, and that migration to the border was the main influencing factor on animal utilization strategy in the region after the Han Dynasty. This study is important for understanding important scientific issues such as prehistoric and Han Dynasty animal utilization strategies in the Hexi Corridor, human-environment interactions, and communication and mutual appreciation among different cultures and populations.

6 Conclusion

The study is important for understanding significant scientific issues such as animal utilization strategies and human-environment interactions during the prehistoric times and the Han Dynasty in the Hexi Corridor. Our zooarchaeological and isotopic study in the Heishuiguo Cemetery provides valuable new data to reconstruct animal utilization strategies in the Hexi Corridor during the Han Dynasty. The results suggest the significance of domestic chickens, pigs, and sheep in livelihoods was likely much higher than other livestock including cattle, horses, and dogs. Humans may have fed pigs and dogs plenty of C_4 foods (probably millets or their byproducts), fed chickens a small amount of C_4 foods with evident difference, while cattle and sheep mainly ate C_3 plants.

In contrast to previous studies in the Hexi Corridor, the trajectory of animal utilization strategies change from the late Neolithic to the Han Dynasty can be preliminarily outlined. The importance of herbivorous livestock in animal utilization strategies and C_3 foods in fodders gradually increased in the Hexi Corridor during ~2,300–200 BCE. However, the trend changed in Han Dynasty, with the chickens, pigs, and sheep becoming the most important livestock, and the significance of C_4 plants in fodders being notably enhanced. This was mainly due to the introduced customs of immigrants from the Yellow River valley of north China, occurring after the Han Empire controlled the Hexi Corridor.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

The study was designed by XL, LR, WW, ML, and LD conducted field works and sample collection. LR, WW, and MM completed experiments and data correction. WW, XL, and LR analyzed data and designed the figures. XL, WW, MM, ML, LD, YY, GC, and LR wrote the manuscript. All authors discussed the results and commented on the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2022.1064803/full#supplementary-material

References

Atahan, P., Dodson, J., Li, X., Zhou, X., Hu, S., Bertuch, F., et al. (2011). Subsistence and the isotopic signature of herding in the bronze Age Hexi corridor, NW Gansu, China. *J. Archaeol. Sci.* 38, 1747–1753. doi:10.1016/j.jas.2011.03.006

Chen, F. H., Dong, G. H., Zhang, D. J., Liu, X. Y., Jia, X., An, C. B., et al. (2015). Agriculture facilitated permanent human occupation of the Tibetan Plateau after 3600 BP. *Science* 347, 248–250. doi:10.1126/science.1259172

Chen, N. (2006). "Analysis of animal bones unearthed from Ganguya and sanbadongzi in Jiuquan,". in Chinese, *Gansu Province Institute of Cultural Relics and Archaeology Research, Beijing Daxue Kaogu Wenbo Xueyuan School of Archaeology and Museology, Peking University*. Editors Ganguya in Jiuquan (Beijing: Cultural Relics Press).

Chen, N. B., Ren, L. L., Du, L. Y., Hou, J. W., Mullin, V. E., Wu, D., et al. (2020). Ancient genomes reveal tropical bovid species in the Tibetan Plateau contributed to the prevalence of hunting game until the late Neolithic. *Proc. Natl. Acad. Sci. U. S. A.* 117, 28150–28159. doi:10.1073/pnas.2011696117

Dodson, J. R., Li, X., Zhou, X., Zhao, K., Sun, N., and Atahan, P. (2013). Origin and spread of wheat in China. *Quat. Sci. Rev.* 72, 108–111. doi:10.1016/j.quascirev.2013.04.021

Dong, G., Du, L., Yang, L., Lu, M., Qiu, M., Li, H., et al. (2022). Dispersal of crop-livestock and geographical-temporal variation of subsistence along the Steppe and Silk Roads across Eurasia in prehistory. *Sci. China Earth Sci.* 65, 1187–1210. doi:10.1007/s11430-021-9929-x

Dong, G. H., Du, L. Y., and Wei, W. Y. (2020). The impact of early trans-Eurasian exchange on animal utilization in northern China during 5000–2500 BP. *Holocene* 31, 294–301. doi:10.1177/0959683620941169

Dong, G. H., Yang, Y. S., Liu, X. Y., Li, H. M., Cui, Y. F., Wang, H., et al. (2018). Prehistoric trans-continental cultural exchange in the Hexi Corridor, northwest China. *Holocene* 28, 621–628. doi:10.1177/0959683617735585

Dong, G., Yang, Y., Han, J., Wang, H., and Chen, F. (2017). Exploring the history of cultural exchange in prehistoric Eurasia from the perspectives of crop diffusion and consumption. *Sci. China Earth Sci.* 60, 1110–1123. doi:10.1007/s11430-016-9037-x

Dong, G., Yang, Y., Ren, L., and Ma, M. (2020). *The prehistoric life pattern and the interaction between human-environment in the Hexi Corridor*. Beijing: Science Press.

Fan, X. J. (2016). Analysis of carbonized botanic remains in Xichengyi site. Master's thesis. Ji'nan (China): Shandong University.

Fang, D. G. (2003). Large animal burial pits found at Luozhuang han tomb in jinan, Shandong. *Agric. Archaeol.* 9 (01), 238.

Fernández-Crespo, T., Snoeck, C., Ordoño, J., De Winter, N. J., Czermak, A., Mattielli, N., et al. (2020). Multi-isotope evidence for the emergence of cultural alterity in Late Neolithic Europe. *Sci. Adv.* 6, eaay2169. doi:10.1126/sciadv.aay2169

Flad, R., Li, S. C., Wu, X. H., and Zhao, Z. J. (2010). Early wheat in China: Results from new studies at donghuishan in the Hexi corridor. *Holocene* 20, 955–965. doi:10.1177/0959683609358914

Frachetti, M. D. (2012). Multiregional emergence of mobile pastoralism and nonuniform institutional complexity across Eurasia. *Curr. Anthropol.* 53, 2–38. doi:10.1086/663692

Frachetti, M. D., Smith, C. E., Traub, C. M., and Williams, T. (2017). Nomadic ecology shaped the highland geography of Asia's Silk Roads. *Nature* 543, 193–198. doi:10.1038/nature21696

France, D. L. (2008). *Human and nonhuman bone identification: A color atlas*. Florida: CRC Press.

Fu, L. (2016). "Analysis of animal bones unearthed from Ganguya and sanbadongzi in Jiuquan," in *The Ganguya in jiuquan, Gansu Province Institute of cultural relics and Archaeology research, beijing daxue kaogu wenbo xueyuan school of Archaeology and museology* (Beijing: Peking UniversityCultural Relics Press).

Gao, R. (2014). Research on food crops of Hexi area in han dynasty. *Agricultural History of China* 33, 21–29.

Gao, X. (2010). The development of irrigating farming of the Hexi Corridor in the West Han dynasty and its impact on ecological environment (in Chinese). *J. Shihezi Univ. (Philosophy Soc. Sci.* 03, 90–92. doi:10.13880/j.cnki.cn65-1210/c.2010.03.024

Ge, C. (2018). Steed or Camel-New interpretation on the silk-road symbol in the Han dynasty. *Palace Mus. J.* 55–64, 159–160. doi:10.16319/j.cnki.0452-7402.2018.01.004

Ge, Q., Hao, Z., Zheng, J., and Shao, X. (2013). Temperature changes over the past 2000 yr in China and comparison with the Northern Hemisphere. *Clim. Past.* 9, 1153–1160. doi:10.5194/cp-9-1153-2013

GPICRA (2019). *Excavation report of heshuiguo han cemetery in Ganzhou, Zhangye*. Lanzhou: Gansu Educational Publishing House.

Han, J. (2008). *Natural environment and cultural development in northwest China in pre-Qin period*. Beijing: Cultural Relics Press.

Han, M. (2012). *Historical agricultural geography of China*. Beijing: Beijing University Press.

Hu, Y. (2021). Human subsistence strategies and adaptations in the lower Yangtze River region during the prehistoric era. *Front. Earth Sci.* 9, 654416. doi:10.3389/feart.2021.654416

Hu, Y. (2018). Thirty-four years of stable isotopic analyses of ancient skeletons in China: An overview, progress and prospects. *Archaeometry* 60, 144–156. doi:10.1111/arcm.12367

Jeong, C., Wilkin, S., Amgalantugs, T., Bouwman, A. S., Taylor, W. T. T., Hagan, R. W., et al. (2018). Bronze Age population dynamics and the rise of dairy pastoralism on the eastern Eurasian steppe. *Proc. Natl. Acad. Sci. U. S. A.* 115, E11248–E11255. doi:10.1073/pnas.1813608115

Jiang, W., Wu, H., Li, Q., Lin, Y., and Yu, Y. (2019). Spatiotemporal changes in C4 plant abundance in China since the Last Glacial Maximum and their driving factors. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 518, 10–21. doi:10.1016/j.palaeo.2018.12.021

Jiang, Y., Chen, G., and Li, S. (2017). Analysis of the results of the 2010-year flotation for the Xichengyi site at Zhangye in Gansu. *Huaxia Archaeol.* 1, 62–68. doi:10.16143/j.cnki.1001-9928.2017.01.011

Li, S. (2011). *Investigation report on prehistoric archaeology in Hexi corridor*. Beijing: Cultural Relics Press.

Li, X. (2021). Human diets and its influencing factors during han and jin periods in the Hexi corridor and its adjacent areas. PhD thesis. Lanzhou (China): Lanzhou University.

Li, Y., Hu, L., Zhao, Y., Wang, H., Huang, X., Chen, G., et al. (2021b). Meltwater-driven water-level fluctuations of Bosten Lake in arid China over the past 2, 000 years. *Geophys. Res. Lett.* 48, e2020GL090988. doi:10.1029/2020GL090988

Li, Y., Zhang, C., Taylor, W. T. T., Chen, L., Flad, R. K., Boivin, N., et al. (2021a). Reply to Shelach-Lavi et al.: Implications of the horse assemblages from Shirenzigou and Xigou. *Proc. Natl. Acad. Sci. U. S. A.* 118, e2025947118. doi:10.1073/pnas.2025947118

Librado, P., Khan, N., Fages, A., Kusliy, M. A., Suchan, T., Tonasso-Calvière, L., et al. (2021). The origins and spread of domestic horses from the Western Eurasian steppes. *Nature* 598, 634–640. doi:10.1038/s41586-021-04018-9

Liu, J. (2010). On the exploitation of Gansu Corridor in Han dynastie from the perspective of cultural dissemination. Master's thesis. Xi'ning (China): Qinghai Normal University.

Liu, X., Jones, P. J., Matuzeviciute, G. M., Hunt, H. V., Lister, D. L., An, T., et al. (2019). From ecological opportunism to multi-cropping: Mapping food globalisation in prehistory. *Quat. Sci. Rev.* 206, 21–28. doi:10.1016/j.quascirev.2018.12.017

Liu, Z. Z. (2015). An analysis of the contents of flora and fauna for subordinate burial of princes'tombs in Han Dynasty and related issues. *Cult. Relics South. China* (03), 134–142.

Ljungqvist, F. C. (2010). A new reconstruction of temperature variability in the extra-tropical Northern Hemisphere during the last two millennia. *Geogr. Ann. Ser. A, Phys. Geogr.* 92, 339–351. doi:10.1111/j.1468-0459.2010.00399.x

Lv, P., and Yuan, J. (2018). Communication and transformation: Preliminary exploration on the means of livelihood in the pre-Qin period in the upper reaches of the Yellow River (part one). *Cult. Relics South. China.* 02, 170–179.

Ma, M., Dong, G., Jia, X., Wang, H., Cui, Y., and Chen, F. (2016). Dietary shift after 3600 cal yr BP and its influencing factors in northwestern China: Evidence from stable isotopes. *Quat. Sci. Rev.* 145, 57–70. doi:10.1016/j.quascirev.2016.05.041

Ma, M., Ren, L., Li, Z., Wang, Q., Zhao, X., and Li, R. (2021). Early emergence and development of pastoralism in Gan-Qing region from the perspective of isotopes. *Archaeol. Anthropol. Sci.* 13, 93–15. doi:10.1007/s12520-021-01331-2

Marcott, S. A., Shakun, J. D., Clark, P. U., and Mix, A. C. (2013). A reconstruction of regional and global temperature for the past 11300 years. *Science* 339, 1198–1201. doi:10.1126/science.1228026

Ning, C., Li, T., Wang, K., Zhang, F., Li, T., Wu, X., et al. (2020). Ancient genomes from northern China suggest links between subsistence changes and human migration. *Nat. Commun.* 11, 2700–2709. doi:10.1038/s41467-020-16557-2

Piperno, D. R., and Dillehay, T. D. (2008). Starch grains on human teeth reveal early broad crop diet in northern Peru. *Proc. Natl. Acad. Sci. U. S. A.* 105, 19622–19627. doi:10.1073/pnas.0808752105

Qi, G. (1998). "Identification report on animal bones from the Donghuishan cemetery site," in (in Chinese), *The Archaeology of donghuishan in minle CountyGansu provincial Institute of cultural relics and Archaeology research, northern Archaeology laboratory of jilin university*. Editors Archaeology of Donghuishan in Minle County (Beijing: Science Press), 184–185.

Qiu, M., Li, H., Lu, M., Yang, Y., Zhang, S., Li, R., et al. (2022). Diversification in feeding pattern of livestock in early bronze Age northwestern China. *Front. Ecol. Evol.* 10, 908131. doi:10.3389/fevo.2022.908131

Ramsey, B. C. (2021). OxCal version 4.4.4. Available at: https://c14.arch.ox.ac.uk/oxcal.html.

Reimer, P. J., Austin, W. E. N., Bard, E., Bayliss, A., Blackwell, P. G., Ramsey, C. B., et al. (2020). The IntCal20 northern Hemisphere radiocarbon Age calibration curve (0–55 cal kBP). *Radiocarbon* 62, 725–757. doi:10.1017/RDC.2020.41

Ren, L., Yang, Y., Qiu, M., Brunson, K., Chen, G., and Dong, G. (2022). Direct dating of the earliest domesticated cattle and caprines in northwestern China reveals the history of pastoralism in the Gansu-Qinghai region. *J. Archaeol. Sci.* 144, 105627. doi:10.1016/j.jas.2022.105627

Schmid, E. (1992). *Dongwu guge tupu*. Wuhan: Zhongguo Dizhi Daxue Chubanshe.

Shao, H., and Yang, J. (2006). A study on the early Scythian culture and the origins of animal-style art in the Eurasian Steppes. *West. Regions Stud.* 04, 73–77. doi:10.16363/j.cnki.xyyj.2006.04.010

Song, Y., Chen, G., Wang, H., Fan, X., and Jin, G. (2016). Faunal remains analysis of Xichengyi site of Zhangye city in 2014. *East Asia Archaeol.* 1, 233–242.

Spengler, R., Frachetti, M., Doumani, P., Rouse, L., Cerasetti, B., Bullion, E., et al. (2014). Early agriculture and crop transmission among Bronze Age mobile pastoralists of Central Eurasia. *Proc. R. Soc. B* 281, 20133382. doi:10.1098/rspb.2013.3382

Su, P., Xie, T., and Zhou, Z. (2011). Geographical distribution of C4 plant species in desert regions of China and its relation with climate factors. *J. Desert Res.* 02, 267–276.

Vaiglova, P., Reid, R. E., Lightfoot, E., Pilaar Birch, S. E., Wang, H., Chen, G., et al. (2021). Localized management of non-indigenous animal domesticates in Northwestern China during the Bronze Age. *Sci. Rep.* 11, 15764–15813. doi:10.1038/s41598-021-95233-x

Wang, H. (2003). Gansu archaeology: Retrospect and prospect at the turn of the century. *Archaeology* 06, 487–498.

Wang, J. K., Huang, J. L., and Lv, L. D. (1988). Study on the animal remains unearthed from the nanyue king's tomb in xianggang hill, guangzhou. *Acta Sci. Nat. Univ. Sunyatseni* 15 (01), 13–20.

Wang, T., Wei, D., Chang, X., Yu, Z., Zhang, X., Wang, C., et al. (2019). Tianshanbeilu and the isotopic millet road: Reviewing the late Neolithic/bronze Age radiation of human millet consumption from north China to Europe. *Natl. Sci. Rev.* 6, 1024–1039. doi:10.1093/nsr/nwx015

Wang, Z. (2017). *A study on the historical materials of Han and Hexi society (in Chinese)*. Beijing: The Commercial Press

Xiong, J., Du, P., Chen, G., Tao, Y., Zhou, B., Yang, Y., et al. (2022). Sex-biased population admixture mediated subsistence strategy transition of Heishuiguo people in Han Dynasty Hexi Corridor. *Front. Genet.* 13, 827277. doi:10.3389/fgene.2022.827277

Xu, S. (2016). Study on the horse industry in Hexi disrtict of the Han dynasty. Master's thesis. Lanzhou (China): Lanzhou University.

Yang, B., Qin, C., Bräuning, A., Osborn, T. J., Trouet, V., Ljungqvist, F. C., et al. (2021). Long-term decrease in Asian monsoon rainfall and abrupt climate change events over the past 6, 700 years. *Proc. Natl. Acad. Sci. U. S. A.* 118, e2102007118. doi:10.1073/pnas.2102007118

Yang, F. (2010). A study of demographic structure of the population in the frontier counties along the Hexi corridor in the han dynasty: A careful checking up inscription of the han bamboo slips. *Dunhuang Res.* 3, 78–85.

Yang, J., Shao, H., and Pan, L. (2016). *The metal road in the eastern part of Eurasia*. Shanghai: Shanghai Chinese Classics Publishing House.

Yang, Y., Ren, L., Dong, G., Cui, Y., Liu, R., Chen, G., et al. (2019a). Economic change in the prehistoric Hexi corridor (4800–2200 bp), north-west China. *Archaeometry* 61, 957–976. doi:10.1111/arcm.12464

Yang, Y., Zhang, S., Oldknow, C., Qiu, M., Chen, T., Li, H., et al. (2019b). Refined chronology of prehistoric cultures and its implication for re-evaluating human-environment relations in the Hexi Corridor, northwest China. *Sci. China Earth Sci.* 62, 1578–1590. doi:10.1007/s11430-018-9375-4

Zhang, F., Ning, C., Scott, A., Fu, Q., Bjørn, R., Li, W., et al. (2021). The genomic origins of the bronze Age Tarim Basin mummies. *Nature* 599, 256–261. doi:10.1038/s41586-021-04052-7

Zhang, Q. (2020). Exploration of camels of northwest borders county in Han dynasty based on bamboo and wooden slips. *Agric. Archaeol.* 01, 162–167.

Zhao, Y., and Yu, Z. C. (2012). Vegetation response to Holocene climate change in East Asian monsoon-margin region. *Earth-Science Rev.* 113, 1–10. doi:10.1016/j.earscirev.2012.03.001

Zhou, F. (2013). The horses materials in Chinese northwestern bamboo slips. Master's thesis. Lanzhou (China): Northwest Normal University.

Zhou, X., Li, X., Dodson, J., and Zhao, K. (2016). Rapid agricultural transformation in the prehistoric Hexi corridor, China. *Quat. Int.* 426, 33–41. doi:10.1016/j.quaint.2016.04.021

Zhou, X., Yu, J., Spengler, R. N., Shen, H., Zhao, K., Ge, J., et al. (2020). 5, 200-year-old cereal grains from the eastern Altai Mountains redate the trans-Eurasian crop exchange. *Nat. Plants* 6, 78–87. doi:10.1038/s41477-019-0581-y