

<https://doi.org/10.1038/s40494-025-02090-2>

Multi-proxy investigations of subsistence strategy during Bronze Age in Inner Mongolia, China

Xin Sun^{1,2}, Xue Shang²✉, Gouming Yue³ & Qian Li³

Investigations of ancient subsistence strategies are important to understand early civilizations. However, the emergence of high complexity and how groups adapted to the harsh environment in the loess-desert transition zone remain unclear, especially in the Inner Mongolian region. Here, we first present new evidence of archaeobotanical ($n = 24$) and stable isotope analyses ($n = 23$) of humans, animals, and plants from the Sharitala site in Inner Mongolia. It is shown that the foxtail millet has the highest proportion (90.9%) among all the crops. The average $\delta^{15}\text{N}$ value of foxtail millet seeds is 5.1‰, which implies the existence of a certain degree of fertilization behavior. The ancestors of this region mainly consumed C_4 type crops and/or the livestock raised on C_4 type crops. By integrating data from 15 archaeological sites of the loess-desert transition zone, we found that the subsistence strategies were influenced by natural and social factors.

Social complexity constitutes a crucial analytical framework in the study of early civilizations¹. The extent of social sophistication exhibits significant variation across different regions and is influenced by diverse subsistence patterns². These differences and complexities are evident in the interactions among individuals of different distinct cultural groups, social strata, and genders³.

The loess-desert transition zone in northern China primarily encompasses the sandy and wind-eroded regions of the Ordos Plateau and the sandy loess area of the Loess Plateau⁴. The administrative division includes central-southern Inner Mongolia, northern Shanxi Province, and Shaanxi Province. This area is distinguished by its limited water resources and ecologically fragile environment, which exhibits high sensitivity to environmental changes⁵. Despite these challenges, around 4000 BP, a remarkable civilization center emerged in this region, known as the Shimao Culture (石峁) (Fig. 1), and rapid population growth occurred⁶. The wide distribution of defensive facilities, such as stone-walled cities and ring trenches⁶, suggests high social complexity in the loess-desert transition zone during this period. Archaeological evidence suggests that settlements exhibited characteristics similar to those of the Shimao site⁷. The size of the settlements exhibited clear hierarchical differences: the Shimao site encompassed an area exceeding 4 million square meters, the sites had stone walls with areas of 500,000 to 1 million square meters, and some sites with stone walls were smaller than 500,000 square meters. Furthermore, numerous undefended settlements existed^{6,8}, forming a hierarchical settlement system.

The pattern of livelihood serves as the foundation for social development⁹. There is a significant correlation between the degree of agricultural intensification and the complexity of societal structures¹⁰. Relatively similar pottery assemblages were excavated from the Shimao site and nearby sites⁷, suggesting that the dietary structure and eating habits in the region were likely consistent¹¹. The livelihood mode of occupants in the region was based on millet agriculture, complemented by the raising of pigs (*Sus domesticus* Linnaeus, 1758), cattle (*Bos taurus* Linnaeus, 1758), and sheep/goat (*Ovis aries* Linnaeus, 1758/*Capra hircus* Linnaeus, 1758)^{12–26}.

Before the Shimao culture formed, occupants from south-central Inner Mongolia had already traveled southward into northern Shaanxi²⁷, and the development of the archaeological culture and subsistence mode exemplified by Shimao in the loess-desert transition zone region was closely related to occupants from south-central Inner Mongolia. Previous research on subsistence practices in this region has predominantly focused on northern Shaanxi, with relatively limited attention devoted to the south-central part of Inner Mongolia^{12,18,28–31}. Additionally, limited studies have examined the variations in agricultural development across sites of different grades within this region. What are the similarities and differences in crop structure and field management between non-stone-walled sites and stone-walled sites? How do these similarities and differences influence the subsistence economy and the level of social complexity of a region's societies? Investigating these questions is essential for understanding both the adaptive strategies of human populations to harsh climatic conditions and the development of social structures and complexity within the region.

¹Key Laboratory of Vertebrate Evolution and Human Origins, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing, China. ²Department of Archaeology and Anthropology, University of Chinese Academy of Sciences, Beijing, China. ³Institute of Cultural Relics and Archaeology Inner Mongolia Autonomous Region, Hohhot, China. ✉e-mail: shangxue@ucas.ac.cn

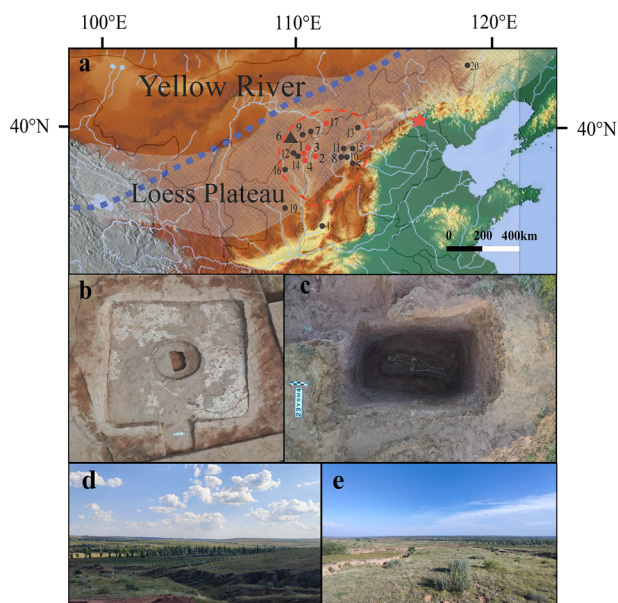


Fig. 1 | Site locations and site pictures. **a** Location of Sharitala and related sites. This paper covers the following sites: 1. Shimao, 2. Bicun, 3. Zhaimao, 4. Zhaimaoliang, 5. Hengshan, 6. Sharitala, 7. Dakou, 8. Yadi, 9. Zhukaigou, 10. Shangyuan, 11. Shangshen, 12. Shengedaliang, 13. Jijiazhuang, 14. Muzhuzhuliang, 15. Xinzhang, 16. Huoshiliang. Other relevant sites: 17. Houchengzui, 18. Taosi, 19. Lushanmao, 20. Xiajiadian. The red star represents Beijing. The blue dotted line indicates the 400 mm rainfall contours. The red circle highlights ranges with similar cultural profiles⁷. The gray shading delineates the loess-desert transition zone. **b** The remains of house F1 at the Sharitala site in the 2023 excavation. **c** The burial remains M4 at the Sharitala site in the 2023 excavation. **d, e** The modern environment around the Sharitala site.

In this study, integrated bioarchaeological methods were applied to provide new evidence from the Sharitala site, to examine the subsistence strategies in Inner Mongolia, a key location in the loess-desert transition zone dating to approximately 4000 BP. Additionally, flotation and stable isotope published results from plants, animals, and humans across 15 sites within the region spanning 4200–3700 BP were synthesized to provide robust scientific evidence for understanding the relationship between the agricultural characteristics and the regional social structure during this remarkable period, with a significant increase in social complexity.

Methods

Sites and archaeological background

The Sharitala site (109°52'E, 39°25'N, 1364 a.s.l) is located in the village of Sharitala, Ejin Horo Banner, Ordos city, Inner Mongolia Autonomous Region, in south-central Inner Mongolia. The site is approximately 45 kilometers southwest of the Zhukaigou site, 100 kilometers northwest of the Shimao site, 20 kilometers west of the Ulan Moron River, and 120 kilometers south of the Yellow River. This region is characterized by a temperate continental climate, marked by aridity, limited water resources, and high sensitivity to climatic fluctuations⁵. According to meteorological data from 1970 to 2009 in Ejin Horo Banner, the average annual precipitation was approximately 345 mm. The mean summer temperature was 20.5 °C, while the mean winter temperature was −6.3 °C. The Sharitala site is located within the loess-desert transition zone, classified as a temperate semiarid grassland characterized by steppe vegetation.

The Sharitala site covers an area of approximately 500,000 square meters. During the 2023 excavation, which covered an area of 500 square meters, archaeologists uncovered five house sites, four ash pits, six burials, three ash ditches, and one pedestal. Artifacts, including pottery shards, stone tools, bone tools, and animal remains (e.g., pigs, dogs, cattle, sheep/goats, and shellfish) were also discovered³². Based on the cultural remains

excavated, archaeologists have determined the Sharitala site as belonging to the Dakou II culture, marking a critical transition phase from the late Neolithic period to the Bronze Age. The stratigraphic layers at the site are relatively thin, and all identified remains appear contemporaneous based on the artifacts recovered.

The sample about the white-plaster surface of the walls was analyzed for AMS-¹⁴C dating at the BETA laboratory in Miami, Florida, USA. The charcoal samples were analyzed for AMS-¹⁴C dating at the ¹⁴C laboratory of the Center for Scientific Archaeology, Institute of Archaeology, Chinese Academy of Social Sciences. All conventional ¹⁴C ages were calibrated to calendar years using OxCal 4.4.4 software^{33,34} with the IntCal20 calibration curve³⁵. The samples from F1 and F2 date to 4220–3850 cal BP and 4070–3726 cal BP, respectively (Table 1).

Archaeobotanical analysis

A total of 24 flotation samples were collected from the Sharitala site, including 8 samples from stove pits (Z), 7 samples from ash ditches (G), and 9 samples from house sites (F, which refers to the area of the house sites except for the stove pits). The cumulative volume of these flotation samples was 244 liters, averaging about 10 L per sample. The sampling points covered almost all excavation areas, and the sampling units covered all types of remains found at the site.

The botanical remains were retrieved through flotation in small buckets using an 80-mesh sieve (0.2 mm aperture). The samples were dried and forwarded to the Department of Archaeology and Anthropology of the University of Chinese Academy of Sciences for identification and analysis. The charred plant remains were categorized into charcoal fragments and seeds. Seeds were meticulously selected and identified under a Leica S9D stereo microscope. For seed counting, only those that were intact and clearly identifiable in the embryo area were included, while other seed fragments were excluded. The precision of the balance used was 0.01 mg. Absolute counts and the frequency of occurrence statistics served as the primary research indicators. To account for variations in seed weight, a weight correction model was applied to ensure more reliable comparisons of relative seed yields³⁶.

The formula for calculating the weight percentage of foxtail millet (*Setaria italica* L.) is as follows:

$$P_{(\text{foxtail millet})} = \frac{N_{\text{foxtail millet}}^{2.6}}{N_{\text{foxtail millet}}^{2.6} + N_{\text{common millet}} \times 7.5}$$

The formula for calculating the weight percentage of common millet (*Panicum miliaceum* L.) is as follows:

$$P_{\text{common millet}} = \frac{N_{\text{common millet}} \times 7.5}{N_{\text{foxtail millet}}^{2.6} + N_{\text{common millet}} \times 7.5}$$

Stable isotope analysis

Stable carbon and nitrogen isotope analysis of plants. The quantity of common millet unearthed from the same unit was limited, so only a portion of the foxtail millet was selected for the study of plant carbon and nitrogen stable isotopes. Charred foxtail millet with clean and intact surfaces was meticulously selected and photographed under a microscope to record the state of the seeds before treatment. Both with and without husk samples were analyzed to evaluate potential differences between them. For each sample, approximately 10 mg of intact foxtail millet grains with clearly defined morphology were selected for mixing and grinding. The samples were pretreated by the acid treatment method³⁷: the samples were placed in test tubes, 10 ml of 0.5 mol/L HCl was added, and the mixture was heated in a water bath at 80 °C for 30–60 min. The solution was poured off and washed with deionized water until neutral. The samples were lyophilized, ground, and tested. The sample information is shown in Table 3.

Stable carbon and nitrogen isotope analysis of animals and humans. Preparation and testing methods of bone collagen are as follows: The inner

Table 1 | Sharitala site dating results

Lab number	Sample	Location	¹⁴ Cdate (a B. P.)	Calibrated age(cal BP)	
				1σ (68.2%)	2σ (95.4%)
Beta-677359	white-plaster surface of the walls	23YSF1	3730 ± 30	(22.1%) 4148–4115 (14.2%) 4098–4076 (32.0%) 4040–3991	(1.8%) 4220–4208 (93.6%) 4154–3980
ZK-13208	charcoal	23YSF1-Z	3635 ± 25	(68.3%) 3980–3902	(11.7%) 4080–4037 (82.9%) 3995–3872 (0.8%) 3858–3850
ZK-13209	charcoal	23YSF2	3590 ± 40	(10.6%) 3965–3947 (57.7%) 3926–3840	(2.3%) 4070–4044 (86.5%) 3988–3822 (4.1%) 3794–3768 (2.6%) 3749–3726

Table 2 | The flotation results of the Sharitala site

	Species	Count	Percentage (%)	Ubiquity (%)	Density (grain/L)
Crops	<i>Setaria italica</i>	538	90.9	62.5	2.2
	<i>Panicum miliaceum</i>	51	8.6	33.3	0.2
Non-crops	<i>Melilotus officinalis</i>	2	0.3	8.3	0.01
	<i>Lespedeza bicolor</i>	1	0.2	4.2	0.01
Total		592			2.4

and outer surfaces of the bone samples were polished to remove contaminants. Then, the samples were soaked in 0.5 mol/L HCl solution at 4 °C, and the acid solution was replaced every two days until the bone samples were soft and there were no obvious air bubbles on the surface of the bone samples. The bone samples were washed with deionized water until neutral, 0.125 mol/L NaOH solution was added, and the samples were soaked at 4 °C for 20 h and then rewashed to neutral. The bone samples were immersed in 0.001 mol/L HCl solution and heated at 70 °C for 48 h. After the bone samples were completely dissolved in the solution, they were filtered into hot test tubes to obtain the collagen solution. The collagen solution was freeze-dried to obtain collagen^{38,39}. Detailed sampling information is provided in Table 4.

Isotope samples of plants, animals, and humans were tested at the Stable Isotope Archaeology Laboratory, Department of Archaeology and Anthropology, University of Chinese Academy of Sciences. The analysis was conducted using an elemental analyzer (Vario Pyro Cube) coupled with an isotope mass spectrometer (IsoPrime-100 IRMS). Two-point calibration was used to calibrate the raw isotope values. Carbon and nitrogen isotopic compositions were measured and calibrated to VPDB and AIR with USGS40 ($\delta^{13}\text{C} = -26.39\text{‰}$, $\delta^{15}\text{N} = -4.52\text{‰}$) and USGS41 ($\delta^{13}\text{C} = 37.63\text{‰}$, $\delta^{15}\text{N} = 47.57\text{‰}$). The laboratory-prepared collagen standard sample ($\delta^{13}\text{C} = -14.7 \pm 0.2\text{‰}$, $\delta^{15}\text{N} = 7.0 \pm 0.2\text{‰}$) was included within the sample sequence to monitor instrumental stability throughout the analytical process. Stable isotope abundances of carbon and nitrogen were converted to δ values to reflect isotopic variation, expressed in per mille. The precision for C and N was determined to $\pm 0.2\text{‰}$ of calibration standards and check standards.

The method for establishing the isotopic baseline of plants. Plant nitrogen isotopes are influenced by various external environmental factors, including soil properties, atmospheric CO₂ concentration, nitrogen deposition, and precipitation^{40,41}. By comparing the $\delta^{15}\text{N}$ values of charred seeds with the local $\delta^{15}\text{N}$ isotope baseline, researchers can evaluate the degree to which crop $\delta^{15}\text{N}$ values reflect human field management practices, independent of natural environmental influences on plant seed nitrogen isotopes⁴². The baseline for wild vegetation isotopes is typically established using nitrogen stable isotope measurements from wild herbivores, with the isotopic enrichment associated with trophic level elevation being subtracted. As no carbon and nitrogen stable isotope data are currently available for wildlife at the Sharitala site, this study uses nitrogen stable isotope values

from wild animals at the Wuzhuangguoliang site as a proxy (Wuzhuangguoliang Site is also located in the desert loess transitional zone).

The average $\delta^{15}\text{N}$ value of the wild grass rabbit unearthed from the Wuzhuangguoliang site in northern Shaanxi is 4.9‰ ($n = 3$, $\text{SD} = 0.1\text{‰}$)⁴³. Considering that the value of $\delta^{15}\text{N}$ enrichment at each trophic level can be between 3 and 5‰⁴⁴, the $\delta^{15}\text{N}$ value of the local wild vegetation at the Wuzhuangguoliang site and the neighboring area would be around -0.1‰ to 1.9‰ .

Data analysis methods. This study draws on established statistical methods from prior archaeological research^{45,46}. Given that the isotope data for plants, animals, and human bones involved in this study are based on relatively small sample sizes, this study interprets the results more rigorously by not only comparing mean values but also incorporating a comprehensive analysis of the 95% confidence intervals, which are indicated in square brackets throughout the text. To prevent over interpretation of limited data, descriptive statistical methods were prioritized in the analytical approach. All statistical analyses were conducted using SPSS 27.0 software, including the calculation of mean values, estimation of confidence intervals, and performance of t-tests for significance testing.

Results

The flotation results of the Sharitala site

The total number of carbonized plant seeds obtained from flotation was 592, including four genera (see Table 2 and Supplementary Material Table 2 for details). Most of the plant remains were crops (99.5%), including foxtail millet and common millet. There were 538 foxtail millet seeds and 51 common millet seeds, and the absolute number ratio of foxtail millet to common millet was 10.5. The probability of emergence (ubiquity) was 62.5% for foxtail millet and 33.3% for common millet. The weight correction of the number of seeds by the thousand-kernel weight of the crop seed gave a weight-percentage ratio of 3.7 for foxtail and common millet (Fig. 2).

The plant remains were highly charred and black, and some of the charred foxtail millet had formed solid aggregates. Approximately 141 specimens of foxtail millet retained their husk and exhibited irregular granular protrusions on their surfaces. The ubiquity of foxtail millet with husk was 25%, accounting for 23.8% of the total excavated plant seeds. Ninety percent of the foxtail millet with husk was excavated in the hearth of the house site.

Fig. 2 | Proportions of millet at the Sharitala site.

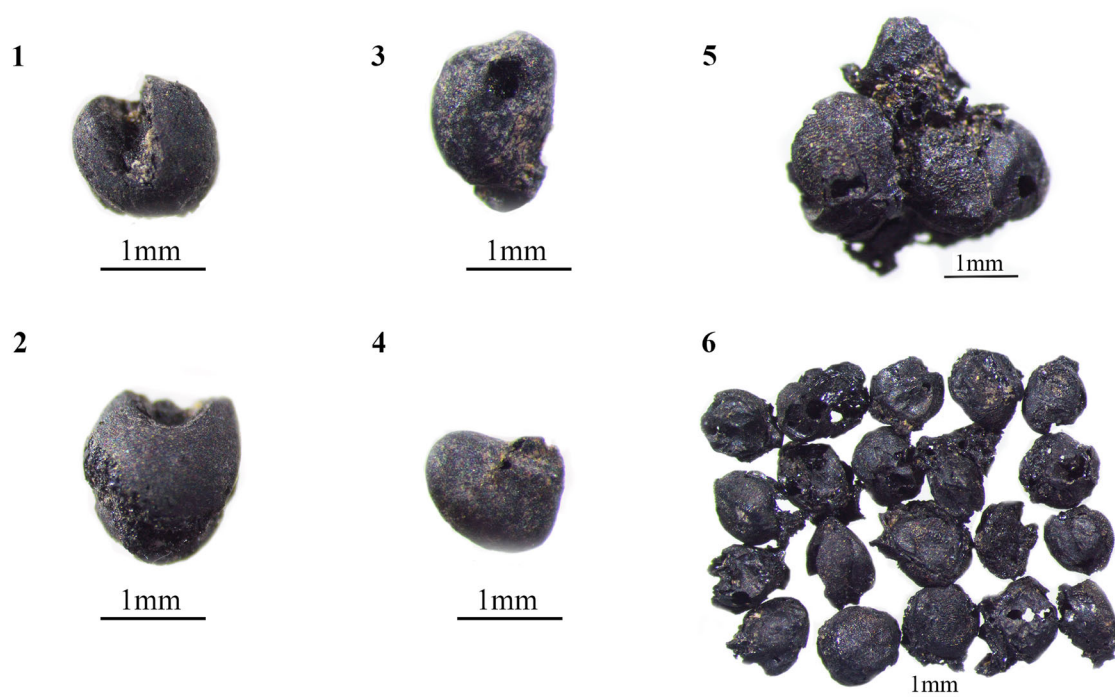
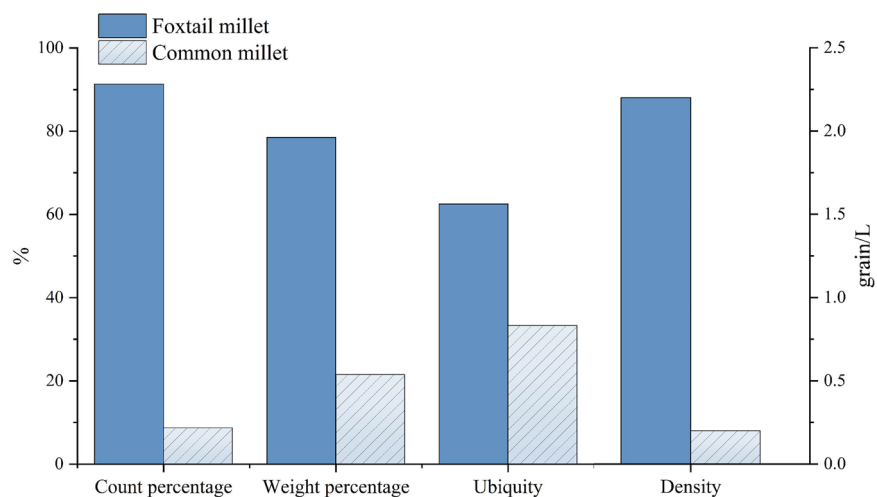


Fig. 3 | Charred seeds from the Sharitala site. 1. *Setaria italica*; 2. *Panicum miliaceum*; 3. *Lespedeza bicolor*; 4. *Melilotus officinalis*; 5-6. Foxtail millet with husk.

The types and quantities of non-agricultural crop remains were relatively small, comprising only two species of Fabaceae plants, *Lespedeza bicolor* L. and *Melilotus officinalis* L., which accounted for 0.2% and 0.3% of the total excavated plant seeds, with ubiquity of 4.2% and 8.3%, respectively. Images of these seeds are presented in Fig. 3.

The charcoal recovered from the Sharitala site is entirely in fragmented form. According to the size of the charcoal fragments, they are categorized into the following size classes: >10 mm, 4–10 mm, 1–4 mm, and <1 mm. The total weight of the charcoal was 5.682 g, and the average concentration of carbonized wood charcoal was 0.0233 g/L. The content of wood charcoal varied among flotation units, and the wood charcoal in the soil sample from hearths at the site was 1.6 g.

Stable carbon and nitrogen isotopes of the plants

The relevant data are presented in Table 3. The $\delta^{13}\text{C}$ values of charred foxtail millet ranged from -9.3‰ to -8.8‰ , with an average of $-9.0 \pm 0.2\text{‰}$ [-9.2 , -8.8] ($n = 10$). The $\delta^{15}\text{N}$ values ranged from 4.6‰ to 5.9‰,

averaging $5.1 \pm 0.4\text{‰}$ [4.8, 5.4] ($n = 10$). Considering the effect of charring on seed $\delta^{15}\text{N}$ values, 0.3‰ was subtracted to adjust the $\delta^{15}\text{N}$ values of charred foxtail millet⁴⁷. After correction for charring, the $\delta^{15}\text{N}$ values of foxtail millet ranged from 4.3‰ to 5.6‰ [4.5, 5.1] (see Fig. 4).

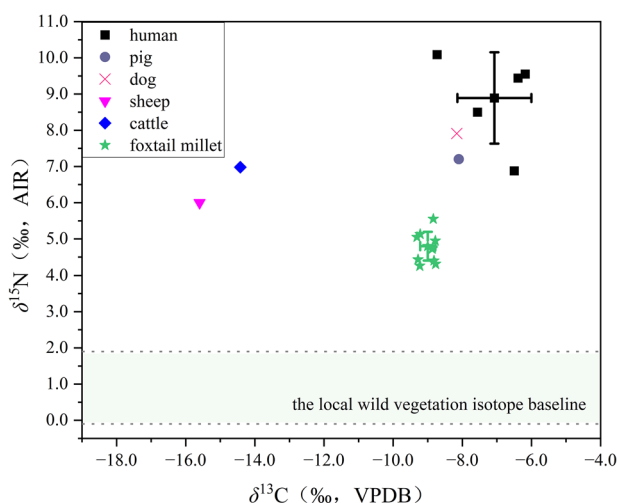
The mean $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of hulled millet were both lower than those of unhulled millet. Independent samples t-tests further revealed that there was no significant difference in the $\delta^{15}\text{N}$ values between hulled millet ($5.0 \pm 0.4\text{‰}$, $n = 4$) [4.3, 5.7] and unhulled millet ($5.1 \pm 0.4\text{‰}$, $n = 6$) [4.6, 5.6] ($t(8) = -0.254$, $P = 0.806 > 0.05$). In contrast, a statistically significant difference was observed in the $\delta^{13}\text{C}$ values between hulled millet ($-9.3 \pm 0.1\text{‰}$, $n = 4$) [-9.3 , -9.2] and unhulled millet ($-8.8 \pm 0.1\text{‰}$, $n = 6$) [-8.9 , -8.8] ($t(8) = -11.952$, $P < 0.01$).

Stable carbon and nitrogen isotopes of humans and animals

As shown in Table 4, collagen was successfully extracted from all samples except samples S5 and S15. The carbon content of the collagen ranged from 15.3% to 47.0%, while the nitrogen content varied between 5.5% and 17.3%.

Table 3 | $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ (uncorrected) values of archaeobotanical samples measured at the Sharitala site

Location	Lab number	Sample type	C(%)	N(%)	C: N	$\delta^{13}\text{C}$ (‰)	$\delta^{15}\text{N}$ (‰)
G1	FX24-1	Foxtail millet without husk	54.24	3.13	20.2	-8.8	4.7
G1	FX24-2	Foxtail millet without husk	59.64	3.19	21.8	-8.8	4.6
G1	FX24-3	Foxtail millet without husk	219.02	11.53	22.2	-8.9	5.0
G1	FX24-4	Foxtail millet without husk	59.92	3.2	21.8	-8.9	5.1
G1	FX24-5	Foxtail millet without husk	59.23	3.31	20.9	-8.8	5.3
G1	FX24-6	Foxtail millet without husk	61.73	3.61	19.9	-8.8	5.9
F1	FX22-1	Foxtail millet with husk	58.85	3.46	19.8	-9.3	4.7
F1	FX22-2	Foxtail millet with husk	60.97	3.42	20.8	-9.2	4.6
F1	FX18-1	Foxtail millet with husk	61.53	3.36	21.4	-9.3	5.4
F1	FX18-2	Foxtail millet with husk	62.85	3.39	21.6	-9.2	5.4

**Fig. 4 |** Scatter plot of isotopic data from humans, animals, and plants at Sharitala.

The C/N molar ratios were within the range of 2.9–3.6^{48,49}, so the samples could be regarded as uncontaminated. Although the C content of sample S7 was slightly higher than the standard value, it had a normal C/N molar ratio, so it was viewed as standard data and was not excluded. The remaining samples met the standard and could be used for subsequent stable carbon and nitrogen isotope analysis.

Data from the long bones and pelvic bones are used in the discussion that follows. The $\delta^{13}\text{C}$ values of humans ranged from -8.7‰ to -6.2‰ with a mean value of $-7.1 \pm 1.0\text{‰}$ [-8.4, -5.8] ($n = 5$). The $\delta^{15}\text{N}$ values of humans ranged from 6.9‰ to 10.1‰ with a mean value of $8.9 \pm 1.1\text{‰}$ [7.3, 10.5] ($n = 5$). The distribution of $\delta^{15}\text{N}$ in bone collagen varied, with a range of 3.2‰ between the minimum and maximum values.

The carbon and nitrogen isotope values for pig were -8.1‰ ($\delta^{13}\text{C}$, $n = 1$) and 7.2‰ ($\delta^{15}\text{N}$, $n = 1$), respectively. The carbon and nitrogen isotope values for the dog were -8.2‰ ($\delta^{13}\text{C}$, $n = 1$) and 7.9‰ ($\delta^{15}\text{N}$, $n = 1$), respectively. The carbon and nitrogen isotope values for cattle were -14.4‰ ($\delta^{13}\text{C}$, $n = 1$) and 7.0‰ ($\delta^{15}\text{N}$, $n = 1$). The carbon and nitrogen isotope values for sheep/goat were -15.6‰ ($\delta^{13}\text{C}$, $n = 1$) and 6.0‰ ($\delta^{15}\text{N}$, $n = 1$).

Discussion

The stable carbon and nitrogen isotope values of human bones provide insights into the dietary patterns of occupants⁵⁰. The mean value of $\delta^{13}\text{C}$ of humans in Sharitala is $-7.1 \pm 1.0\text{‰}$ [-8.4, -5.8] ($n = 5$), which indicates that humans mainly consumed C_4 food (including C_4 plants and C_4 plant-dominated animals) during their lifetime. Since the Neolithic period, foxtail millet and common millet of C_4 were the main crops consumed by humans in this area^{31,51}, and the plant seeds excavated at the Sharitala site were

mainly foxtail millet and common millet, it is reasonable to conclude that humans of Sharitala should have used millet or millet-fed animals as their staple food.

In previous studies, human $\delta^{15}\text{N}$ values have been widely used to infer the consumption levels of animal protein during an individual's lifetime⁵². However, recent research suggests that the proportion of animal protein in prehistoric human diets may have been overestimated⁵³. Since the Neolithic period, inhabitants of northern China began applying organic fertilizers to foxtail millet and common millet, a practice that has been shown to elevate the $\delta^{15}\text{N}$ values of these staple grains⁵⁴. The average $\delta^{15}\text{N}$ value of occupants from the Sharitala site is $8.9 \pm 1.1\text{‰}$ [7.3, 10.5], indicating that plant-based resources played a significant role in their diet. Therefore, when analyzing the nitrogen stable isotope composition in human bone collagen, it is essential to account for the isotopic contribution of foxtail millet, which has a mean $\delta^{15}\text{N}$ value of $4.8 \pm 0.4\text{‰}$ [4.5, 5.1]. Assuming a trophic level enrichment factor of approximately 4‰⁴⁴, the expected $\delta^{15}\text{N}$ values for occupants consuming only foxtail millet would fall within the range of 8.5‰ to 9.1‰. However, some occupants from the Sharitala site exhibit $\delta^{15}\text{N}$ values above this interval, suggesting that their diet included millet as a staple and a notable amount of animal protein.

Considering the bones of pigs, cattle, and sheep/goats excavated from the site, it was plausible that the sources of animal protein in Sharitala occupants may have been pigs, cattle, and sheep/goats. The $\delta^{15}\text{N}$ values of humans in this study showed no clustering of data, and the difference between the lowest and highest values exceeded 3‰, which is the minimum enrichment typically associated with a single trophic level. This suggests considerable variation in animal protein consumption within the group. The presence of different sizes of burials and jade artifacts⁵⁵, implies that social stratification was already evident in the Sharitala community at that time and that the uneven distribution of meat resources may be closely associated with this hierarchical structure.

The $\delta^{13}\text{C}$ values of pig and dog from the Sharitala site were close to humans, suggesting that C_4 food constituted a significant portion of their diets. The $\delta^{15}\text{N}$ values of dogs are similar to those of humans, indicating comparable levels of protein consumption between the two. Dogs were closely related to humans, and humans provided food scraps for dogs⁵⁶; thus, dogs at the Sharitala site may have consumed human food leftovers.

The $\delta^{13}\text{C}$ value of -18.0‰ is used as a criterion for distinguishing between C_3 and C_3/C_4 mixed feeding⁵⁷. The wild vegetation in southern-central Inner Mongolia is dominated by C_3 plants⁵⁸, and the dietary structure of completely free-ranging herbivores should theoretically show a bias toward C_3 characteristics. Grazing on C_3 plants supplemented by some foddering with C_4 (millet) is indicated in the $\delta^{13}\text{C}$ values. The dietary structure of cattle and sheep/goat suggested that occupants used grazing as the mainstay of their diet, supplemented by foddering.

Houses, burials, ash ditches, and a platform were found at the Sharitala site, indicating that occupants had a relatively stable settled life⁵⁵. Agricultural tools and a large number of daily-use pottery were found, suggesting

Table 4 | $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of humans and animals measured at the Sharitala site

Location	Gender	Age	Lab number	Sample type	C (%)	N (%)	C:N	$\delta^{13}\text{C}$ (‰)	$\delta^{15}\text{N}$ (‰)
2023M1	Male	18–23	S1	Ribs	44.67	15.76	3.3	−6.4	7.6
			S2	long bones	39.49	13.88	3.3	−6.5	6.9
2023M2	Female	28–36	S3	Ribs	42.07	14.90	3.3	−7.0	8.7
			S4	long bones	15.52	5.54	3.3	−7.6	8.5
2023M5	Unknown	Child	S5	Ribs	-	-	-	-	-
			S6	long bones	43.38	15.49	3.3	−6.4	9.4
2023M3	Female	Middle and old age	S7	long bones	47.16	16.69	3.3	−6.2	9.6
			S8	Ribs	40.85	14.29	3.3	−6.2	9.4
2023M4	Male	18–23	S9	Ribs	46.29	16.02	3.4	−9.5	10.3
			S10	Pelvis	42.49	14.91	3.3	−8.7	10.1
23YSG2	-	-	S11	Dog	34.74	12.28	3.3	−8.2	7.9
			S12	Pig	41.12	14.61	3.3	−8.1	7.2
			S13	Sheep	45.54	16.03	3.3	−15.6	6.0
			S14	Cattle	46.80	16.32	3.3	−14.4	7.0
			S15	Cattle	-	-	-	-	-

that agricultural production existed at the site around 4000BP. As illustrated in Fig. 1d, e, the terrain surrounding the Sharitala site is predominantly flat, thereby offering favorable conditions for agricultural activities.

The density of charred seeds from the Sharitala site was approximately 2 grains/L, which was relatively low compared with that of the surrounding sites⁵⁹, and the diversity of plant species was limited. The low density may indicate that the area where the flotation unit is located is at an advanced stage of crop processing. The plant seeds were mostly foxtail millet and common millet, and Sharitala occupants used the C₄ type of millet as their staple food. The probability, density, and absolute quantity of foxtail millet were greater than those of common millet, and occupants utilized foxtail millet more than common millet.

A large number of husked millet were recovered from the site, posing interesting questions about the use of hulled foxtail millet. This study analyzed the stable carbon and nitrogen isotopes of both foxtail millet with husk and foxtail millet without husk to compare their differences and explore the reasons for the prevalence of foxtail millet with husk at the site. The $\delta^{15}\text{N}$ values of foxtail millet with [4.3, 5.7] and without husk [4.6, 5.6] are very close. The $\delta^{13}\text{C}$ value difference between foxtail millet with husk and foxtail millet without husk is 0.44‰. This relatively minor difference may be attributed to the compositional distinctions between the husk and the seed tissues⁶⁰. Therefore, stable carbon and nitrogen isotope analysis did not provide a satisfying answer to this question.

The content of charcoal chips and the morphology of the foxtail millet provide ideas for understanding the large amount of foxtail millet with husk excavated at the site. If the Sharitala community used wood fuel, the charcoal debris on the hearth would be abundant¹⁴. The charcoal content of the hearth was lower (1.6 g, 28.1%) than that of the other units at Sharitala. Approximately 90% of the foxtail millet with husk at the site was found mainly in the hearth. The contents of foxtail millet flow out after being subjected to rapid heat, forming tar that causes the seeds to stick and clump together⁶¹. Foxtail millet with husk exhibiting a high degree of charring and clumping was discovered at Sharitala, indicative of exposure to relatively high temperatures. At the Taosi site, pottery kilns utilized crop by-products as fuel⁶². Similarly, the Sharitala community likely used crop by-products such as threshing straws and husks as fuel. The charring of foxtail millet remaining on these straws has been preserved to the present day. Pollen analysis of the study area at approximately 4000 BP revealed a predominance of herbaceous pollen over woody pollen⁶³, suggesting that tall trees were scarce in the vicinity of the Sharitala site at that time. Therefore, it was plausible that occupants relied on crop by-products for fuel.

In the northern regions of China, the fertilization behavior can be traced back to the middle to late Neolithic period⁵⁴. Fertilizer application has the potential to influence both soil and crop $\delta^{15}\text{N}$ values⁶⁴. The $\delta^{15}\text{N}$ values of the carbonized, corrected charred foxtail millet from Sharitala ranged from 4.3‰ to 5.6‰, which were higher than the $\delta^{15}\text{N}$ baseline of the wild vegetation. The average values of millets suggest fertilizers were likely used during cultivation. It should be noted that due to the small sample size, the effectiveness of the statistical analysis is limited.

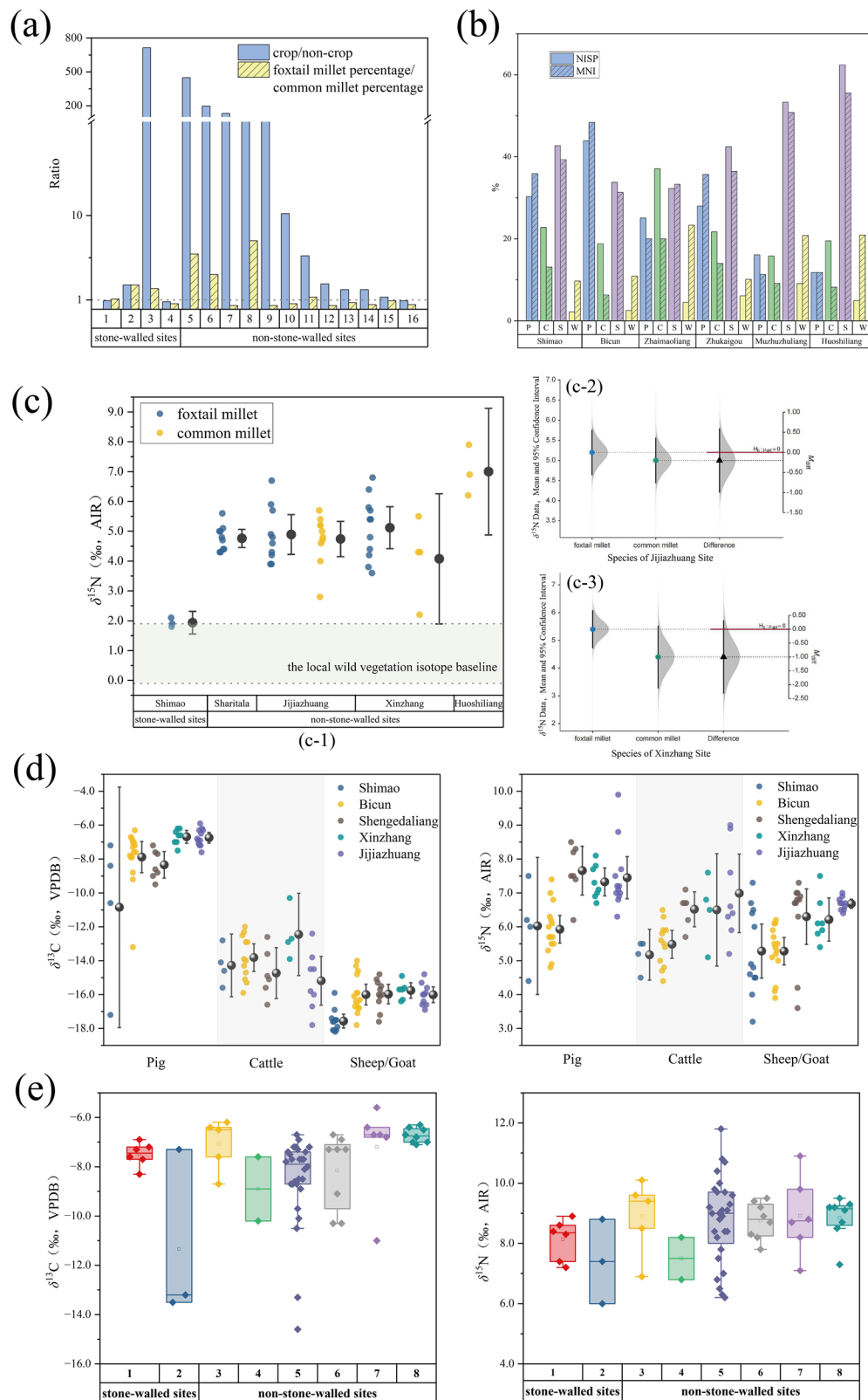
The $\delta^{15}\text{N}$ values of the carbonized foxtail millet from Sharitala are greater than those of the unfertilized foxtail millet grains from the Lintong planting experiment (2.9‰ to 3.7‰)⁶⁵. This suggests that the millet excavated from the Sharitala site may have been treated with fertilizers during the planting period. Fertilizing with sheep/goat manure for one year increased the $\delta^{15}\text{N}$ values of foxtail millet by 0.8‰⁶⁶. Thus, it is plausible that the Sharitala occupants fertilized their farmland for many years. The presence of cattle and sheep/goat at the site would have facilitated this practice.

Furthermore, the nitrogen stable isotope values of cattle and sheep/goat might have been influenced by the indirect effect of foxtail millet and common millet fertilization. Similarly, the nitrogen stable isotope values of the people who consumed these animals and millet would also be affected by the same factors.

In summary, during the 4000 BP period, the Sharitala community was engaged mainly in millet agriculture, complemented by animal husbandry involving pigs, cattle, and sheep/goats. The discovery of fishing and hunting tools at the site suggests that occupants likely participated in fishing and hunting activities to supplement their diet. Occupants had a certain level of farmland management and fertilized cultivated land. The utilization of plant resources was relatively limited, focusing on foxtail millet rather than common millet, and crop byproducts were used as fuel. Livestock management incorporated both free-range and confined breeding practices for cattle and sheep/goats.

To assess the relationship between social complexity and agricultural strategies in the surrounding loess-desert transition zone at 4000 BP, we integrated our data from Sharitala with previously published isotopic and archaeobotanical /archaeozoological data from 15 additional sites. We employed the presence or absence of stone walls as a proxy for social complexity. The stone-walled sites include Shimao, Bicu, Zhaimao, Zhaimaoliang, etc (see Supplementary Material Table 1 for details).

By 4000 BP, social complexity within this region had intensified, leading to the formation of a multi-level settlement system. Within this hierarchy, stone-walled sites functioned as central settlements relative to



nearby regional sites. Archaeologically, the scale and grade of these stone-walled sites were demonstrably higher than those of non-stone-walled sites, reflecting their greater social complexity⁶⁷. The substantial labor and material resources required for stone wall construction indicate both the high cost of these structures and the special status held by these walled sites.

This hierarchical differentiation between sites may have influenced occupants' choices in agricultural strategy. For example, at 2400 BP, the diversity of botanical remains was greater at high-status sites than at non-stone-walled sites in the Ali region of Tibet. Occupants at large sites had a more flexible agricultural strategy⁶⁸. At 2500 BC, higher-ranked sites in southeastern Shandong demonstrated a preference for C₃ crops than non-

Fig. 5 | Data graph of carbon and nitrogen stable isotopes of plants, animals, and human bones, as well as animal and plant remains from the 4200BP site in the desert loess transition zone. **a** Plant remains excavated from sites in the loess-desert transition zone: 1. Shimao 2. Bicun 3. Zhaimao 4. Zhaimaoliang 5. Hengshan 6. Sharitala 7. Dakou 8. Yadi 9. Zhukaigou 10. Shangyuan 11. Shangshen 12. Shengedaliang 13. Jijiazhuang 14. Muzhuzhuliang 15. Xinzhang 16. Huoshiliang (see Supplementary Material Table 3 for details). **b** Percentage of animal remains in the loess-desert transition zone area: P: Pig, C: Cattle, S: Sheep/goat, W: Wild animals (see Supplementary Material Table 5 for details). **c** Isotopic data from millet at sites in the loess-desert transition zone (see Supplementary Material Table 4 for details).

c-1 The scattered points represent the $\delta^{15}\text{N}$ values of the plants, and the upper and lower edges of the black box plot indicate the boundaries of the 95% confidence interval range of the data, and black points are the mean value. **c-2, c-3** Error bars represent 95% confidence intervals. **d** Box-plot of isotopic data from animals at sites in the loess-desert transition zone (see Supplementary Material Table 4 for details). The upper and lower edges of the black box plot indicate the boundaries of the 95% confidence interval range of the data, and black points are the mean value. **e** Box-plot of isotopic data from humans at sites in the loess-desert transition zone: 1. Shimao 2. Bicun 3. Sharitala 4. Dakou 5. Shengedaliang 6. Muzhuzhuliang 7. Jijiazhuang 8. Xinzhang (see Supplementary Material Table 4 for details).

stone-walled sites did⁶⁹. Similarly, late prehistoric societies in Ohio consumed more maize and had a greater number of kernels per cob than general settlements by AD 1000¹⁰.

From the point of view of the composition of crops unearthed, the stone-walled sites Shimao site unearthed foxtail millet, common millet, rice, soybeans, and other varieties of plants. The Bicun site also yielded rice remains, and the crop composition is relatively diverse, whereas the other sites contained only two millet varieties, resulting in a relatively limited diversity of crops⁷⁰. Rice may have been used for brewing⁷¹, which explains its presence primarily at stone-walled sites. Given that the region's environmental conditions are not conducive to rice cultivation, the quantity of rice remains excavated is very low. The study area is in a semiarid region^{72,73}. Foxtail millet and common millet are suitable for growth in arid environments because of their high water-use efficiency⁷⁴. Foxtail millet and common millet have a long history of cultivation in northern China⁷⁵, leading to a preference for millet cultivation in this area.

In 4200BP, the occupants' preference for millet can be observed in absolute numbers and weight percentages. Across all archaeological sites examined, the quantity of foxtail millet consistently exceeded that of common millet. Considering the different millet yields, comparisons were made after adjusting the weights of the millet seeds³⁶. The weight percentages of foxtail millet and common millet at the Shimao, Bicun, Zhaimao, Hengshan, Sharitala, Yadi, and Shangshen sites were greater than 1, indicating that the total production of foxtail millet at these sites likely surpassed that of common millet. Overall, inhabitants of the stone-walled settlements demonstrated a greater utilization of foxtail millet compared to common millet.

Factors such as the water and temperature required for crop growth, ease of cultivation, and yield of the crop would have influenced the choice of crops by occupants. Studies indicate that foxtail millet exhibits lower drought resistance and water use efficiency compared to common millet⁷⁶. Its growing period is longer than that of common millet⁷⁷, and its planting conditions are more complex²⁰. Consequently, cultivating foxtail millet requires significant labor and material resources. In contrast, inhabitants at non-stone-walled sites favored the more easily cultivated common millet.

Under optimal water and fertilizer conditions, the productivity of common millet is lower than that of foxtail millet⁷⁸, and the yield of foxtail millet can be twice as high as that of common millet⁷⁹. Shimao, Bicun, and Zhaimao, the stone-walled sites, featured extensive settlement areas and substantial populations. Within these settlements, there was a division of labor⁸⁰, allowing a dedicated group to focus on agricultural cultivation and crop management⁸¹. Owing to their substantial population sizes, these sites required a larger food supply, leading them to prioritize higher-yielding crops such as foxtail millet. The non-stone-walled site, Sharitala, has yielded a relatively large number of jade artifacts⁵⁵, suggesting that this site was relatively high status and that occupants utilized foxtail millet more than common millet did.

At the Miaoliang Site, located in the desert loess transition zone, the weight percentage of foxtail millet and common millet recovered from the site at 5000 BP (0.7%) was significantly lower than that recovered at 4500 BP (10.6%)^{18,82}. This suggests that foxtail millet may have gradually gained importance in the daily lives of the occupants of Miaoliang Site. Additionally, the Guanzhong and Central Plains regions demonstrated a gradual upward trend in the percentage of foxtail millet weight⁸³. Consequently, the

relatively high importance of foxtail millet in the stone-walled settlements and the Sharitala site might, to some extent, have been influenced by neighboring regions.

The $\delta^{15}\text{N}$ values of millet samples excavated from the Shimao, Sharitala, Jijiazhuang, Xinzhang, and Huoshiliang sites were greater than those of the local wild vegetation isotope baseline. These findings suggest that these crops were fertilized to some extent during cultivation.

First, we examined the soil fertility of stone-walled sites. The lowest $\delta^{15}\text{N}$ values were observed at the Shimao site (Fig. 5c), indicating relatively poor soil fertility in the cultivation areas. Despite the substantial amount of meat resources available at the stone-walled sites of Shimao and Bicun⁸⁴, the $\delta^{15}\text{N}$ values for humans and animals at these sites were lower than those at non-stone-walled sites (Fig. 5c, d). This discrepancy may be attributed to the lower $\delta^{15}\text{N}$ values of the millet cultivated at these sites, suggesting relatively poorer soil fertility during millet cultivation.

Continuous cultivation of cereal crops leads to a significant decrease in the soil nitrogen content⁸⁵. Long-term crop succession and increased aridity have resulted in a gradual decline in soil fertility in Mesopotamia over thousands of years⁸⁶. The $\delta^{15}\text{N}$ values of charred plants at sites surrounding the Shimao site have gradually declined²¹, which may also be attributed to prolonged crop succession. The manpower and material resources required for field management are extremely large. However, such stone-walled sites as Shimao and Bicun are unlikely to lack resources for fertilization and farming. Therefore, we considered the impact of continuous cropping on agricultural practices at these sites. The cultural layer thickness at Shimao ranges from 108 to 168 cm⁸⁷, suggesting prolonged human occupation. The large size of the settlements and the substantial populations at Shimao and Bicun likely led to over-exploitation of the land and degradation of soil fertility.

The cultural layer at the Huoshiliang site measures approximately 0.5 m in thickness, and excavators believe that it represents a seasonal camp²⁰. The high $\delta^{15}\text{N}$ value of the charred common millet excavated from the Huoshiliang site may be associated with this seasonal occupation pattern. The $\delta^{15}\text{N}$ values of millet from the Sharitala, Xinzhang, and Jijiazhuang sites were similar (Fig. 5c). Additionally, the $\delta^{15}\text{N}$ values of millet samples from the Sharitala, Xinzhang, and Jijiazhuang sites were similar (Fig. 5c), indicating comparable levels of soil fertility and human fertilizer input across these locations.

The variability in crop $\delta^{15}\text{N}$ values at the same site can be an approximate indicator of centralized crop management during cultivation. Under identical planting conditions, the $\delta^{15}\text{N}$ values of foxtail millet tend to be relatively consistent, while common millet shows greater variability, with differences of less than 3%⁶⁵. Isotope samples from the Jijiazhuang, Xinzhang, and Huoshiliang sites were collected from different ash pits and ditches^{21,22}, suggesting that these samples may originate from different household waste products. The relatively dispersed distribution of $\delta^{15}\text{N}$ values for millet at these three sites indicates nonuniform fertilization practices, implying that individual households likely managed small plots of arable land.

The isotopic samples of charred foxtail millet from the Shimao site were collected from different units²¹. The relatively concentrated distribution of their $\delta^{15}\text{N}$ values suggests that the foxtail millet was cultivated under consistent field management practices. The $\delta^{15}\text{N}$ values of foxtail millet

Table 5 | A table presenting Chenopodiaceae seed remains from the site in the desert-loess transition zone at 4200 BP

Site	Chenopodiaceae (n)	Chenopodiaceae: Foxtail millet	Chenopodiaceae: Total
Shimao	7535	0.90	0.32
Zhaimao	0	0.00	0.00
Zhaimaoliang	2758	1.83	0.50
Bicun	243	0.08	0.05
Shengedaliang	63	0.27	0.11
Muzhuzhuliang	1044	0.24	0.10
Huoshiliang	79	1.08	0.27
Dakou	0	0.00	0.00
Zhukaigou	5	0.01	0.01
Hengshan	0	0.00	0.00
Yadi	10	0.02	0.02
Shangyuan	5	0.01	0.01
Shangshen	1	0.01	0.01
Jijiazhuang	938	0.31	0.14
Xinzhang	276	0.10	0.04

excavated from the Sharitala site indicate more uniform fertilizer management, possibly due to the higher status or organization level of the Sharitala site. At the Jijiazhuang site⁸⁸ and the Xinzhang site⁸⁹, immature foxtail millet was excavated, reflecting a lower level of farmland management. This finding suggests that, at some non-stone-walled sites, crop cultivation was not centrally managed, resulting in relatively low levels of agricultural management.

Subsequently, we discussed the different labor inputs used for millet cultivation. The weight percentages of foxtail millet and common millet excavated from Jijiazhuang (0.7) and Xinzhang (0.9) were lower than 1 (Fig. 5a), suggesting that occupants at these sites probably cultivated more common millet than foxtail millet. The $\delta^{15}\text{N}$ values of common millet are greater than those of foxtail millet under identical fertilization conditions by over 2‰⁶⁵. In terms of crop nitrogen stable isotopes, the mean $\delta^{15}\text{N}$ values of foxtail millet excavated from the Jijiazhuang site and the Xinzhang site ($4.9 \pm 0.8\text{‰}$, $n = 10$; $5.1 \pm 1.0\text{‰}$, $n = 11$) were greater than those of common millet ($4.7 \pm 0.8\text{‰}$, $n = 10$; $4.1 \pm 1.4\text{‰}$, $n = 4$). At the Jijiazhuang Site, the calculated difference between common millet and foxtail millet is 95% CI $[-1.0, 0.6]$. At the Xinzhang Site, the difference is 95% CI $[-2.4, 0.4]$. This finding indicated that fertilizer management for foxtail millet at these two sites was more intensive than that for common millet. Although occupants made more use of common millet than foxtail millet, they invested more resources in foxtail millet in terms of fertilization. This may be attributed to the high-yield potential of foxtail millet and the high requirements of foxtail millet cultivation.

Baseline $\delta^{15}\text{N}$ values can vary between regions. This study assumes a uniform isotope baseline for all sites, a simplification that may lead to some inaccuracies. However, cross-site comparisons are still essential to identify patterns in isotope data and understand the environmental and human factors behind them. Future research should focus on developing more precise, site-specific nitrogen isotope baselines to improve interpretation accuracy.

The combination of climate change and population growth significantly influences the development of agricultural strategies. At approximately 4000 BP, the loess-desert transition zone experienced a clear trend of drying and cooling, marked by a significant decline in annual precipitation^{63,90,91}. A reduction in the average annual temperature of 1 °C resulted in a decrease in grain yield of approximately 10% per mu⁹² (Mu is a traditional Chinese unit of land area, 1 ha = 15 mu), indicating that temperature fluctuations likely played a critical role in diminished grain production during this period.

A study of human remains from the Wuzhuangguoliang site in the desert-loess transition zone at 4500 BP revealed that the dental enamel of

these individuals exhibited periodic developmental defects⁹³. These defects are likely indicative of seasonal malnutrition caused by the one-crop-per-year farming system. Such seasonal malnutrition may reflect periodic shortages in food supply. By around 4200 BP, the region experienced an increase in sociocultural complexity, as evidenced by a rise in both the number and spatial extent of archaeological sites, suggesting a growing population⁹⁴. However, agricultural technology developed at a relatively slow pace. From 4500 BP to 4200 BP, the region remained predominantly reliant on a single annual millet-based cropping system. Consequently, the increased population at 4200 BP may have exacerbated pre-existing food shortages, potentially leading to even more severe nutritional stress than in earlier periods. The large population of the region⁹⁵, the high demand for millet by humans and animals (Fig. 5d, e), a drier and colder climate, and poorer soil conditions put more significant food pressure.

Agricultural intensification at different sites, including increased labor and resource inputs into the land and crop yields per unit of land area, was necessary to address the region's relatively infertile natural environment and high food demand. Inhabitants at the stone-walled sites invested more labor in centralized crop management, likely applied fertilizers, and prioritized the cultivation of the more productive foxtail millet. In contrast, at the non-stone-walled sites, the soil fertility levels were relatively uniform. While inhabitants still applied fertilizers to enhance soil productivity, resources were allocated more heavily towards foxtail millet compared to common millet. The fertilization and centralized management of agricultural land reflected the advancement of the region's agricultural economy, enabling societies to support larger populations and thereby contributing to societal expansion. The development of agricultural production and increased labor inputs into the land have accelerated the process of land privatization and intensified the region's social complexity.

Nevertheless, agricultural production technology was insufficient to alleviate food pressure in the loess-desert transition zone. Over-exploitation of the land led to a decline in soil fertility at stone-walled sites, contributing to reduced millet yields. At non-stone-walled sites, the level of field fertilization for millet was inconsistent, possibly due to inadequate labor and fertilizer resources for centralized crop management. The privatization of arable land further exacerbated inconsistencies in field management. Collectively, constrained agricultural technologies, declining soil fertility, and limited crop productivity likely contributed to varying degrees of food pressure across multiple settlements.

Occupants adopted additional measures to cope with food pressure. Firstly, the utilization of Chenopodiaceae plants helped alleviate food

shortages to some extent. The growing season of millet crops is short, and the time for planting is limited⁷⁷; therefore, planting only millet crops is not a safe choice. As shown in Table 5, at the Zhaimaoliang¹⁴, Shimao⁵⁹, and Jijiazhuang⁸⁸ sites, significant quantities of concentrated Chenopodiaceae seeds were discovered, which may have been intentionally selected and cultivated. Most Chenopodiaceae species can be utilized as vegetables or crops, although they are generally less palatable. These plants can serve as an alternative to millet during shortages of agricultural produce⁹⁶. The cultivation and storage of Chenopodiaceae by various social groups have mitigated the risk of crop failure.

The introduction of cattle and sheep/goat was also a good option for occupants to cope with pressure. Approximately 4000 BP, the loess-desert transition zone experienced a second wave of *Bos Taurus* introductions⁹⁷. The environment in the region at approximately 4000 BP was typical grassland vegetation dominated by *Artemisia*/Chenopodiaceae⁶³, which was favorable for cattle and sheep/goat husbandry. Archaeological evidence from this region includes a significant number of animal bones and bone tools, with cattle and sheep/goat remains accounting for more than 50% of all animal remains (Fig. 5b; Supplementary Material Table 5). Cattle and sheep/goat husbandry emerged as crucial pillars of the local economy^{27,98}, leading to the establishment of a new economic model that replaced the previous reliance on pure millet agriculture.

Cattle and sheep/goats utilize mainly wild resources. The mixed C₃/C₄ diet of these animals reflected the combination of captive and grazing (Fig. 5d), which consumed less arable land and enhanced human utilization of wild resources. The integration of millet agriculture and animal husbandry constituted a relatively stable economic model, supporting the sustained operation of social systems.

Studies conducted in the eastern Tianshan of Xinjiang indicate that approximately 3000 years ago, there was a decline in soil fertility and reduced fertilizer application; at the same time, human communities became more dependent on nomadic practices⁹⁹. This shift in subsistence strategy closely parallels the transformation observed in the loess-desert transition zone around 4200 years ago, where diminishing agricultural productivity similarly prompted early inhabitants to place greater emphasis on animal husbandry.

Overall, the relatively infertile soils of the loess-desert transition zone, the progressively cooler and drier climate at 4000 BP, and increasing population may have contributed to increased food supply pressure. In response, the inhabitants of the region adopted various strategies to mitigate these challenges.

First, specific agricultural strategies, including crop selection, labor inputs, and fertilizer inputs, were used. Enhanced field management through increased agricultural intervention aimed at increasing crop yields. These practices served as a social risk-buffering strategy, contributing to livelihood sustainability and social stability. The differences in agricultural strategies between stone-walled sites and non-stone-walled sites reflect the complexity of agricultural development during this period, which may have been influenced by environmental factors and limited social resources. The intensification of agricultural production and increased labor input likely accelerated the process of land privatization and deepened the region's social complexity. The significance of millet increased over time, likely influenced by nearby regions.

In addition to adjusting their agricultural strategies, the inhabitants responded to food pressure by incorporating Chenopodiaceae into their diet and introducing livestock such as cattle and sheep/goats. This diversification of food sources facilitated a shift in the economic model from pure millet agriculture to one where millet agriculture remained the mainstay, supplemented by animal husbandry.

Data availability

Data is provided within the manuscript or supplementary information files.

Received: 9 June 2025; Accepted: 29 September 2025;

Published online: 09 October 2025

References

- Zheng, J. & Chen, C. A Comparative Study of Prehistoric Social Complexity between the Circum-Taihu Lake and the Ningshao Plain. *Cultural Relics South. China* **17**, 19–27 (2005).
- Xu, F. 'Complexification' and 'Sinicization': reflections on two concepts in the study of regional social processes. *Cultural Relics Cent. China* **48**, 62–68 (2024).
- Rothman, M. S. Studying the Development of Complex Society: Mesopotamia in the Late Fifth and Fourth Millennia BC. *J. Archaeol. Res.* **12**, 75–119 (2004).
- Cao, H. Wind-water composite erosion camping forces and geomorphologic patterns in the desert-loess transition zone. *M.S. Dissertation*. (Beijing Normal University; Beijing, 2010).
- Sun, J., Ding, Z. & Liu, T. Environmental evolution of the desert-loess transitional zone over the last 0.5Ma. *Arid Land Geogr.* **18**, 1–9 (1995).
- Sun, Z. An examination of the process of social complexity in the northern regions during the third millennium B.C.E.-centered on archaeological data from the Yulin region. *Archaeol. Cultural Relics* **37**, 70–79 (2016).
- Sun, Z., Shao, J. & Di, N. Definition, distribution, and chronology of the Shimao culture. *Archaeology* **66**, 101–104 (2020).
- Pei, X. Research on the settlement pattern of the Shimao culture. *Archaeology* **69**, 109–120 (2023).
- Yuan, J. The Relationship between Subsistence and the Development of Early Chinese Civilization in the Central Plains. *West. Archaeol.* **11**, 1–12 (2016).
- Schurr, M. R. & Schoeninger, M. J. Associations between Agricultural Intensification and Social Complexity: An Example from the Prehistoric Ohio Valley. *J. Anthropol. Archaeol.* **1**, 315–399 (1995).
- Dai, X. Culture and Society in the Loess Region of the Longshan Period from the Two Great Changes in Taosi. *A Collect. Stud. Archaeol.* **31**, 281–304 (2022).
- Atahan, P. et al. Temporal trends in millet consumption in northern China. *J. Archaeol. Sci.* **50**, 171–177 (2014).
- Chen, X., Guo, X., Hu, Y., Wang, W. & Wang, C. Analysis of the subsistence practice at the Muzhuzhuliang Site in Shenmu, Shaanxi. *Archaeol. Cultural Relics* **36**, 112–117 (2015).
- Gao, S., Sun, Z., Shao, J., Wei, X. & Zhao, Z. Flotation results and analysis of the Zhaimaoliang site, Yulin, Shaanxi, China. *Agric. Archaeol.* **36**, 14–19 (2016).
- Chen, X. et al. The subsistence patterns of the Shengedaliang site (~4,000 yr BP) revealed by stable carbon and nitrogen isotopes in northern Shaanxi, China. *Sci. Sin.(Terra.)* **47**, 95–103 (2017).
- Guo, X. Late Longshan period livelihoods in northern Shaanxi-The botanical and faunal remains of the Muzhuzhuliang and Shengedaliang sites as examples. *Agric. Archaeol.* **37**, 5 (2017).
- Bao, Y. et al. Evolution of prehistoric dryland agriculture in the arid and semi-arid transition zone in northern China. *PloS one* **13**, e0198750 (2018).
- Bao, Y. et al. Evolution and bioenvironmental adaptation of Neolithic and Bronze age agriculture in the North Chinese Loess Plateau. *Acta Anthropol. Sin.* **39**, 12 (2020).
- Hou, L. et al. The subsistence patterns of Xinding Basin, Shanxi, China during ~ 4000 yr BP by stable isotopes and plant microfossils analysis. *Sci. Sin.(Terra.)* **50**, 369–379 (2020).
- Sheng, P., Shang, X. & Zhang, P. Crop Choice in the Yulin Area Between the Late Longshan and Early Xia Periods. *Archaeol. Cultural Relics* **41**, 114–121 (2020).
- Sheng, P. et al. Feeding Shimao: Archaeobotanical and Isotopic Investigation into Early Urbanism (4200–3000 BP) on the Northern Loess Plateau, China. *Environ. Archaeol.* **29**, 425–439 (2021).
- Li, Y. Research on farmland management technology in the late longshan period in north region of Shanxi province: a case study of Jijiazhuang Site in Datong and Xinzhang Site in Yuanping. *M.A. Dissertation*. (Shanxi University; Taiyuan, 2023).

23. Gong, Y. The subsistence economy in Datong Basin during c. 4000a BP: Evidence from stable isotopes. *M.A. Dissertation* (Shanxi University; Taiyuan, 2023).
24. Jiang, Y. & Wang, X. Flotation results and analysis of Xiaoyuliang terrace at Bicun Site, Xingxian county, Shanxi. *J. Chin. Antiquity* **38**, 115–123 (2024).
25. Li, H. et al. Spatiotemporal variation of agricultural patterns in different geomorphologic and climatic environments in the eastern Loess Plateau, north-central China during the late Neolithic and Bronze Ages. *Sci. China:Earth Sci.* **65**, 934–948 (2022).
26. Hou, L., Yang, L., Wang, B., Jia, Y. & Zhang, G. The subsistence economy on the northwest edge of the Loess Plateau during c. 4000 a BP: Evidence from stable isotopes. *J. Archaeol. Sci. Rep.* **45**, 103616 (2022).
27. Han, M. Vicissitude of the Shimao Culture from the perspective of man-nature relationship. *Historical Res.* **70**, 50–69 (2023).
28. Zhang, J. Neolithic primitive economic types in south-central Inner Mongolia. *Steppe Cultural Relics* **000**, 60–65 (2005).
29. Chang, L. Preliminary study on the Neolithic livelihoods in central and southern Inner Mongolia from the perspective of production tools. *Agric. Archaeol.* **39**, 28–35 (2019).
30. Huang, Y. Identification and study of the animal bones from the Zhukaigou Site, Inner Mongolia. *Acta Archaeologica Sin.* **61**, 515–536 (1996).
31. Feng, B. A preliminary study of the evolution of the pre-Qin period livelihood pattern in south-central Inner Mongolia. *Cultural Relics South. China* **33**, 98–105 (2021).
32. Dang, Y. Overview on the Cultural Relics and Archaeology Work of Inner Mongolia Autonomous Region in 2023. *Steppe Cultural Relics* **44**, 1–12 (2024).
33. Ramsey, C. B. Bayesian Analysis of Radiocarbon Dates. *Radiocarbon* **51**, 337–360 (2009).
34. Ramsey, C. B. Methods for Summarizing Radiocarbon Datasets. *Radiocarbon* **59**, 1809–1833 (2017).
35. Reimer, P. J. et al. The IntCal20 Northern Hemisphere Radiocarbon Age Calibration Curve (0–55 cal kBP). *Radiocarbon* **62**, 725–757 (2020).
36. Zhou, X., Li, X., John, D. & Zhao, K. Rapid agricultural transformation in the prehistoric Hexi corridor, China. *Quat. Int.* **0**, 33–41 (2016).
37. Vaiglova, P., Snoeck, C., Nitsch, E., Bogaard, A. & Lee-Thorp, J. Impact of contamination and pre-treatment on stable carbon and nitrogen isotopic composition of charred plant remains. *Rapid Commun. Mass Spectrom.* **28**, 2497–2510 (2014).
38. Richards, M. P. & Hedges, R. E. M. Stable isotope evidence for similarities in the types of marine foods used by late mesolithic humans along the Atlantic coast of Europe. *J. Archaeol. Sci.* **717–722**, <https://doi.org/10.1006/jasc.1998.0387> (1999).
39. Brown, T. A. Improved collagen extraction by modified Longin method. *Radiocarbon* **30**, 171–177 (1988).
40. Houlton, B. Z., Sigman, D. M. & Hedin, L. O. Isotopic evidence for large gaseous nitrogen losses from tropical rainforests. *Proc. Natl. Acad. Sci. USA*. **8745–8750**, <https://doi.org/10.1073/pnas.0510185103> (2006).
41. Qu, Y. *Archaeology of China from the Perspective of Stable Isotope Food Spectrum Analysis* (Science Press, 2019).
42. Bogaard, A. et al. Crop manuring and intensive land management by Europe's first farmers. *Proc. Natl. Acad. Sci.* **110**, 12589–12594 (2013).
43. Guan, L. et al. Stable Isotopic analysis on animal bones from the Wuzhuangguoliang Site, Jingbian, Northern Shaanxi. *Quat. Sci.* **51**, 1160–1165 (2008).
44. Hedges, R. E. & Reynard, L. M. Nitrogen isotopes and the trophic level of humans in archaeology. *J. Archaeol. Sci.* **34**, 1240–1251 (2007).
45. Vaiglova, P. How can we improve statistical training in archaeological science?. *J. Archaeological Sci.* **179**, 106220 (2025).
46. Styring, A. K. et al. Recommendations for stable isotope analysis of charred archaeological crop remains. *Front. Environ. Archaeol.* **3**, 1–14 (2024).
47. Nitsch, E. K., Charles, M. & Bogaard, A. Calculating a statistically robust $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ offset for charred cereal and pulse seeds. *Sci. Technol. Archaeol. Res.* **1**, 1–8 (2015).
48. Deniro, M. J. & Hastorf, C. A. Postmortem preservation and alteration of in vivo bone collagen isotope ratios in relation to palaeodietary reconstruction. *Nature* **317**, 806–809 (1985).
49. Ambrose, S. H. Preparation and characterization of bone and tooth collagen for isotopic analysis. *J. Archaeol. Sci.* **17**, 431–451 (1990).
50. Cox, G. & Sealy, J. Investigating Identity and Life Histories: Isotopic Analysis and Historical Documentation of Slave Skeletons Found on the Cape Town Foreshore, South Africa. *Int. J. Hist. Archaeol.* **1**, 207–224 (1997).
51. Sun, Y. & Chang, J. A preliminary study on the means of livelihood from late yangshao period to longshan period in Northern Shaanxi Province. *J. Liaoning Norm. Univ.(Soc. Sci. Ed.)* **41**, 8 (2018).
52. Ambrose, S. H., Butler, B. M., Hanson, D. B., Hunter-Anderson, R. L. & Krueger, H. W. Stable isotopic analysis of human diet in the Marianas archipelago, western Pacific. *Am. J. Phys. Anthropol.* **104**, 343–361 (1997).
53. Kuhnle, G. G. C., Kneale, C. J., O'Connell, T. C. & Tasevska, N. The diet-body offset in human nitrogen isotopic values: a controlled dietary study. *Am. J. Phys. Anthropol.* **149**, 426–434 (2012).
54. Wang, X. et al. Millet manuring as a driving force for the Late Neolithic agricultural expansion of north China. *Sci. Rep.* **8**, 5552 (2018).
55. Gao, X., Yang, J., Li, S. & Zhang, X. Sharitala Site, Yijinholo Banner, Inner Mongolia. *Pop. Archaeol.* **10**, 12–13 (2022).
56. Song, Y. Zooarchaeology Research of Neolithic Period, Haidai Region. *Ph. D. Dissertation* (Shandong University; Jinan, 2012).
57. Ma, M. et al. Dietary shift after 3600 cal yr BP and its influencing factors in northwestern China: Evidence from stable isotopes. *Quat. Sci. Rev.* **145**, 57–70 (2016).
58. Wu, J. Evolution of C3 and C4 plants and their response to climate and CO2 changes on the Loess Plateau since the Last Ice Age. *M.S. Dissertation* (University of Chinese Academy of Sciences; Beijing, 2015).
59. Gao, S. The study on plant remains unearthed at Shimao Site, Shenmu country, northern Shaanxi. *M.A. Dissertation* (Northwest University; Xian, 2018).
60. Yang, Q., Li, X., Liu, W., Zhou, X. & Sun, N. Carbon isotope fractionation during low temperature carbonization of foxtail and common millets. *Org. Geochem* **42**, 713–719 (2012).
61. Yang, Q. et al. Characterization of the sub-microscopic structure of corn and millet seeds during charring and its application to phytoarchaeology. *Chin. Sci. Bull.* **56**, 700–707 (2011).
62. Zhao, Z. & He, N. Taosi City Site 2002 Annual Flotation Results and Analysis. *Archaeology* **52**, 77–86 (2006).
63. Zhang, Y. et al. Pastoralism and millet cultivation during the Bronze Age in the temperate steppe region of northern China. *Front. Earth Sci.* **9**, 748327 (2021).
64. Bogaard, A., Heaton, T. H. E., Poulton, P. & Merbach, I. The impact of manuring on nitrogen isotope ratios in cereals: archaeological implications for reconstruction of diet and crop management practices. *J. Archaeol. Sci.* **34**, 335–343 (2007).
65. Ouyang, H. et al. Experimental archaeological study in China: implications for reconstruction of past manuring and dietary practices indicated by $\delta^{15}\text{N}$ values of *Setaria italica* and *Panicum miliaceum*. *Herit. Sci.* **12**, 1–16 (2024).
66. Wang, X. The perspective of isotope Study on fertilization management in the middle reaches of the Yellow River In Late Neolithic China. *Ph. D. Dissertation* (University of Chinese Academy of Sciences; Beijing, 2018).

67. Chang, L. Prehistoric Stone Cities in North China and Their Civilizational Evolution in the Early Stage. *J. Chin. Nation Stud.* **2**, 132–144 (2023).
68. Tang, L. et al. Prehistoric agricultural decision making in the western Himalayas: ecological and social variables. *Antiquity* **96**, 1214–1231 (2022).
69. Dong, Y. et al. Social and environmental factors influencing dietary choices among Dawenkou culture sites, Late Neolithic China. *Holocene* **31**, 271–284 (2020).
70. Yang, R. et al. Subsistence strategies of early Xia Period: analysis of flotation results from the Shimao Site in Yulin area, Shaanxi province. *Quat. Sci.* **42**, 101–118 (2022).
71. He, Y., Liu, L., Sun, Z., Shao, J. & Di, N. Proposing a toast from the first urban center in the north Loess Plateau, China: Alcoholic beverages at Shimao. *J. Anthropol. Archaeol.* **64**, 101352 (2021).
72. Xu, Q. et al. Discussion on the environment changes and the effects of human impacts in the east ordos plateau since 4000 aB. *P. Quat. Sci.* **45**, 105–112 (2002).
73. Shaanxi Academy of Archaeology & Yulin Institute of Cultural Relics Protection. *Xinhua site in Shenmu* (Science Press, 2005).
74. Guedes, J. D. A. et al. Moving agriculture onto the Tibetan plateau: The archaeobotanical evidence. *Archaeol. Anthropol. Sci.* **6**, 255–269 (2014).
75. An, Z. Prehistoric agriculture in China. *Acta Archaeologica Sin.* **53**, 369–381 (1988).
76. Hu, H., Zhang, R. & Huang, G. *Dryland Agriculture on the Loess Plateau - Theory, Technology, Potentials* (China Agriculture Press 2002).
77. Saseendran, S. A. et al. Modeling responses of dryland spring triticale, proso millet and foxtail millet to initial soil water in the High Plains. *Field Crops Res* **113**, 48–63 (2009).
78. Zhang, X. *Production and development of small mixed grains on the loess plateau* (China Agricultural Science and Technology Press, 2007).
79. Chai, Y. & Feng, B. Present situation and developing strategies of minor grain crops in China. *Agric. Res. Arid Areas* **21**, 145–151 (2003).
80. Li, W. Production, exchange and consumption: bone working at Shimao site—bone needles-based material. *M.A. Dissertation* (Shandong University; Jinan, 2021).
81. Sheng, P. F. et al. North-south patterning of millet agriculture on the Loess Plateau: Late Neolithic adaptations to water stress, NW China. *Holocene* **28**, 1554–1563 (2018).
82. Fu, W. et al. Analysis of flotation results of the Miaoliang site in Jingbian County. *Quat. Sci.* **42**, 119–128 (2022).
83. Jin, D. et al. Agricultural practices during the middle and late Yangshao periods (6000–4500 BP) in the Guanzhong Basin, North China. *J. Archaeol. Sci.: Rep.* **53**, 104345 (2024).
84. Hu, S., Yang, M., Sun, Z. & Shao, J. A study of faunal remains unearthed at Shenmu Shimao Site, Shaanxi, China, 2012–2013. *Archaeol. Cultural Relics* **37**, 109–121 (2016).
85. Yang, X. Effects of continuous cropping on millet growth and rhizosphere soil environment *M.S.A. Dissertation*. (Shanxi Agricultural University; Taiyuan, 2022).
86. Araus, J. L., Ferrio, J. P., Voltas, J., Aguilera, M. & Buxó, R. Agronomic conditions and crop evolution in ancient Near East agriculture. *Nat. Commun.* **5**, 3953 (2014).
87. Wei, S. Shaanxi Shenmu Shimao site investigation and trial excavation newsletter. *Prehistory* **1**, 92–100 (1983).
88. Xiao, Q. Analysis of Carbonized Plant Remains in Jijiazhuang Site, Datong *M.A. Dissertation*. (Shanxi University; Taiyuan, 2022).
89. Zhang, H. Analysis on the plant remains of Xinzhang Site in Yuanping of Shanxi province. *M.A. Dissertation*. (Shanxi University; Taiyuan, 2022).
90. Shi, P. *Theory and practice of research on the evolution of the geographic environment*. (Science Press, 1991).
91. Zhang, G., Zhou, X., Zhao, K., Yang, Q. & Li, X. Climate and environment change of desert/loess transition zone and its impact on prehistoric human activities since 6ka B.P. *Quat. Sci.* **38**, 874–886 (2018).
92. Zhang, J. Possible impacts of climatic variation on agriculture in China. *Geographical Res.* **1**, 8–15 (1982).
93. Chen, L., Zhang, X., Sun, Z. & Yang, L. Human nutrition and health status at the early stage of agriculture in Northern China: A bioarchaeological study of Wuzhuangguoliang site. *Quat. Sci.* **40**, 379–380 (2020).
94. Zhou, H. & Li, Q. The Changes in Prehistoric Human-Environment Relations and the Rise and Fall of Stone-walled Cities in the Northern Shaanxi Plateau. *J. Arid Land Resour. Environ.* **37**, 94–101 (2023).
95. Wang, J. et al. Difference and its palaeoclimate reason of settlement evolution between Yulin area of Shaanxi Province and Luoyang area of Henan Province around 4 ka BP. *J. Palaeogeogr. (Chin. Ed.)* **17**, 841–850 (2015).
96. Zhao, Z. The development of agriculture in the time of Yangshao Culture and the establishment of agricultural society: an analysis on the flotation result of Yuhazhai Site. *Jiangnan Archaeol.* **38**, 98–108 (2017).
97. Yang, Y. The cattle road: from the Volga Valley to the Yellow River Valley. *Agric. Hist. China* **43**, 3–14 (2024).
98. Zhang, C. The regional features of the subsistence economic structure in north China during the early stage after the introduction of crops and domestic animals from the western old world. *Huaxia Archaeol.* **31**, 89–97 (2017).
99. Tian, D. et al. Varying cultivation strategies in eastern Tianshan corresponded to growing pastoral lifeways between 1300 BCE and 300 CE. *Front. Ecol. Evol.* **10**, <https://doi.org/10.3389/fevo.2022.966366> (2022).

Acknowledgements

The authors are grateful to Mr. Jingang Yang from the Institute of Archaeology, Chinese Academy of Social Sciences, for assisting with the identification of seeds. This work was supported by the National Social Science Fund of China [grant number 21BK040]. We thank Mengjie Cui, Dan Jin, Huiyong Ouyang, and Ruixue Li for their guidance and help in sampling and experiments.

Author contributions

Xin Sun: Writing – review & editing, Writing – original draft, Investigation. Xue Shang: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. Gouming Yue: Resources. Qian Li: Resources.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s40494-025-02090-2>.

Correspondence and requests for materials should be addressed to Xue Shang.

Reprints and permissions information is available at <http://www.nature.com/reprints>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2025