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Human planting strategies and its relation to climate change during ~4,800–3,900 BP in the mid-lower Hulu River Valley, northwest China

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The response of agricultural societies to global climate events during the Neolithic (e.g., 4.2 ka event) is a scientific issue of general interest. In the mid-lower Hulu River Valley of northwest China, millet cultivation became the primary subsistence during the late Neolithic. Local paleoclimate studies have detected a notable decline in temperature and precipitation around 4,400 BP (Before Present), while the Qijia culture (4,200–3,600 BP) sites far outnumber those of the Lower Changshan culture (4,800–4,400 BP) in the area. Why the intensity of millet farming groups increased when climate was relatively cold and dry, however, has not been well understood. To explore the issue, we performed archaeobotanical analysis, grain size measurement, stable isotope analysis and radiocarbon dating in the excavated sites of the Zhongtianxingfucheng (ZTXFC) and Wangjiayangwan (WJYW), which were dated to between ~4,800–4,400 BP and ~4,200–3,900 BP, respectively. Our results demonstrate the overall declines in the proportion, grain sizes and carbon isotope values of millets from the WJYW site compared to ZTXFC. The nitrogen isotopes of millets from the two sites are similar [foxtail millet: 6.8‰ ± 1.9‰ (ZTXFC), 7.5‰ ± 1.5‰ (WJYW); broomcorn millet: 7.3‰ ± 2.0‰ (ZTXFC), 7.5‰ ± 1.2‰ (WJYW)]. These results suggest that the degree of field management during ~4,200–3,900 BP was lower than ~4,800–4,400 BP in the mid-lower Hulu River Valley. Instead of improving cultivation management or altering cropping patterns, Qijia millet farmers might have adopted a strategy of expanding cultivated lands to promote the social development under a relatively cold-dry climate.

KEYWORDS

archaeobotanical analysis, grain size, carbon and nitrogen isotope analysis, subsistence strategy, mid-lower Hulu River Valley, late Neolithic

1 Introduction

The response of human societies to global climate events during the Neolithic era, such as the 8.2 ka event, the 5.5 ka event and the 4.2 ka event, is a widely studied multidisciplinary issue (e.g., Flohr et al., 2016; Goldsmith et al., 2017; Wu et al., 2018; Park et al., 2019; Zhao, 2020). With the development and expansion of agriculture across Eurasia (Liu X et al., 2019; Dong et al., 2022a), global population significantly increased with the extensive expansion of farmer habitats during the late Neolithic (Styring et al., 2017; Dong et al., 2022b), which resulted in the rise of survival stress and social vulnerability to climate change (Kelly et al., 2012). Therefore, the impact of the 4.2 ka event on social evolution in the Old World has been intensively discussed in recent decades (Weiss, 2016; Ran and Chen, 2019; Manning et al., 2020). The 4.2 ka event has been proposed as an important trigger for the collapse of ancient civilizations in Mesopotamia (Cullen et al., 2000; Weiss, 2017) and India (Staubwasser et al., 2003). Additionally, the 4.2 ka event is suggested to have transformed the human settlement patterns in late Neolithic China (Xiao et al., 2019; He et al., 2022), resulting in the expansion and shrinkage of areas settled by millet farming groups and rice farming groups (He et al., 2022).

The responses of millet farming groups to the climatic deterioration event around 4,200 BP in different areas of north China were diverse. For example, settlement intensity of millet farming groups in east Inner Mongolia evidently declined (Xiao et al., 2019) and increased in the Yi-Luo River Valley and Gansu-Qinghai region (Liu and Feng, 2012; Liu L et al., 2019; He et al., 2022). In the mid-lower Hulu River Valley (MLHRV) of the western Loess Plateau, northwest China, intensive rain-fed agriculture was focused on millet cultivation since ~5,900 BP (Barton, 2009), and was the primary subsistence in the area during the late Neolithic period (Li et al., 2022a; Yang J et al., 2022; Yang Y et al., 2022). Paleoclimate studies from a lake in the nearby Liupan Mountains suggest that temperature and precipitation in the MLHRV declined around 4,400 BP and the overall climate trend was colder and dryer during ~4,400–3,600 BP than ~4,800–4,400 BP (Zhao et al., 2010; Chen et al., 2015). However, the third national archaeological survey in the MLHRV revealed that the site numbers of the Lower Changshan culture (4,800–4,400 BP) was much smaller than the Qijia culture (4,200–3,600 BP) (Figure 1; Li et al., 1993). This indicates that millet farming groups substantially expanded in the area under a relatively cold-dry climate. Previous studies have suggested that Neolithic groups might have successfully adapted to climate events in different ways, including the alteration of cropping patterns (Pokharia et al., 2017; Chen et al., 2020; Li R et al., 2020), the improvement of field management (Masi et al., 2014; Ren et al., 2021) and the enlargement of the cultivated land area (An et al., 2021). Nevertheless, differences in planting strategies between the Lower Changshan period and the Qijia period in the MLHRV remains unclear due to the absence of systematic archaeobotanical studies.

Recent archaeobotanical and stable isotope analysis of crops remains from investigated sites in the MLHRV provided a valuable dataset to facilitate understanding of cropping pattern variations and water and soil management for crops since ~6,000 BP (Li et al., 2022b). However, data from the excavated sites of the Lower Changshan and Qijia cultures are still scarce. Moreover, the measurement of millets grain sizes from archaeological sites in the MLHRV has not been reported, which is valuable to evaluate cropping strategies in prehistory (Motuzaite-Matuzeviciute et al., 2012; Bao et al., 2018). Recent excavations at the Zhongtianxingfucheng (ZTXFC) site of the Lower Changshan culture and the Wangjiayangwan (WJYW) site of the Qijia culture provide a rare opportunity to study strategies for millet farming and their relation to climate change during these two periods. In this paper, we report the results of radiocarbon dating, identification of plant remains, grain size measurement and carbon/nitrogen isotope analysis of charred millets grains from ZTXFC and WJYW sites. Results are then integrated with published archaeological and paleoclimate data to explore how millet farmers in the MLHRV responded to climate change during the Lower Changshan and Qijia periods.

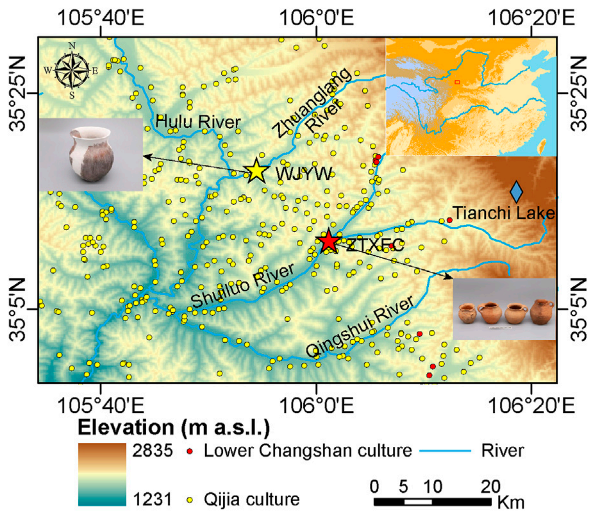

FIGURE 1
Distribution of the Lower Changshan and Qijia cultural sites in the mid-lower Hulu River Valley.

2 Study areas

The Lower Changshan culture is named after the discovery of the lower cultural remains at the Changshan site in Zhenyuan, Gansu (Hu, 1981). This has elements of the Yangshao culture and features of the Qijia culture, indicating a transitional stage from Yangshao culture to Qijia culture (Hu, 1991; Li et al., 1993). The Lower Changshan culture is mainly distributed in the Loess Plateau, such as Longdong area and southern Ningxia, and is dated to 4,800–4,400 BP in the Gansu (Li et al., 1993). The Lower Changshan cultural potteries includes clay potteries and coarse potteries, which are primarily orange and reddish brown (Hu, 1981). These potteries were mainly decorated with basket pattern and pile pattern (Li et al., 1993). The burial forms include vertical pit graves and earth-caved tombs (Li et al., 1993; Wei, 2021), and the skeletal position is mainly flexed and lying on the side (Wei, 2021).

The Qijia culture is widely distributed in the Gansu-Qinghai region and likely developed from the Lower Changshan culture through the Caiyuan type and was influenced by the Keshengzhuang culture (Wang, 2012). Qijia cultural potteries include clay red potteries, gray and red coarse potteries (Ye, 2014), decorated with cord-marking and vertical basket veins (Li et al., 1993; Underhill, 2013). The burial forms mainly include vertical pit graves, vertical and side chambers (Xie, 1986; Qian et al., 2014; Yang, 2017), and the skeletal position is mainly supine and extended and flexed and lying on the side (Chen, 2003; Underhill, 2013). The Qijia culture, dating to 4,600–3,500 BP, is mainly centered around 4,300–3,900 BP (Wang, 2012), and is dated between 4,200 and 3,600 BP in the mid-lower Hulu River Valley (Li et al., 2022b; Yang Y et al., 2022). Based on limited studies (Chen et al., 2020; Li et al., 2022b), the Lower Changshan and Qijia populations were mainly engaged in millet farming, supplemented by pig raising and hunting (Xie, 1975; The Institute of Archaeoloogy Chinese Academy of Social Sciences, 1999; Womack et al., 2021).

The Hulu River (34.72°–36.5°N, 105.5°–106.5°E) is located on the western Loess Plateau, with the Liupan Mountains to the east and the Qinling Mountains to the south (Han et al., 2020). The terrain gradually decreases from north to south and from east to west, and the vast majority of the basin is a loess hilly area with loose soil and sparse vegetation (Wang F et al., 2022). The study area is characterized by a temperate continental monsoon climate with relatively pronounced seasonal changes-hot and rainy in summer, rapidly cooling in autumn, and cold in winter (Han et al., 2020). According to the meteorological stations located on the mid-lower Hulu River (Jingning, Zhuanglang, and Qin'an), the mean annual temperature is 9.03°C and the mean annual precipitation is 444.3 mm (see http://data.cma.cn). The Hulu River is the largest tributary in the upper reaches of the Wei River. The basin is crisscrossed by ravines with a well-developed river composed of many tributaries, such as the Zhuanglang River, Shuiluo River, Qingshui River (Xin et al., 2016; Wang L et al., 2022).

The Zhongtianxingfucheng site (35.2°N, 106.0°E) is in the hilly and ravine region of the Loess Plateau, located on the terrace of the Shuiluo River in Zhuanglang county. In 2019, the Gansu Provincial Institute of Cultural Relics and Archaeology conducted rescue excavation of the ZTXFC site, with an excavated area of 2,100 m^2. The main part of the ZTXFC site is the Lower Changshan Period, and items including pottery, stone implements, bones, and teeth were unearthed. There are a wide variety of vessel classifications, the most common types are sand monaural pots excavated in ash pits, which could likely be early relics of the ZTXFC site from the Lower Changshan culture (Yang, 2012).

The Wangjiayangwan site (35.3°N, 105.9°E) is located in Zhuanglang county, situated on the terrace of the Zhuanglang River. In 2019, the Gansu Provincial Institute of Cultural Relics and Archaeology also conducted rescue excavation of the WJYW site, and the excavation area of WJYW is 3,100 m^2. The site includes two periods: the Qijia culture and the Qing Dynasty (1,644–1,912 AD). The later relics are located in the cultivated layer and come from the Qing Dynasty. Based on the distinctive convex shape with the white-grey floor as the building structure and the large double-ear pots unearthed in the house relics, it can be concluded that the early relics of the WJYW site are from the Qijia culture (Womack et al., 2017).

3 Materials and methods

To illuminate cropping patterns changes in the mid-lower Hulu River Valley during ~4,800–3,900 BP, we excavated two sites in 2019 within the study region shown in Figure 1. We used a targeted sampling strategy to sample the sediments in each layer of each unearthed relic unit. We sampled as far as possible to the middle of each layer to avoid inter-layer disturbance. Given the two sites were severely damaged, there were 84 samples collected from the WJYW site, all from house relics, and 18 samples were collected from the ZTXFC site and 16 samples of the samples were from ash pits and two of the samples were from house relics and kiln.

A total of 102 flotation soil samples were collected from two sites. The total amount of flotation soil collected from WJYW was 978.5 and 181 L from ZTXFC, with an average of 11.37 L per sample and a total of 1,159.5 L. The collected soil samples were all floated using the manual bucket flotation technique (Zhao, 2010). The floated objects with a specific gravity lighter than water, such as charcoal and charred plant seeds, floated upward. The objects were gathered with 0.2 mm aperture sieves, wrapped in gauze, and hung in a shady and cool area for desiccation. Then they were sorted through 0.35, 0.7, 1.2, and 4.0 mm mesh sieves. All seeds were selected using a ×40 stereo microscope (Zhao, 2010). The charred plant seeds were identified in the Environment Archaeology Laboratory, Lanzhou University.

One bone sample and three charred plant grain samples from the two sites were selected for accelerator mass spectrometry (AMS) radiocarbon dating (Table 1). One charred broomcorn millet seeds sample was measured at Beta Analytic in Miami, United States. The other samples were dated at the MOE Key Laboratory of Western China's Environmental Systems, Lanzhou University. The IntCal 20 calibration curve (Reimer et al., 2020) and the Libby half-life of 5,568 years were used in the calculation of all dates and the calibration was performed using OxCal v.4.4.4 (Ramsey, 2021). All ages are reported as 'cal. yr BP'.

To analyze the structure of past agricultural activities in the study area, the number of different plant species was recorded. However, different crop plants can vary considerably in weight and behave differently during harvesting, utilization, and carbonization (Yang et al., 2011). Therefore, simple ratios produced between species may not accurately correspond to the actual proportion of different species in use. To counteract this, we used a modified method of the Weight Ratio Function for different crops, proposed by Zhou et al. (2016) and Sheng et al. (2018). The Weight Ratio Function takes the average weight of 1,000 grains of the two main crops as conversion factors for estimating the actual yield percentage. This calculation is based on the results of the statistical analysis of the flotation samples (Eq. 1).

$$P(S) = \frac{N_s \times F_s}{N1 \times F1 + N2 \times F2} \tag{1}$$

Where N1 = number of foxtail millet grains, F1 = 2.6, N2 = number of broomcorn millet grains, F2 = 7.5, Ns = number of that certain crop, Fs = conversion factors of that certain crop, and P(S) = actual yield percentage of that certain crop.

The length, width, and thickness of the millet seeds were measured using a vernier caliper at the MOE Key Laboratory of Western China's Environmental Systems, Lanzhou University, Gansu Province, China. 462 mature and intact charred millets were selected for particle size

TABLE 1 Calibrated radiocarbon dates from ZTXFC and WJYW sites.

Site	Lab number	Sampling feature	Dated material	^{14}C age	Calibrated age (cal yr BP) 2 σ	Culture	Dating method	References
ZTXFC	LZU20315	Ash pit	Sheep bone	4,010 ± 30	4,567–4,414	Lower Changshan	AMS	Dong J et al. (2022)
ZTXFC	LZU20320	Tomb	Human bone	4,040 ± 30	4,612–4,418	Lower Changshan	AMS	Dong J et al. (2022)
ZTXFC	LZU20321	Tomb	Human bone	4,080 ± 20	4,795–4,446	Lower Changshan	AMS	This study
WJYW	Beta567015	House relic	Broomcorn millet	3,730 ± 30	4,221–3,981	Qijia	AMS	This study
WJYW	LZU20157	House relic	Pig bone	3,700 ± 20	4,144–3,976	Qijia	AMS	Dong J et al. (2022)
WJYW	LZU21266	House relic	Foxtail millet	3,650 ± 20	4,082–3,895	Qijia	AMS	This study
WJYW	LZU21249	House relic	Wheat	—	—	Modern	AMS	This study

measurement. The millets were placed in the sand tray in a suitable position. The longest, widest, and thickest parts of the millet seeds were measured under a stereoscopic microscope (Olympus SZX16), respectively, and recorded these data.

Forty-three randomly selected charred millet seeds were subjected to isotopic analysis. The charred millets were put into a test tube with 0.5 mol/L hydrochloric acid and then placed in a pot of water at 80°C for 30 min. Next the millets were repeatedly rinsed with pure water several times to neutral and then dried in an oven at 70°. Finally, the samples were ground into powder with a mortar and put into tinfoil bags. The δ^{13}C and δ^{15}N values of millet samples were measured with an automated carbon and nitrogen analyzer coupled with a Thermo Finnigan Flash DELTAplus XL mass spectrometer (Finnigan, Germany) at the MOE Key Laboratory of Western China's Environmental System at Lanzhou University. After ten samples, a standard (Graphite, δ^{13}C: −16.0‰; Protein, δ^{15}N: 5.94‰) was inserted into the sample list for calibration and stability monitoring. The analytical precision of the δ^{13}C and δ^{15}N values were ±0.2‰. All C and N isotopes were measured relative to Vienna Pee Dee Belemnite (V-PDB) and Ambient Inhalable Reservoir (AIR) standards, respectively.

In order to better use plant carbon isotope indicators to reflect ancient human management practices for agriculture, we used Farquhar et al. (1982) to air-correct δ^{13}C and obtain Δ^{13}C values (Eq. 2). Where $\delta^{13}C_{air}$ represents the $\delta^{13}C_{air}$ value in air at that time (Leuenberger et al., 1992; Francey et al., 1999; Ferrio et al., 2005), and $\delta^{13}C_{plant}$ represents the δ^{13}C value in plants.

$$\Delta^{13}C = \frac{\delta^{13}C_{air} - \delta^{13}C_{plant}}{1 + \delta^{13}C_{plant}} \qquad (2)$$

4 Results

4.1 AMS radiocarbon dating

The calibrated ^{14}C ages are given with 2σ age ranges in Table 1; Figure 6D. Three bone samples were dated to between 4,795 and 4,414 cal yr BP, corresponding to the Lower Changshan period. One bone sample and two charred plant remain samples were dated to between 4,221 and 3,895 cal yr BP, corresponding to the Qijia period. One charred wheat was dated to be modern in the WJYW site, and it may have been redeposited from the upper sediments (Table 1).

4.2 Crop assemblages in different periods in the mid-lower Hulu River Valley during ~4,800–3,900 BP

A total of 8,258 charred crop seeds were identified from 102 flotation samples collected from two sites (Supplementary Table S1), including: 6,935 foxtail millet seeds (*Setaria italica*; Figure 2A), 558 broomcorn millet seeds (*Panicum miliaceum*; Figure 2B), 11 wheat seeds (*Triticum aestivum*; Figure 2C), and 16 barley seeds (*Hordeum vulgare*; Figure 2D). The remaining 738 seeds were composed of uncultivated species or weed remains (such as *Setaria viridis*, *Melilotus suaveolens*, *Atriplex patens*, *Salsolacollina pall*, *Avena fatua*, *Kochia scoparia*, *Digitaria sanguinalis*, *Carex tristachya*, *Rumex acetosa*, *Galium tricorne* and so on.) (Figure 2E–P). The wheat/barley are modern seeds from house relics in WJYW site, and they may have been redeposited from younger cultural layers. Therefore, we will not discuss it here, which has no influence on the final results and discussion.

Using the new additions to the archaeological record, linked both by agricultural practice and chronologically defined context, it is possible to chart agricultural development during ~4,800–3,900 BP in the MLHRV (Supplementary Table S1; Figure 6). 2,599 foxtail millet seeds (77.21% of weight) and 266 broomcorn millet seeds (22.79% of weight) were identified from 18 samples (181 L of soil in total) in the ZTXFC site. This indicates the predominance of a millet-based agriculture during the 4,800–4,400 BP. Between 4,200 and 3,900 BP, a mixed farming practice gradually emerged. 4,336 foxtail millet seeds (83.73% of weight), and 292 broomcorn millet seeds (16.27% of weight) were collected from 84 samples totaling 978.5 L of soil. 11 wheat and

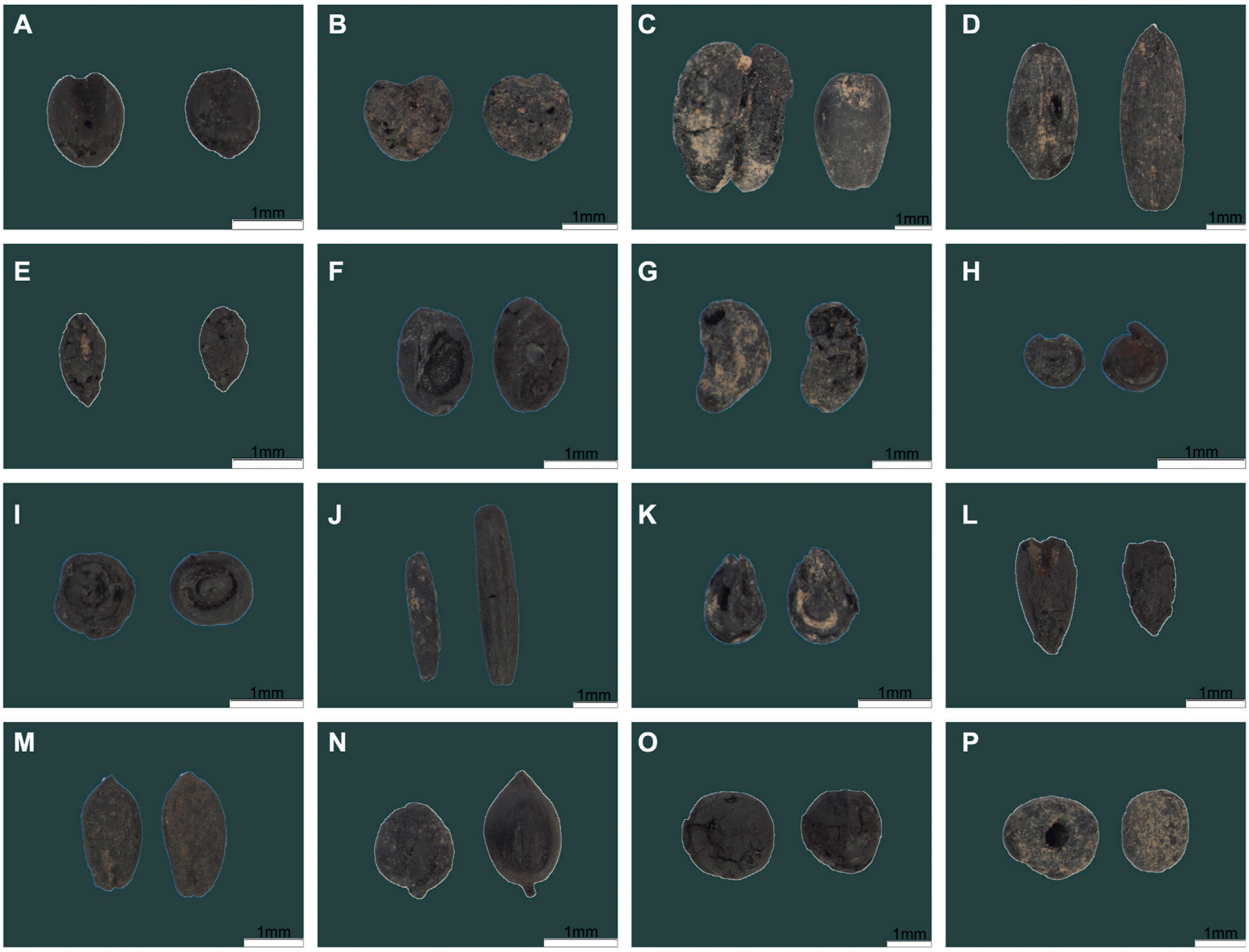

FIGURE 2
Charred plant seeds collected from ZTXFC and WJYW sites (scale bar: 1 mm): **(A)** *Setaria italica*, **(B)** *Panicum miliaceum*, **(C)** *Triticum aestivum*, **(D)** *Hordeum vulgare*, **(E)** *Setaria viridis*, **(F)** *Astragalus membranaceus*, **(G)** *Melilotus suaveolens*, **(H)** *Atriplex patens*, **(I)** *Salsolacollina pall*, **(J)** *Avena fatua*, **(K)** *Kochia scoparia*, **(L)** *Digitaria sanguinalis*, **(M)** *Carex tristachya*, **(N)** *Rumex acetosa*, **(O)** *Perilla frutescens*, **(P)** *Galium tricorne*.

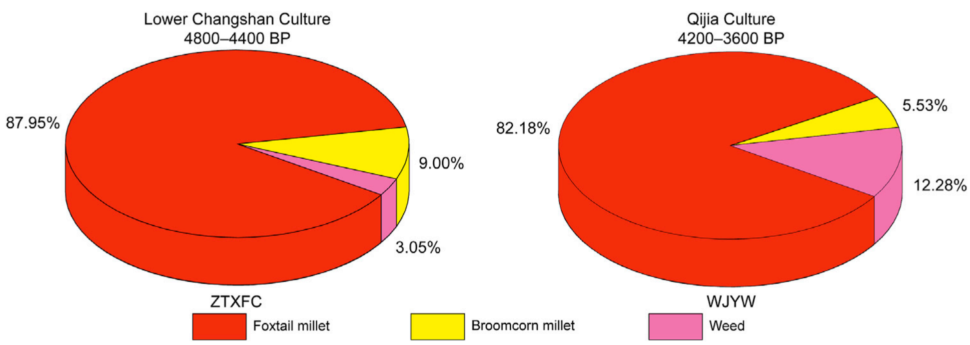

FIGURE 3
Results of archaeobotanical analysis from the ZTXFC and WJYW sites.

16 barley grains were identified from WJYW, which was probably due to a disturbed context given that similar issues were also encountered in previous studies (Table 1; e.g.; Dodson et al., 2013; Jia et al., 2013). It is worth noting that the dominant species (foxtail millet) continues to account for four-fifths of the total seeds in the assemblage (Figure 3).

TABLE 2 Statistical results regarding length, width, and thickness of single millet from ZTXFC and WJYW sites.

Site	Species	Type	Number	Mean (mm)	SD	Range (mm)
ZTXFC	Foxtail millet	Length	186	1.33	0.11	0.90–1.62
		Width	186	1.12	0.09	0.89–1.33
		Thickness	186	0.91	0.14	0.58–1.29
ZTXFC	Broomcorn millet	Length	63	1.61	0.13	1.38–1.96
		Width	63	1.53	0.13	1.32–1.89
		Thickness	63	1.32	0.15	1.03–1.80
WJYW	Foxtail millet	Length	140	1.36	0.18	0.95–1.99
		Width	140	1.12	0.14	0.74–1.77
		Thickness	140	0.84	0.18	0.50–1.55
WJYW	Broomcorn millet	Length	73	1.65	0.20	1.20–2.20
		Width	73	1.44	0.19	0.97–1.84
		Thickness	73	1.24	0.22	0.63–1.74

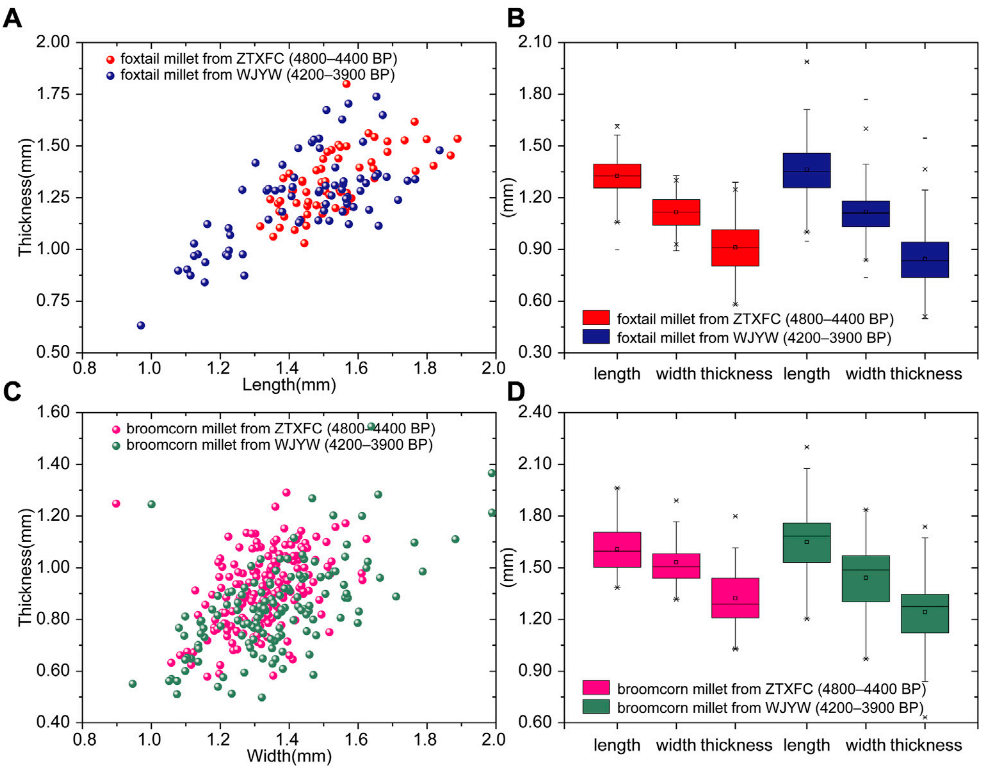

FIGURE 4
Scatter diagram and box plot detailing the length, width, and thickness of foxtail and broomcorn millets from ZTXFC and WJYW sites. **(A, B)** represent the result of foxtail millets; **(C, D)** represent the results of broomcorn millets.

4.3 Size of foxtail and broomcorn millet remains in the mid-lower Hulu River Valley during ~4,800–3,900 BP

A total of 326 foxtail millets and 136 broomcorn millets were measured and the mean values, ranges and standard deviations of length, width and thickness were calculated in this study (Table 2; Figure 4). The length, width, and thickness of the foxtail millets from ZTXFC site (4,800–4,400 BP) ranged from 0.90 to 1.62 mm (mean = 1.33 ± 0.11 mm), from 0.89 to 1.33 mm (mean = 1.12 ± 0.09 mm), and from 0.58 to 1.29 mm (mean = 0.91 ± 0.14 mm), respectively. For the broomcorn millets, the same measurements ranged from

TABLE 3 Summary results of δ^{13}C and δ^{15}N of millets from ZTXFC and WJYW sites.

Site	Species	Number	δ^{13}C (‰)			δ^{15}N (‰)		
			Mean	SD	Range	Mean	SD	Range
ZTXFC	Foxtail millet	11	−9.2	0.2	−9.6–−8.8	6.8	1.9	4.9–12.1
ZTXFC	Broomcorn millet	10	−9.7	0.3	−10.6–−9.3	7.3	2.0	5.0–13.0
WJYW	Foxtail millet	11	−9.5	0.3	−9.8–−8.8	7.5	1.5	5.7–11.5
WJYW	Broomcorn millet	11	−10.2	0.6	−11.7–−9.7	7.5	1.2	5.9–10.7

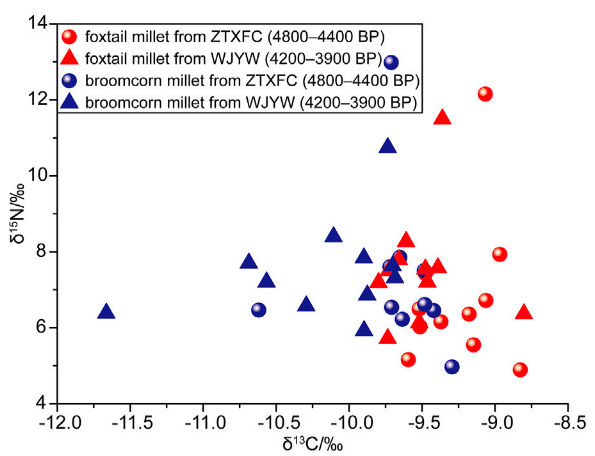

FIGURE 5
Scatter diagram of carbon and nitrogen isotope values for millets from ZTXFC and WJYW sites.

1.38 to 1.96 mm (mean = 1.61 ± 0.13 mm), from 1.32 to 1.89 mm (mean = 1.53 ± 0.13 mm), and from 1.03 to 1.80 mm (mean = 1.32 ± 0.15 mm), respectively. While the length, width, and thickness of the foxtail millets from WJYW site (4,200–3,900 BP) ranged from 0.95 to 1.99 mm (mean = 1.36 ± 0.18 mm), from 0.74 to 1.77 mm (mean = 1.12 ± 0.14 mm), and from 0.50 to 1.55 mm (mean = 0.84 ± 0.18 mm), respectively. The broomcorn millets ranged from 1.20 to 2.20 mm (mean = 1.65 ± 0.20 mm), from 0.97 to 1.84 mm (mean = 1.44 ± 0.19 mm), and from 0.63 to 1.74 mm (mean = 1.24 ± 0.22 mm), respectively. Statistical analysis of the grain size data of foxtail millets and broomcorn millets by SPSS showed that the length and thickness of the foxtail millets were statistically significant. For broomcorn millets width and thickness were statistically significant.

4.4 Carbon and nitrogen isotopes of foxtail and broomcorn millet in the mid-lower Hulu River Valley during ~4,800–3,900 BP

Stable isotopic analysis of the 22 foxtail millet samples and 21 broomcorn millet samples are presented in Table 3 and Figure 5. The broomcorn millet has a wider isotopic range than the foxtail millet in terms of δ^{13}C values, while the δ^{15}N values are opposite. During the Lower Changshan culture period (4,800–4,400 BP), the δ^{13}C and Δ^{13}C values of foxtail millet samples ranged from −9.6‰ to −8.8‰ (mean = −9.2‰ ± 0.2‰, n = 11) and 2.5‰–3.3‰ (mean = 3.0‰ ± 0.2‰). δ^{15}N ranged from 4.9‰ to 12.1‰ (mean = 6.8‰ ± 1.9‰, n = 11). The δ^{13}C and Δ^{13}C values of broomcorn millet samples ranged from −10.6‰ to −9.3‰ (mean = −9.7‰ ± 0.3‰, n = 10) and 3.0‰–4.4‰ (mean = 3.4‰ ± 0.3‰), respectively. δ^{15}N ranged from 5.0‰ to 13.0‰ (mean = 7.3‰ ± 2.0‰, n = 10). In the foxtail millet samples from the Qijia Culture period (4,200–3,900 BP), the δ^{13}C, Δ^{13}C, and δ^{15}N values ranged from −9.8‰ to −8.8‰ (mean = −9.5‰ ± 0.3‰, n = 11), from 2.4‰ to 3.4‰ (mean = 3.1‰ ± 0.3‰), and from 5.7‰ to 11.5‰ (mean = 7.5‰ ± 1.5‰, n = 11), respectively. The δ^{13}C, Δ^{13}C, and δ^{15}N values of broomcorn millet samples ranged from −11.7‰ to −9.7‰ (mean = −10.2‰ ± 0.6‰, n = 11), from 3.3‰ to 5.3‰ (mean = 3.8‰ ± 0.6‰), and from 5.9‰ to 10.7‰ (mean = 7.5‰ ± 1.2‰, n = 11), respectively.

5 Discussion

5.1 Human planting strategies in the mid-lower Hulu River Valley during ~4,800–3,900 BP

The results of archaeobotanical analysis from the ZTXFC and WJYW sites (Supplementary Table S1; Figure 3) show that foxtail millet was the dominant cultivated crop, and broomcorn millet acted as the auxiliary crop in the MLHRV during both ~4,800–4,400 BP and ~4,200–3,900 BP. Although the charred wheat was found in the sediment of the Xishanping site that dated was to 4,650 BP, the wheat was not directly dated (Li et al., 2007). Wheat remains excavated at the Gaozhuang site in Zhuanglang County were dated to 3,561–3,405 BP (Li, 2018), which is the earliest evidence for wheat appearing in the MLHRV. Though few charred grains of wheat and barley were identified from the WJYW site, the direct radiocarbon date of one charred wheat grain suggests that these West Asian domesticated crop remains were likely derived by disturbance from modern periods (Table 1). This phenomenon was also reported in archaeobotanical studies from other Neolithic sites of North China (Zhang et al., 2018). This indicates that humans may have not yet incorporated wheat and barley into their cropping patterns in the Hulu River Valley during this period. Nevertheless, the radiocarbon date of foxtail millet remains from the same flotation sample that yielded the wheat/barley (Table 1) reveals

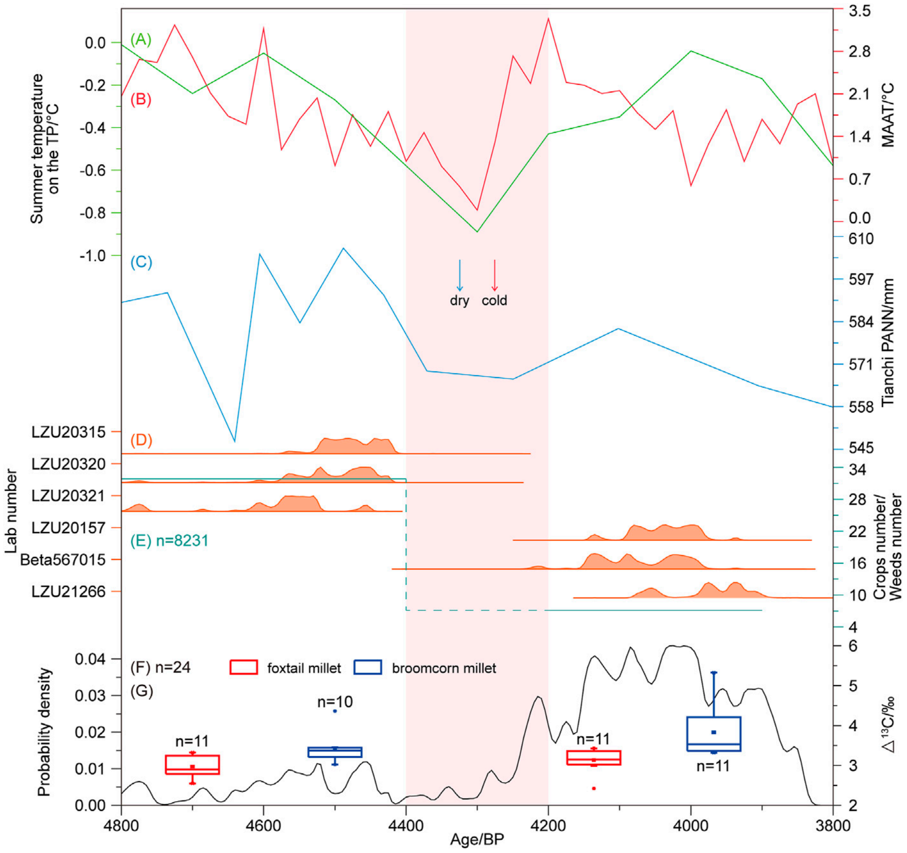

FIGURE 6
Human planting strategies and its relation to climate change during ~4,800–3,900 BP in the mid-lower Hulu River Valley, northwest China, compared with climate records, radiocarbon dates and $\Delta^{13}C$ values of millets. **(A)** Summer temperature reconstruction on the Tibetan Plateau (Zhang et al., 2022). **(B)** Mean annual air temperature (MAAT/°C) record from the Agassiz ice cap (Lecavalier et al., 2019). **(C)** Pollen-based annual precipitation (PANN/mm) reconstructed from Tianchi Lake in the past 6,000 years (Zhao et al., 2010; Chen et al., 2015). **(D)** Radiocarbon dates from the ZTXFC and WJYW sites. **(E)** Crop number/Weed number, n is the sum of crops number and weeds number from two sites. **(F)** Frequency during ~4,800–3,900 BP in the mid-lower Hulu River Valley. **(G)** $\Delta^{13}C$ value of foxtail and broomcorn millets from ZTXFC and WJYW. VPDB, Vienna Pee Dee Belemnite.

these remains of indigenous crop were utilized in Qijia period. In addition, other Qijia sites in the study area mainly grew foxtail and broomcorn millets, and only a very small amount of barleys were excavated from the Gaozhuang site (Li, 2018). Isotopic evidence also suggests that C_4 crops were mainly consumed in the western Loess Plateau during 5,300–4,000 BP (Dong J et al., 2022). The number and mass percent of foxtail millet remains in total plant remains in the ZTXFC and WJYW sites account for 87.95%/77.21% and 82.18%/83.73%, respectively. The same values for broomcorn millet at these two sites were 9.00%/22.79% and 5.53%/16.27%, respectively. This suggests that cropping patterns in the MLHRV were roughly similar during the Lower Changshan and Qijia periods. The significance of foxtail millet in plant subsistence strategy was slightly higher in the Qijia period than in the Lower Changshan period.

The increased weight of foxtail millet relative to broomcorn millet as a cropping strategy in the MLHRV during the Qijia period in comparison to the Banpo-Miaodigou period (~6,100–5,500 BP) and the late Yangshao period (~5,500–4,800 BP) were reported in previous archaeobotanical studies (Li et al., 2022b; Yang Y et al., 2022). Our results from the ZTXFC site are the first reported archaeobotanical data of the Lower Changshan culture. The proportion of weed remains in the plant remains at the ZTXFC site is only 3.05%, while the WJYW site reaches ~12.28%. To reduce sampling error (houses vs. ash pits), we compared the Lower Changshan data with all data derived from various Qijia residential contexts in the Western Loess Plateau. We found that the weed proportion of ash pits derived from other Qijia sites was 9%–16.8% (Yang, 2014; Li, 2018; Li et al., 2022b), which is closer to the Qijia result of this study (12.28%). It suggests that results from different residential contexts (houses vs. ash pits) may not be influenced in this case. These data likely indicate that human input to field management in the MLHRV during the Qijia period was less than in the Lower Changshan period (Figure 6E), though the cropping strategy were dominated by foxtail millet with broomcorn millet as an auxiliary during both periods.

Carbon and nitrogen isotopes of crop remains unearthed from archaeological sites were used to study ancient human management behaviors of cultivated land, for example, irrigation and fertilization (Wang et al., 2018; Li et al., 2022b; Dong Y et al., 2022; Liu et al., 2022). The $\delta^{13}C$ value of foxtail and broomcorn millet remains from the ZTXFC and WJYW sites (Table 3; Figure 5) show that the $\delta^{13}C$ values of millets from the WJYW site are more negative than in the ZTXFC site. The $\delta^{15}N$ values of millets from the WJYW site overlap with and are slightly higher than in the ZTXFC site. The mean $\delta^{13}C$ and $\delta^{15}N$ values of foxtail millet remains are different from the broomcorn millet remains, which may be related to the physiological differences between the two species (An et al., 2015).

The $\delta^{13}C$ values of plants might have been affected by varying atmospheric $\delta^{13}C$ values during different periods of the Holocene (Cleveland, 1979; Leuenberger et al., 1992; Francey et al., 1999; Indermühle et al., 1999; Ferrio et al., 2005). Therefore, we air-corrected the carbon isotope values for all samples to obtain $\Delta^{13}C$ values (Eq. (2); Farquhar et al., 1982). The $\Delta^{13}C$ values of crops can be affected by the physiological properties of plants themselves and by external environmental factors (O'leary, 1981; O'leary, 1988; Farquhar et al., 1982; 1989; Farquhar and Richards, 1984; Wallace et al., 2013). Physiological properties of plants include photosynthesis pathway, plant species, and different parts of the same plant species (O'Leary, 1981; 1988; Farquhar et al., 1989; Hattersley and Watson, 1992; An et al., 2015). However, since foxtail and broomcorn millet are gramineous C_4 plants, their $\Delta^{13}C$ values from the ZTXFC and WJYW sites were mainly affected by environmental conditions rather than physiological difference.

Previous analysis of carbon isotopes of millet remains from the archaeological sites in the nearby Qin'an and Lixian counties suggest temperature differences are not the main factor affecting the $\delta^{13}C$ values of millets (Ji, 2007). Therefore, water availability for the growth of millet crops in the study area is closely related to water conditions that may be affected by changes in precipitation or human irrigation behavior. Considering the long-run tradition of rain-fed farming for foxtail and broomcorn millet, even in modern North China, it is unlikely that human irrigated these drought-resistant millets during the late Neolithic. Moreover, the mean $\Delta^{13}C$ values of millet remains from the WJYW and ZTXFC sites are lower than the mean $\Delta^{13}C$ values of *S. viridis* samples grown under modern natural precipitation, indicating that artificial irrigation management was not applied during ~4,800–3,900 BP (An et al., 2015; Li, 2018). Modern experiments on the Loess Plateau and elsewhere indicate that the $\Delta^{13}C$ values of C_4 grasses are negatively correlated with rainfall (Wang et al., 2005; Li, 2018; Sanborn et al., 2021; Dong Y et al., 2022). The $\Delta^{13}C$ values of millet remains at the WJYW site higher than those at the ZTXFC site (Figure 6G), suggesting that water availability of millet crops in the WJYW was likely lower than ZTXFC site. The pollen percentage data from the Tianchi Lake sediment indicated that precipitation was lower during ~4,200–3,800 BP than ~4,800–4,400 BP (Figure 6C; Zhao et al., 2010; Chen et al., 2015). Due to the Tianchi Lake is 30 km away from these two sites, the precipitation reconstruction data derived from the Lake is a suitable and reliable record for human actives in the MLHRV. This is a further demonstration of the relatively low water availability in the Qijia period compared with Lower Changshan period, suggesting that the $\Delta^{13}C$ values of millet remains from the ZTXFC and WJYW sites were primarily affected by the decreased precipitation (Figure 6C), instead of other factors, such as fertilization behavior.

The ranges of $\delta^{15}N$ values for foxtail and broomcorn millet remains in the WJYW and ZTXFC sites are quite wide (Figure 5). However, no statistically significant differences of $\delta^{15}N$ values for foxtail and broomcorn millet remains from these two sites are detected by the statistical analysis of variance (ANOVA, foxtail millet: $p = 0.349$; broomcorn millet: $p = 0.808$). This indicates the soil fertility characteristics for millet crop growth in the WJYW and ZTXFC sites were similar. The $\delta^{15}N$ values for all samples were higher than the estimated moderate fertilization level (3.5‰, Li et al., 2022b), and significantly higher than the local vegetation baseline (1.9‰, Barton, 2009) and fertilization level from the Dadiwan site in the Yangshao period (6,500–4,800 BP, Yang et al., 2022). This suggested humans probably added organic fertilizers (animal manure, sewage, food waste, and so on) to the cultivated lands in the MLHRV during ~4,800–4,400 BP and ~4,200–3,900 BP, as were reported at Neolithic sites in Eurasia (Bol et al., 2005; Bogaard et al., 2007; Aguilera et al., 2008; Bogaard et al., 2013; Araus et al., 2014). However, the relationship between the $\delta^{15}N$ values of crop remains and fertilization behaviors in the area still needs to be further examined by detailed and modern simulation experiments.

The measurement of crop remains grain size provides a perspective for studying human cultivating behavior of the major crops (Willcox, 2004; Motuzaite-Matuzeviciute et al., 2012; Bao et al., 2018). According to grain size data analysis from numerous sites in North China, foxtail and broomcorn millet grain sizes generally increased from the Neolithic to historical periods (Bao et al., 2018). The same diachronic change was also detected in the western Loess Plateau (Li, 2018), suggesting humans continuously performed breeding selection on these two indigenous crops in North China. However, we observe the opposite trend for millets grain size variation in the MLHRV from ~4,800–4,400 BP to ~4,200–3,900 BP which was based on the measurements of millets grain sizes at the ZTXFC and WJYW sites (Table 2; Figure 4). The difference of length and thickness of foxtail millet remians are statistically significant. The same notable divergence in broomcorn millet remains is reflected by the width and thickness. Therefore, the change of foxtail and broomcorn millet grain sizes from the Lower Changshan to Qijia culture can be evaluated by those parameters. The results show that grain sizes for both millet crops at the WJYW site were overall smaller than the ZTXFC site (Figure 4), suggesting human might have not engaged in artificial breeding of millet crops during the Qijia period. This is consistent with other investigated Qijia sites in the study region (Supplementary Table S2). Compared with the grain size of millets from the ZTXFC site (Lower Changshan culture), grain size of millets from all contexts of Qijia sites in this region were overall smaller (Supplementary Table S2).

Crop grain sizes may be influenced by multiple factors, such as domestication and hereditary properties (Li et al., 2011; Fuller et al., 2014), maturity (Motuzaite-Matuzeviciute et al., 2012) and the environmental conditions of crop growth (Araus et al., 1999; Willcox, 2004). Immaturity may be an important influencing factor for the smaller grain size of millets (Motuzaite-Matuzeviciute et al., 2012), which was mainly examined by the morphology of millets grains. According to the evaluative criteria proposed by Song et al. (2012), all measured millet remains from the WJYW and ZTXFC sites were mature millets, as the length-width ratio of foxtail and broomcorn millet remains are basically same at these two sites (Table 2). The primary factor affecting grain size of millet remains at the ZTXFC and WJYW sites may be the environmental conditions of millets growth, such as water stress and soil fertility (Araus et al., 1999; Willcox, 2004). As was mentioned above, the soil fertility for millets growth at the ZTXFC and WJYW sites were basically similar, while water availability for millets growth was lower at WJYW than ZTXFC. This further demonstrated that the decreased precipitation in the MLHRV was responsible for the reduction in the grain sizes of millet crops during the Qijia period in comparison to the Lower Changshan period.

5.2 How millet farming groups responded to climate change in the mid-lower Hulu River Valley during ~4,800–3,900 BP

Climate changes, especially rapid and extreme climate events, are proposed as an important factor for cultural evolution and the transformation of subsistence strategies in different corners of Eurasia during the Neolithic periods (Staubwasser et al., 2003; Wu and Liu, 2004; Weiss, 2017; Park et al., 2019; Ran and Chen, 2019; Zhang H et al., 2021), including northwest China (Dong et al., 2012; Zhou et al., 2016; Cao and Dong, 2020; Ren et al., 2021). While social resilience to climate change gradually increased with innovations and the dispersal of agricultural techniques across Eurasia, Neolithic groups could adopt different strategies to cope with climate change (Yang et al., 2019; Yang et al., 2020; Dong et al., 2021; Tao et al., 2022). In the Apulia region of southern Italy, humans altered cropping patterns as an adaptation response to the rapid dry-humid fluctuations during ~8,500–5,700 BP (Fiorentino et al., 2013). At the Jinchankou site in Qinghai, human increased field management during ~4,100–3,700 BP to cope with climate (Ren et al., 2021). In North China, the areas utilized for millet cultivation extensively expanded, facilitating the growth in population during and after the 4.2 ka climate event (He et al., 2022).

In the MLHRV, a climate event around 5,500 BP triggered the transition of the primary cultivated crop from broomcorn millet to the relatively high-yielding foxtail millet (Yang Y et al., 2022). This might have contributed to the development of millet-pig intensive agriculture in the area (Yang J et al., 2022). Recent studies of lake sediments in the Liupan Mountains, the closest high-resolution paleoclimate archives to the MLHRV, and temperature reconstruction from the Tibetan Plateau and Agassiz ice cap, reveal a rapid decline in temperature and precipitation at ~4,400 BP (Figures 6A–C; Zhao et al., 2010; Chen et al., 2015; Lecavalier et al., 2019; Zhang et al., 2022). This generally corresponds with paleoclimate records in surrounding areas (Tan et al., 2020; Zhang C et al., 2021). The lowest temperature and precipitation of 4,800–3,800 BP in the MLHRV occurred between ~4,400 and 4,200 BP, corresponding to the gap between the Lower Changshan and Qijia periods in the area (Figure 6). This suggests that the cold-dry climate during these two centuries probably led to the collapse of the Lower Changshan society in the MLHRV. This heavily relied on the production of frost-sensitive millet crops which was susceptible to climate change, especially substantial drops of temperature.

Climate turned warmer and wetter to some extent in the MLHRV around 4,200 BP, and Qijia groups settled widely in the area during the subsequent centuries (Figure 1). The number of Qijia sites in the MLHRV reached 381, which was much more than the Lower Changshan sites (8), while climate was colder and dryer during 4,200–3,800 BP than 4,800–4,400 BP. Our results of archaeobotanical analysis, grain size measurement, and stable isotope analysis at the ZTXFC and WJYW sites reveal that the cropping patterns remained consistent, while the level of farmland management was regressive from the Lower Changshan to Qijia periods. There is no evidence to suggest that humans strengthened the behavior of irrigation, fertilization or breeding during the Qijia period in comparison to the Lower Changshan period. Furthermore, the decline of precipitation during the Qijia period compared with Lower Changshan period resulted in the increase of water stress for millet growth and then the reduction of millet grains. However, both the intensity and space of human settlements in the MLHRV during the Qijia period were significantly larger than the Lower Changshan period (Figures 1, 6F). After excluding the extreme values, the ranges of $\delta^{15}N$ values for foxtail millet and broomcorn millet remains during the Qijia period are significantly wider (ANOVA, foxtail millet: p = 0.003, broomcorn millet: p = 0.002) than the Lower Changshan period in the Western Loess Plateau (Supplementary Table S3; Yang, 2021; Li et al., 2022b). This indicated that Qijia populations cultivated millet in farmlands with different fertility conditions and expanded their farmlands. This suggests that Qijia groups may have adopted a strategy of expanding farmlands to promote social development, although climate was relatively cold and dry compared with Lower Changshan and Yangshao periods. This strategy of agricultural extensification was also witnessed in contemporaneous Yellow River Valleys (He et al., 2022). Additionally, massive emigration of millet farming groups occurred in some areas of North China, such as eastern Inner Mongolia, probably due to the spatial differences in social resilience and the amplitude of climate change influencing the growth of millet crops. Qijia population may have adopted new crops, domesticated animals, and metallurgy to cope with climate change in the later period. For instance, humans incorporated wheat and barley farming, animal herding, metallurgy, and luxury (e.g., jade) into their economic system in the Hexi Corridor (Chen, 2017; Yang et al., 2019; Cao, 2022; Ren et al., 2022) and western Loess Plateau during the Qijia period (Li, 2018; Ren et al., 2021; Cao, 2022; Wang L et al., 2022; Zhang, 2022). The diversified economic strategy enhanced Qijia social resilience to cope with climate change.

6 Conclusion

Through archaeobotanical analysis, radiocarbon dating, grain size measurement, and stable isotope studies at the ZTXFC and WJYW sites, we reveal the characteristics of planting strategies in the MLHRV during the Lower Changshan and Qijia periods. The proportions of foxtail millet and broomcorn millet in plant remains account for 87.95%/9.00% and 82.18%/5.53%, while those of weeds are 3.05% and 12.28% in the ZTXFC and WJYW sites, respectively. This suggests that rain-fed agriculture served as the dominant plant utilization strategy, while human input to field management declined from ~4,800–4,400 BP to ~4,200–3,900 BP in the MLHRV. Measurements and stable isotope analysis results of carbonized millet grains demonstrates that the grain size of millets and water availability during the Qijia period was lower than in the Lower Changshan period, which was likely affected by the decline of temperature and precipitation. This pattern of planting strategies is supported from previous archaeobotanical studies in the MLHRV. These indicate that millet farming groups in the area might have neither altered cropping patterns nor improved their farmland management. Instead, they enlarged their cultivated lands to support the rapid growth of local populations during the Qijia period, when climate was relatively cold and dry in comparison to the Lower Changshan period. Our work provides a valuable case study to understand the pattern of human-environment interaction at a local scale in millet farming areas during the late Neolithic.

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 authors.

Author contributions

The study was designed by WW and MM. GC, JD, and ZW conducted field works and sample collection. WW and HL completed experiments and data correction. WW and MM analyzed data and designed the figures. WW, MM, GC, JD, ZW, HL, and XL 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.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2023.1137528/full#supplementary-material

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