Palaeogeography, Palaeoclimatology, Palaeoecology 679 (2025) 113283

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Enhancing sustainability in early millet agriculture: Manuring practices in the Yellow River Valley

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ARTICLE INFO

Editor: Howard Falcon-Lang

Keywords:
Nitrogen stable isotopes
Manuring practices
Early millet farming
Yellow River valley

ABSTRACT

The implementation of various agricultural strategies, including manuring, has long been considered a key factor in supporting the complexity of early societies worldwide. The Yellow River valley in China is recognized as the cradle of millet agriculture and civilization state. However, systematic research on manuring practices within spatiotemporal archaeological contexts in early millet agriculture within this region remains scarce. This paper synthesizes previously published isotopic data from foxtail and broomcorn millet at 33 archaeological sites spanning the late Neolithic to the Bronze Age, aiming to clarify the characteristics of early millet manuring management and its role in the sustainable development of ancient China. Nitrogen isotope results, together with evidence from soil nutrients, livestock husbandry, and archaeobotanical findings, suggest that manuring had been widely adopted in the dryland agriculture of the Yellow River valley since the late Neolithic period. Faced with increasing population pressures and environmental limitations, farmers in the Yellow River valley maintained manuring practices for farmland while expanding cultivated areas, though the intensity exhibited significant spatiotemporal variations. The refinement of agricultural strategies not only promoted the sustainable development and regional expansion of agricultural production but also played a crucial role in shaping the enduring features and trajectory of Chinese civilization.

1. Introduction

The origin and development of agriculture represent a pivotal transformation in human history, marking the shift from a foraging economy to a productive one (Li, 2022; Zhao, 2019). As a key center for agricultural origins, China witnessed the emergence of dryland farming, exemplified by foxtail and broomcorn millet, in the Yellow River valley of northern China approximately 10,000 years ago. The early dryland farming gradually evolved into the economic cornerstone of northern China around 6000 years ago (Yang et al., 2012; Zhang et al., 2024; Zhao, 2017, 2020). Concurrently, the Yangshao Culture, which thrived between 7000 and 5000 years ago in northern China, exhibited unprecedented prosperity, characterized by its extensive distribution, longevity, and profound cultural significance. Subsequently, during the social complexity of the Longshan period, northern China, particularly the middle reaches of the Yellow River, emerged as a prominent region in early civilization, leading Chinese civilization into the stage of "kingdom" civilization with state-level organization (Han, 2015, 2021). During this process, the research of environmental archaeology has revealed that the climate in the Yellow River valley has undergone frequent fluctuations since the Neolithic Age (Zhang, 2009), while early dryland agriculture in China, serving as the material foundation for ancient population growth and social development, is intricately linked to the rise and fall of early Chinese culture and civilization. Against the backdrop of frequent climate and social changes over several millennia, how early dryland agriculture in China achieved sustainable development and provided robust support for population growth and social complexity has long been a significant research topic in academia.

The Yellow River valley, a pivotal region for early dryland farming in China, is predominantly characterized by the Loess Plateau. This area is characterized by widespread loessial soils that are infertile, with shallow plow layers, low productivity, and deficiencies in nitrogen and organic matter content (Shaanxi Soil Survey Office, 1992; Chinese Academy of Sciences Loess Plateau Comprehensive Science Expedition Team, 1992). Effective agricultural management practices, such as manuring, hoeing, and irrigation, are essential for ensuring optimal crop growth, thereby

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https://doi.org/10.1016/j.palaeo.2025.113283
Received 6 June 2025; Received in revised form 9 September 2025; Accepted 9 September 2025
Available online 10 September 2025

supporting the development of early dryland farming in China. Recent advancements in archaeobotany and stable isotope bioarchaeology have shown that the application of organic manure significantly influences nitrogen input during crop growth, thereby impacting the nitrogen stable isotopic signatures of crops (Amundson et al., 2003; Bateman et al., 2005; Choi et al., 2005). Isotopic analysis has emerged as a powerful tool providing direct evidence of manuring practices. The potential of nitrogen stable isotopes in investigating ancient crop manuring has increasingly attracted scholarly attention. Drawing on stable isotope studies of modern C_3 cereal crops, previous researchers have developed models to quantify the intensity of manuring (Bogaard et al., 2013; Fraser et al., 2011). These models have been effectively applied to analyze archaeological remains across Europe, West Asia, East Asia, and beyond, offering valuable insights into early manuring practices and social complexity (Bogaard et al., 2013; Gron et al., 2017, 2021; Li et al., 2022; Styring et al., 2016, 2017).

Due to physiological and photosynthetic differences between C_3 and C_4 crops, recent cultivation experiments on millets—indigenous C_4 crops in China—have demonstrated that the application of organic manure also elevates nitrogen isotope values in millet seeds (Christensen et al., 2022; Dong et al., 2022; Ouyang et al., 2024; Wang et al., 2022a; Yang et al., 2022; Yang et al., 2024a). The enrichment of ^{15}N during manure decomposition constitutes the underlying mechanism driving subsequent manuring effects. In contrast to C_3 wheat, in which seed nitrogen isotope values are higher than those in leaves, these experiments reveal that millet seeds consistently exhibit approximately 0.9 ‰ lower nitrogen isotope values compared to their corresponding leaves (Ouyang et al., 2024; Yang et al., 2024a). Findings from existing manuring experiments have been widely utilized to investigate past manuring practices in key regions such as the Dadiwan site (Yang et al., 2022), the Baishui River valley (Wang et al., 2018), and the Central Plains (Tao et al., 2022a; Wang et al., 2022b) in northern China. However, a comprehensive analysis of the spatiotemporal trajectory of millet manuring—based on previously published isotopic data—has yet to be conducted, resulting in an insufficient understanding of overall manuring practices in early millet agriculture. Key questions concerning the broader patterns of manuring practices during the development of early dryland agriculture in China, the driving factors behind these practices, and their influence on the evolution of early agricultural societies and civilizations remain pivotal issues in current research on archaeobotany and subsistence strategies.

In this study, we compiled previously published nitrogen isotopic data for millet ($n = 472$) from the Yellow River region before 221 BCE. Data from later periods are excluded from this analysis due to increasingly detailed historical records since then. The aim is to elucidate the characteristics of early millet manuring management and their underlying driving factors, with the expectation of enhancing the comprehensive understanding of the early agricultural management activities in China.

2. Materials and methods

2.1. Data acquisition

We compiled nitrogen isotopic data currently available for foxtail and broomcorn millet from 33 archaeological sites along the Yellow River (Fig. 1), primarily sourced from published archaeological research papers and dissertations. The dataset spans from the early Yangshao period to the Shang-Zhou periods (Table S1), with a geographical focus on the Loess Plateau and its adjacent regions, which have historically served as key centers for dryland millet farming. These sites are categorized into five main regions (Table S2): the Tianshui Basin (Li, 2018; Yang et al., 2022), the Northern Shaanxi Plateau (Sheng et al., 2021; Ouyang et al., 2025), the Datong Basin (Li, 2023), the Guanzhong Basin (Cai, 2021; Jin et al., 2024; Wang et al., 2018) and the Yiluo Basin (Tao et al., 2022b; Wang et al., 2022b). Specifically, the data from the Tianshui Basin originates from the Dadiwan Site (Yang et al., 2022) and from samples collected by Li (2018) during field investigations across nearly 50 archaeological sites in Zhuanglang County, Gansu Province. Due to the dense distribution of these sites in Zhuanglang County, they are collectively referred to as the Zhuanglang Site Group. The data from the Northern Shaanxi Plateau mainly derive from the Yan'an and Yulin regions in Shaanxi Province. Given that both the Northern Shaanxi Plateau and the Datong Basin belong to the same geographical and cultural unit called Shanxi-Shaanxi Plateau (晋陕高原) in terms of topography and exhibit relatively consistent cultural features during specific periods (Yang, 2008; Yang and Zhao, 2005), they are collectively referred to as the northern Loess Plateau for convenience. To investigate diachronic changes in millet manuring management practices, our research primarily employs Sun Zhouyong's phase framework for the northern Loess Plateau culture (Sun, 2016) and follows information previously provided or the generally accepted date range, dividing the data into three periods: the late Neolithic Age (7000–4500 BP, $n = 224$), the Longshan period (4500–3800 BP, $n = 199$), and the Bronze Age (3800–2200 BP, $n = 49$). The Longshan period is further subdivided into an early phase (4500–4200 BP) and a late phase (4200–3800 BP).

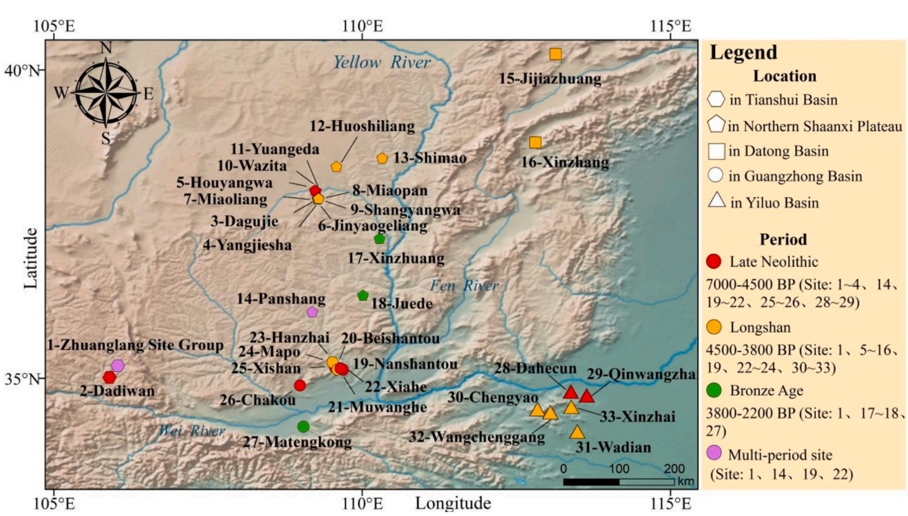

Fig. 1. Locations of the sites in northern China where stable isotope data of foxtail and broomcorn millet were obtained for this study. The base map was obtained from the Natural Earth public domain map dataset (https://www.naturalearthdata.com/downloads/10m-raster-data/).

2.2. Data processing

Numerous cultivation experiments on millet have been conducted to investigate the effects of manuring on stable isotope values (Table S3). Given that the majority of existing stable isotope data for millet are concentrated in the Loess Plateau and its surrounding regions, the soil and climatic conditions in contemporary cultivation experiments in Lintong, Shaanxi Province, closely resemble those of ancient millet cultivation in northern China. Moreover, key variables such as manure type and application level have been examined, further enhancing the relevance and applicability of the experimental results. Consequently, the findings from the modern millet cultivation experiments in Lintong, Shaanxi Province, serve as a pertinent reference for this study.

Crop growth is intricately linked to regional environmental factors such as climate and soil. Elevated $\delta^{15}N$ values in cereal grains may be partly attributed to environmental factors like aridity, which tends to increase plant $\delta^{15}N$ values (Araus et al., 2014). Thus, distinguishing the effects of manuring from those of aridity is crucial to reliably assessing early farming practices at archaeological sites in semi-arid regions. Recent studies have estimated the $\delta^{15}N$ values of plants consumed by herbivores at the same site/phase by subtracting the approximate 4 ‰ offset between consumer and diet from the $\delta^{15}N$ values of preserved herbivore bone collagen, serving as a proxy for unmanured crop $\delta^{15}N$ values (Bogaard et al., 2013). Styring et al. (2016) noted that when faunal bones are absent or poorly preserved, or when the range in herbivore $\delta^{15}N$ values is too broad to establish a meaningful baseline, an alternative method for inferring a plant isotopic baseline is required. Consequently, they utilized the relationship established by Hartman and Danin (2010) between the $\delta^{15}N$ values of unmanaged annual plants and the natural logarithm of mean annual rainfall to estimate expected $\delta^{15}N$ values for unmanured cereals across different rainfall levels. According to the studies by Hartman and Danin (2010), this regression, specifically for annual C_4 plant leaves (formula 1), was selected as the closest analogy to cereals.

$$\delta^{15}N_{leaf} = -3.19[\ln(\text{mean annual rainfall})] + 21.09 \quad (1)$$

This approach has already been successfully applied to reveal agricultural practices through the Yangshao periods in northern China (Jin et al., 2024; Sun et al., 2025). To correlate the $\delta^{15}N$ values of annual plant leaves from the Hartman and Danin study with those of millet grains, we adjusted the regression line using the mean offset in $\delta^{15}N$ between millet grains and leaves from a range of fertilized plots throughout the growing season. The study in Lintong, Shaanxi Province by Ouyang et al. (2024) demonstrated that grain $\delta^{15}N$ values are approximately 0.9 ‰ higher than leaf $\delta^{15}N$ values in millets. Hence, the formula can be adjusted to (2).

$$\delta^{15}N_{grain} = -3.19[\ln(\text{mean annual rainfall})] + 21.09\text{–}0.9 \quad (2)$$

$\Delta^{15}N$ was calculated to represent the difference between the $\delta^{15}N$ values in millet seeds and the expected $\delta^{15}N$ values of unmanured cereals estimated by the regression line. For example, experimental results from Lintong indicated that the $\Delta^{15}N$ of millet seeds after manure application ranged approximately between 2.6 ‰ and 9.2 ‰.

3. Results

3.1. Disentangling the effect of manuring from aridity on crop $\delta^{15}N$ values

In Fig. 2a, we plot the $\delta^{15}N$ values of millet grains against the natural logarithm of mean annual rainfall. The regression line represents the relationship between unmanaged plant $\delta^{15}N$ values, adjusted for the grain-leaf offset, and the natural logarithm of mean annual rainfall. Notably, the $\delta^{15}N$ values of millet grains from all four regions exceed the expected $\delta^{15}N$ values for unmanured millet. Additionally, modern experimental data from Lintong, which include various manuring levels and types, also fall above the estimated baseline and align with the conditions observed in the modern planting experiment. These findings indicate that millet at each site likely experienced human-induced

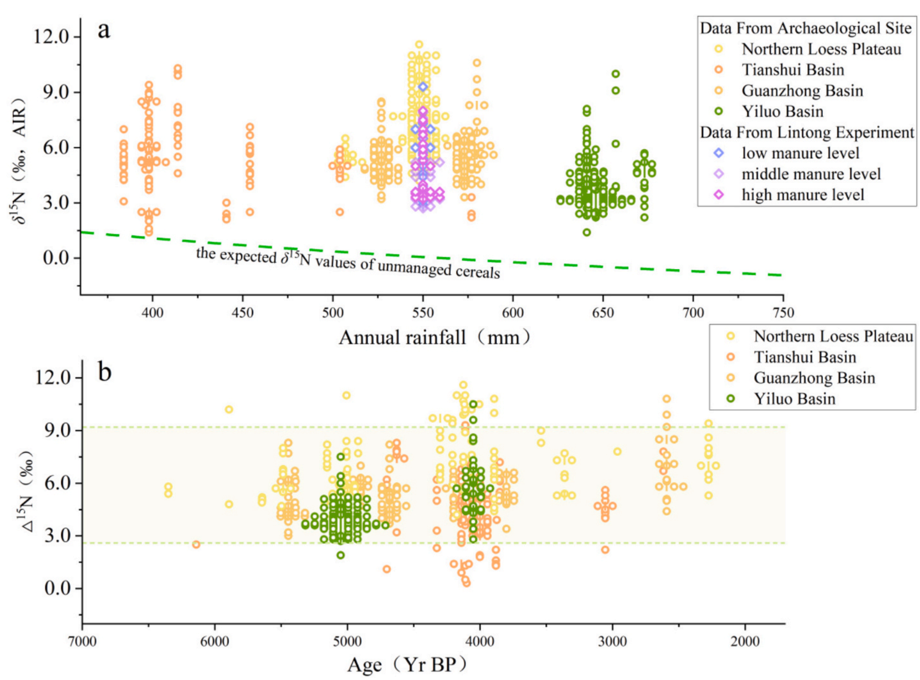

Fig. 2. Scatter plot of millet $\delta^{15}N$ values. (a) plot of millets $\delta^{15}N$ values against a natural log scale of rainfall. Green dashed line represents the expected $\delta^{15}N$ values of unmanured millet grains estimated by the regression line; (b) archaeological millet grain $\Delta^{15}N$ values plotted against date. $\Delta^{15}N$ represents the difference between the $\delta^{15}N$ values in millet seeds and the expected $\delta^{15}N$ values of unmanured cereals estimated by the regression line. The $\delta^{15}N$ symbols are colour coded by regions, with the green band representing the reference range (2.6–9.2 ‰) of manured millets. Present day annual rainfall is derived from the published reference work of Integrated Scientific Investigation Team to the Loess Plateau, Chinese Academy of Sciences Loess Plateau Comprehensive Science Expedition Team (1992). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

nutrient enrichment. When plotting millet $\Delta^{15}N$ values against time (Fig. 2b), the majority of millet grains fall within the reference range established by the Lintong modern experiment. Specifically, 91.3 % of the data points lie within the fertilized reference range, while 5.1 % exceed this range, indicating that millet cultivation involving manuring was widespread across different regions of the Yellow River since the late Neolithic period.

3.2. Spatiotemporal variation of millet $\delta^{15}N$ values

In terms of temporal variation (Fig. 3), the $\delta^{15}N$ values of both foxtail and broomcorn millet within the same region exhibit similar and significant changes over time. In the Guanzhong Basin and the Yiluo Basin, $\delta^{15}N$ values show a gradual increase over time. Specifically, during the Longshan period, the $\delta^{15}N$ values of foxtail and broomcorn millet in the Yiluo Basin were 5.2 ± 1.3 ‰ and 5.4 ± 1.9 ‰, respectively, significantly higher than those in the late Neolithic period ($p < 0.001$). During the Bronze Age, the $\delta^{15}N$ values in the Guanzhong Basin reached 6.7 ± 1.9 ‰ for foxtail millet and 7.0 ± 1.9 ‰ for broomcorn millet, also significantly higher than those in earlier periods. Similarly, the Tianshui Basin also displayed a significant increase, with the $\delta^{15}N$ value reaching a notably high level of 7.9 ± 2.0 ‰ in foxtail millet and 8.3 ± 1.9 ‰ in broomcorn millet during the Qijia Culture phase of the Longshan period. In contrast, the northern Loess Plateau exhibited an overall decreasing trend over time.

At the spatial scale, after accounting for the influence of drought factors, the $\Delta^{15}N$ values across different regions during the same period still exhibited significant regional variations (Fig. 4). During the late Neolithic period, the $\Delta^{15}N$ values in prosperous Yangshao culture areas such as the Guanzhong Basin (5.3 ± 1.1 ‰ for foxtail millet and 5.5 ± 1.0 ‰ for broomcorn millet) and the Yiluo Basin (3.5 ± 0.8 ‰ for foxtail millet and 3.6 ± 1.1 ‰ for broomcorn millet) were lower compared to those in the northern Loess Plateau (8.3 ± 0.9 ‰ for foxtail millet and 6.0 ± 2.6 ‰ for broomcorn millet) and the Tianshui Basin (6.2 ± 1.0 ‰ for foxtail millet and 6.6 ± 1.6 ‰ for broomcorn millet), indicating relatively lower levels. In the Longshan period, the $\Delta^{15}N$ values of the Qijia culture in the Tianshui region were 7.9 ± 1.9 ‰ and 8.3 ± 1.9 ‰ for foxtail and broomcorn millet, respectively, significantly higher than those in other regions. By the Bronze Age, the $\Delta^{15}N$ values of millet in the northern Loess Plateau (5.8 ± 1.2 ‰ and 4.4 ± 1.9 ‰ in foxtail and broomcorn millet, respectively) were notably lower than those in the Tianshui and Guanzhong regions.

3.3. Comparison of $\delta^{15}N$ in foxtail and broomcorn millet

A comparison of $\delta^{15}N$ values between foxtail millet ($n = 264$) and broomcorn millet ($n = 208$) (Fig. 5) reveals reveals little to no significant difference between the two crops across any region or period. Previous studies have shown that grains grown in the same environment generally exhibit similar $\delta^{15}N$ values, which implies that foxtail and broomcorn millet might receive manuring simultaneously and at a consistently similar level across both time and space.

4. Discussion

4.1. Manuring ensures the sustainable development of millet agriculture

The millet-based agriculture in the Yellow River Basin of China is intrinsically linked to loess soil. Characterized by its loose texture, ease of tillage, and rich mineral composition, loess provides a favorable foundation for the origin and development of crop cultivation (Liu et al., 1985; Yao, 2006). However, the inherently low nitrogen content and high susceptibility to organic matter loss in loess soils result in a significant risk of soil fertility depletion after prolonged cultivation (Catt,

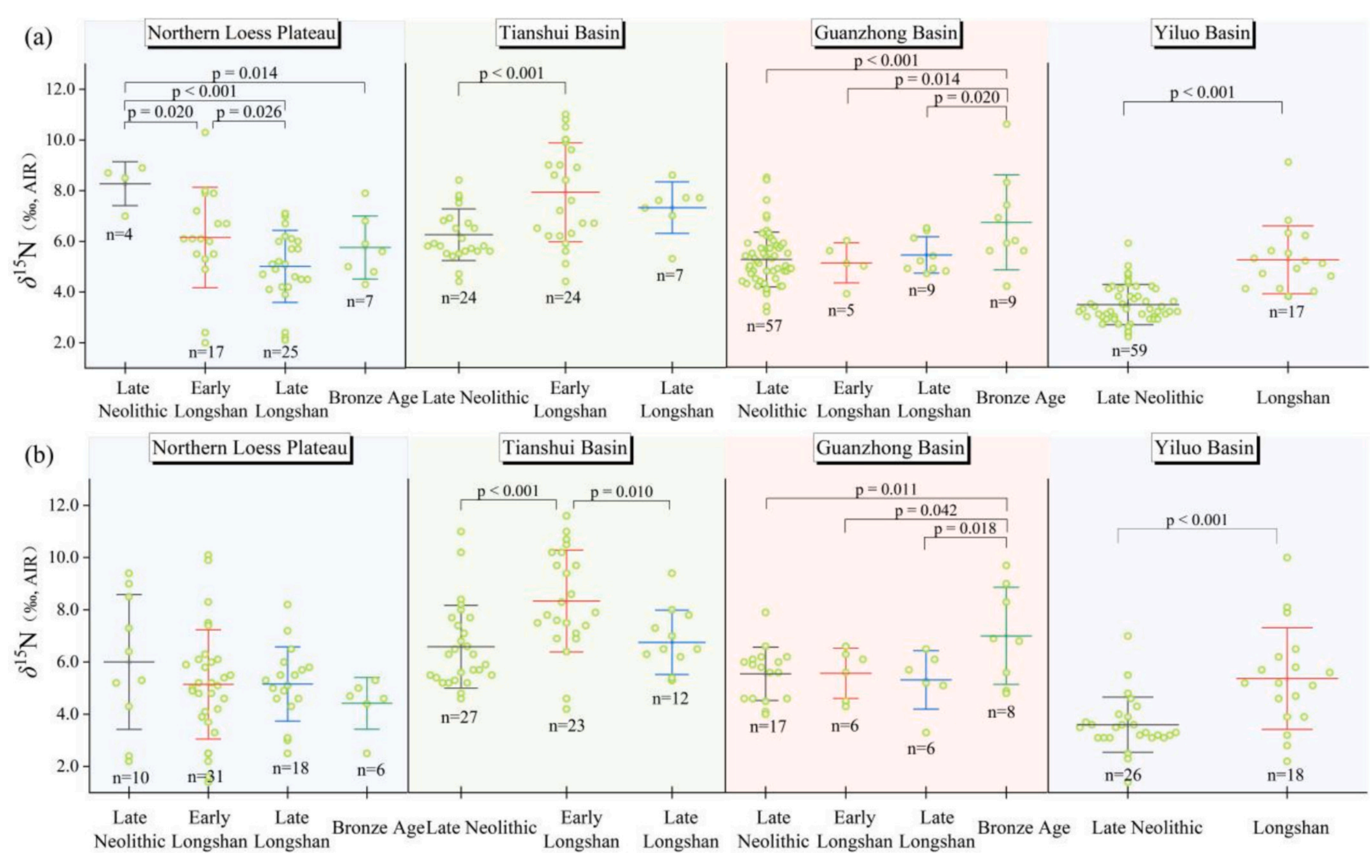

Fig. 3. Changes on the $\delta^{15}N$ values of foxtail millet (a) and broomcorn millet (b) through time. The absolute date ranges for each cultral phase are as follows: Late Neolithic, 7000–4500 BP; Early Longshan, 4500–4200 BP; Late Longshan, 4200–3800 BP; Bronze Age, 3800–2200 BP.

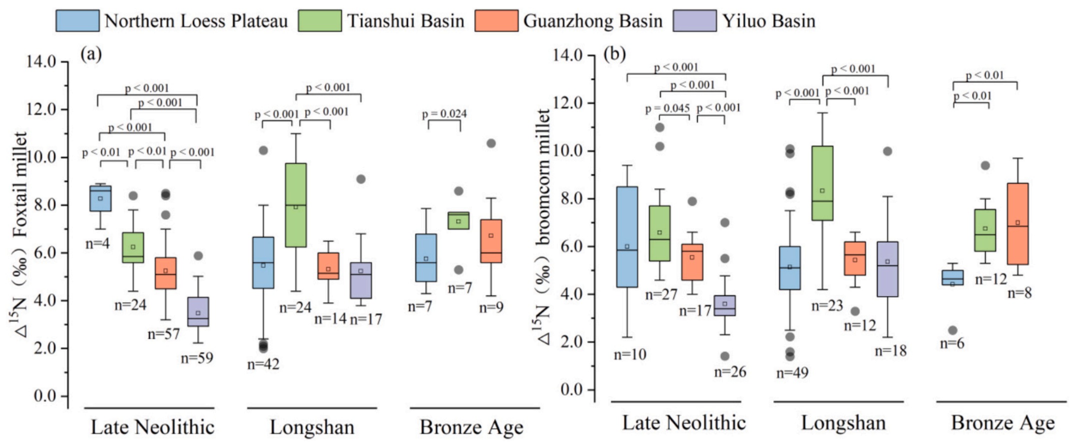

Fig. 4. Comparison of Δ^{15}N values of foxtail millet (a) and broomcorn millet (b) in different regions.

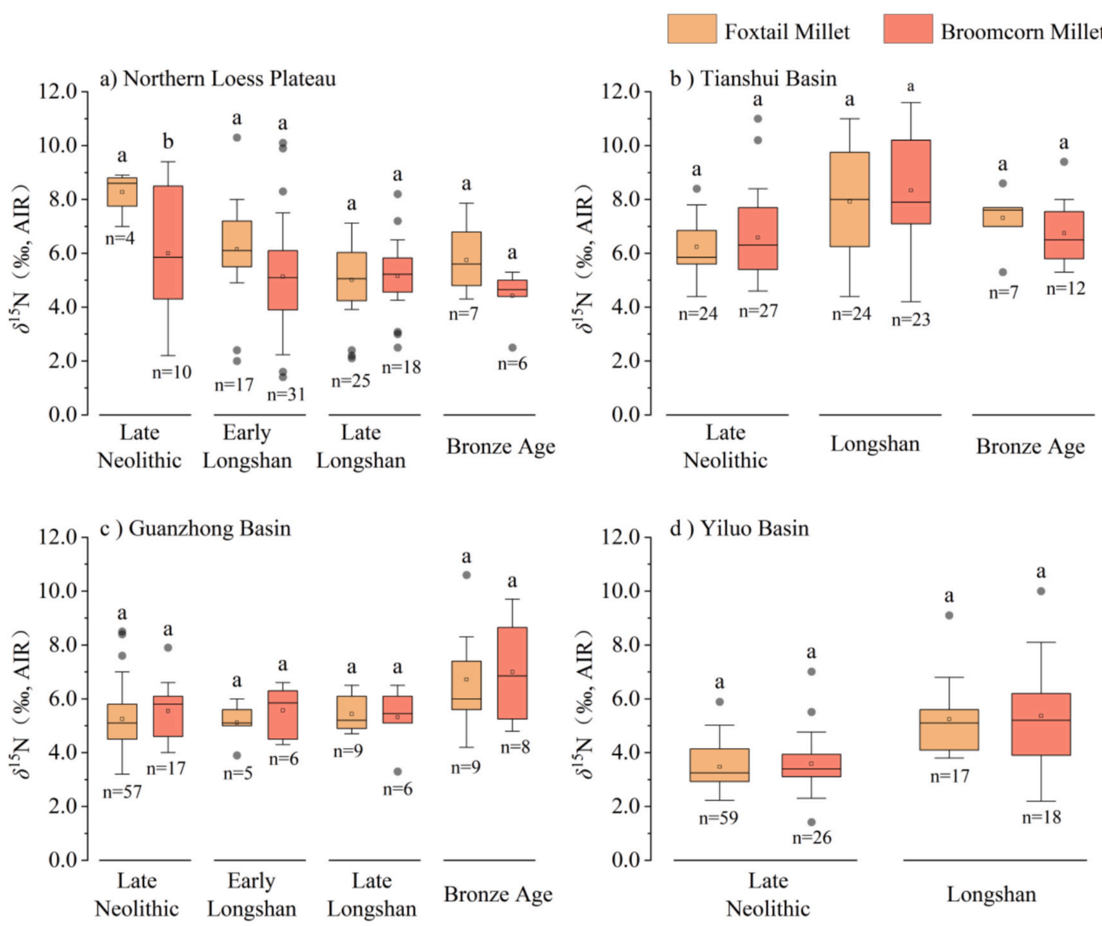

Fig. 5. Comparison of δ^{15}N data of foxtail and broomcorn millet at different periods. (a) Northern Loess Plateau; (b) Tianshui Basin; (c) Guanzhong Basin; (d) Yiluo Basin. Within each periods, the same letters (e.g., "a") denote no statistical significance between foxtail and broomcorn millet in this period at P < 0.05 with the LSD test.

2001; Qiao et al., 2022). This poses a significant constraint on the sustained development of both agriculture and cultural development. Therefore, how did prehistoric human communities overcome the challenges associated with continuous millet cultivation to ensure agricultural sustainability in the Yellow River Valley?

The record (终岁不宜稼，非粪不解) in Qi Min Yao Shu (齐民要术), a Chinese agricultural book written during the late Northern Wei Dynasty (about 530–540 CE) (Jia, 2015), emphasizes the critical role of manure in maintaining and improving soil fertility. According to analyses of the nutrient composition of soils in the Yellow River Basin, especially concerning key indicators such as organic matter and total nitrogen, the region's soil nutrients are at relatively low levels compared to the national average (Shangguan et al., 2013). Referring to the nutrient grading standards from the second national soil census (Table S4), the soil nutrient grade in the area where the site is located is generally at level V or even VI (Fig. 6), indicating extremely deficient nutrient levels. A 10-year monitoring experiment on farmland in the Loess Plateau showed that long-term absence of manuring leads to a significant

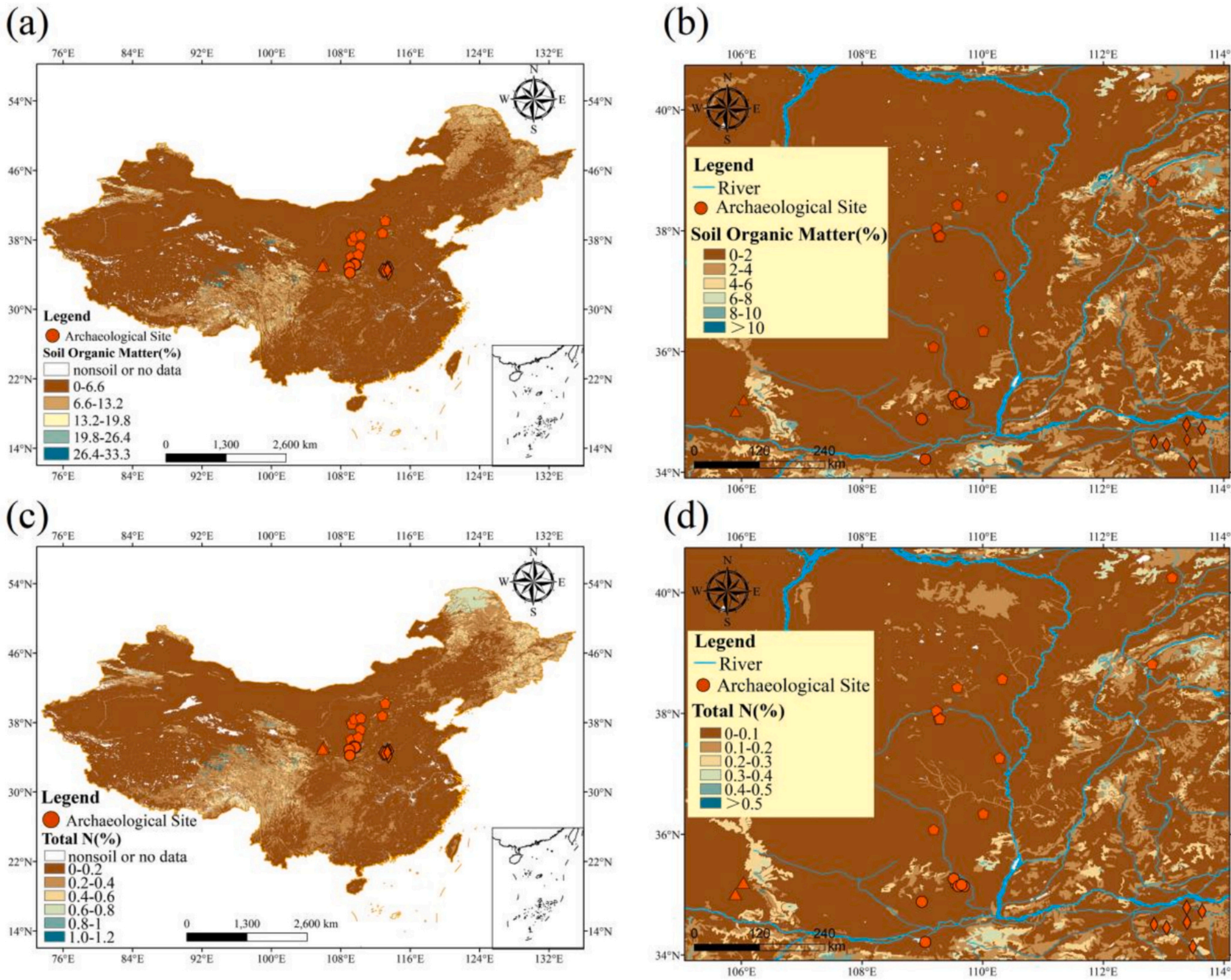

Fig. 6. Soil nutrient concentrations across different regions. Spatial distribution of (a) soil organic matter in China (%, 1 % = 10 g/kg); (b) soil organic matter in the research area; (c) soil total nitrogen (N) in China (%); (d) soil total nitrogen (N) in the research area. The datasets is provided by National Tibetan Plateau/Third Pole Environment Data Center (http://data.tpdc.ac.cn).

decline in soil organic matter and total nitrogen content, with soil nitrogen loss exceeding 80 % (Xu et al., 2016). This underscores that manuring is a necessary and crucial farmland management measure for ensuring sustainable agricultural development in the Yellow River region. Topographic contexts are also worth noting, as soil nitrogen and crop isotopic signatures are intrinsically linked to local geomorphology. As a result, we incorporate DEM-derived slope and altitude metrics for each site following Yang et al. (2024b) (Table S5). Altitude data reveal a consistent pattern from the Late Neolithic to the Bronze Age: Tianshui Basin > Northern Loess Plateau > Guanzhong Basin > Yiluo Basin, with sites in the Guanzhong and Yiluo Basins all situated below 1000 m. In terms of slope data, only a small number of low-elevation sites had slopes less than 3°, indicating that they were distributed on land with small terrain undulations and have potentially higher soil fertility due to the river alluvial deposits. However, 76 % of the sites were located on land with a mean slope above 3°, suggesting that water and nutrients were not easily retained. Cultivating millets and taking appropriate measures to maintain soil fertility were the optimal choices for the majority of these sites, further confirming the necessity of manure utilization.

In this study, we isolated the drought factor to assess the impact of human management on the $\delta^{15}N$ values of millet. The $\delta^{15}N$ data from early dryland agricultural millet samples consistently exceeded the regression line representing the expected $\delta^{15}N$ values for unmanured millet grains. After accounting for drought influence, 91.3 % of the data points fell within the manuring reference range. Other potential factors for changes in $\delta^{15}N$ values (sea spray, burning, and waterlogging) are not relevant in this landscape (Szpak, 2014). These suggests that early farmers likely applied manure during millet cultivation, indicating that early millet-based agriculture in the Yellow River region was characterized by widespread use of manure.

Previous studies on land use in early agriculture, which predominantly relied on indirect evidence such as historical records or ethnological observations, emphasize the pivotal role of slash-and-burn practices in the development of early agricultural systems (Lin, 1993; Morimoto and Li, 1991). Specifically, this entailed utilizing newly cleared and burned forest land for short-term crop cultivation (approximately 1–5 years), followed by abandonment to allow the land to recover, while cultivation was shifted to other newly cleared areas. This method is also known as shifting cultivation in early agricultural systems in Europe and America (Dennell, 1978). Bogaard (2002) conducted a study on weeds in a wheat planting experiment in Hambach, Germany, which simulated six years of wheat cultivation following slash-and-burn practices. Floristic analysis revealed that under the shifting cultivation system, perennial weeds outnumbered annual weeds, with perennial weed samples constituting 57–100 % (averaging

80 %) of all plots. In contrast, land under long-term continuous cultivation exhibited a higher proportion of annual weeds (Bogaard, 2002, 2004). Therefore, we also gathered archaeobotanical evidence from the same period at this site or its surroundings in addition to collecting stable isotope data from crops. The findings indicated that, in terms of absolute quantity and species proportion, annual weeds predominated in these regions since the late Neolithic period (Fig. 7) This suggests that the land had been cultivated extensively for an extended period, indicating intensive soil disturbance rather than the superficial harrowing typical of slash-and-burn agriculture. Although shifting cultivation serves as a simple and reliable method for food production for small populations residing in large forested areas (Ehrmann et al., 2014), experiments conducted in Forchtenberg, Germany, demonstrated its rapid depletion of soil nitrogen. Consequently, annual cultivation is typically viable for only 2–3 years, after which the soil requires a recovery period of approximately 10–15 years (Ehrmann et al., 2014). Furthermore, ethnological observations of Pierian farmers in Greek revealed that clearing land prior to crop growth also demands significant human labor and results in longer intervals before reliable yields can be harvested (Halstead, 2018). These risks must be considered for the survival of early farmers, underscoring that fertilization rather than slash-and-burn farming provides a more reliable guarantee for the sustainable development of early Chinese millet agriculture.

Due to the diversity of the subsistence economy in the Loess Plateau region, prehistoric people had access to a wide variety of animal manure. Zooarchaeological studies show that domestic pigs were already present at the Jiahu site in the Central Plains around 9000 years ago, and thereafter, pig bones were commonly found in archaeological sites along the Yellow River (Yuan, 2014). Particularly in sites where millet farming was the main subsistence method, there was a close relationship between domestic pigs and millet agriculture (Wang et al., 2018; Zhang et al., 2021), and pig manure became an easily accessible organic manure. The livestock industry was also characterized by the raising of cattle and sheep (Chen et al., 2017; Hu et al., 2022), providing cattle and sheep manure as important fertilizer sources for prehistoric agricultural production in pastoral zones and the transitional ecotones between agriculture and pastoralism. Modern field experiments have revealed that within a single growing season, applying organic manure significantly increased millet yield, with both pig and cow manure resulting in a yield increase of over 45 % (Qi, 2004). A comparison of the proportions of domesticated versus wild animals excavated at certain sites in the Yellow River valley from the late Neolithic to the Bronze Age (Fig. 8a) reveals a clear upward trend in the proportion of domesticated animals. This indicates that early farmers likely had abundant access to livestock manure. Given the substantial short-term yield enhancements achieved through manure application, it is plausible that prehistoric people readily recognized its yield-boosting effects and adopted its continuous use. Moreover, archaeological and ethnographic evidence indicates that in addition to being used as manure due to its rich organic matter and nitrogen content, manure was also widely used for fuel, building materials, and other purposes (Gur-Arieh and Madella, 2024). Pollen research shows that the Loess Plateau's tableland areas have been dominated by grassland vegetation throughout the Holocene, with few forest growth (Li et al., 2003), likely strengthening the fuel function of manure. The multi-purpose nature of manure further increased the likelihood of its use as fertilizer.

The stable nitrogen isotope ratios in plants reflect their nitrogen sources (atmospheric nitrogen for N_2-fixing plants or nitrogenous compounds such as NH_4^+ and NO_3^- for non-N_2-fixing plants) and fractionation during nitrogen uptake and assimilation(Evans, 2001). Foxtail millet (an NADP-ME subtype) and broomcorn millet (an NAD-ME subtype) are both C_4 plants but belong to different biochemical subtypes(Hattersley, 1982). Previous studies have identified differences in nitrogen utilization between C_3 and C_4 plants in arid and semi-arid regions (Luo et al., 2018), yet it remains unclear whether there are distinct response mechanisms to nitrogen among different C_4 subtypes, such as foxtail and broomcorn millet. In this study, the $\delta^{15}N$ values of foxtail and broomcorn millet exhibited similar diachronic change trend and did not differ

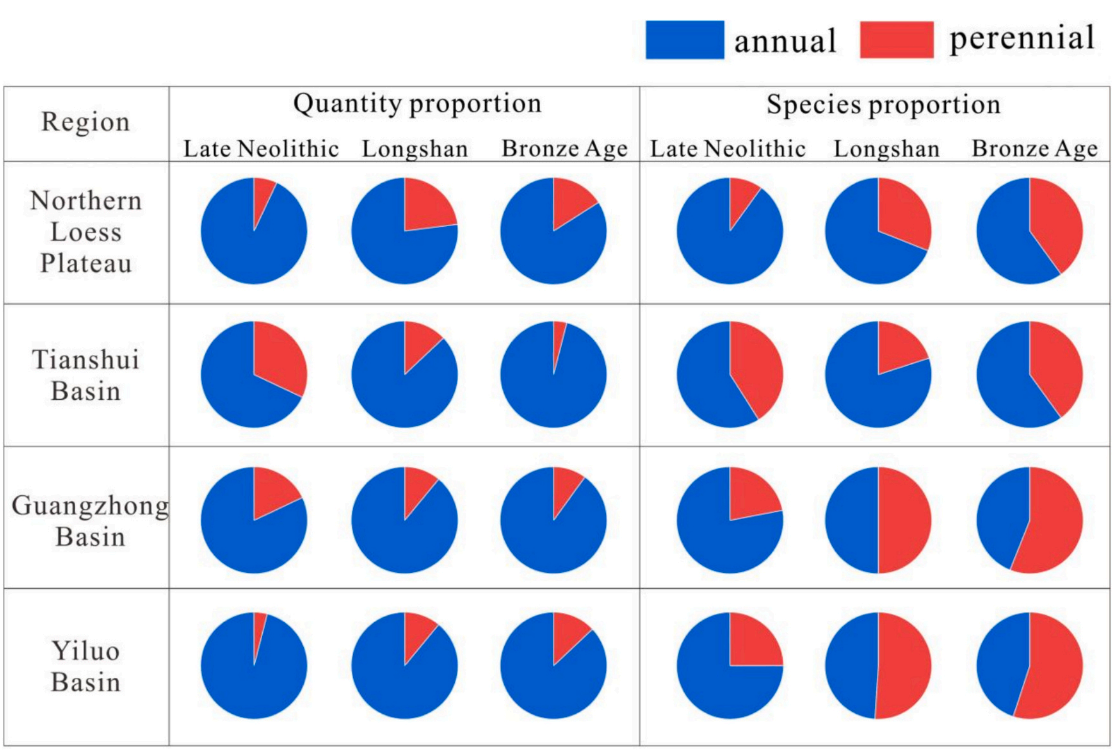

Fig. 7. Comparison of the proportions of annual and perennial weed species and their quantities in Northern Loess Plateau (Gao, 2017; Jin et al., 2023; Liu et al., 2019; Sheng, 2018; Xiao, 2022), Tianshui Basin (Chen, 2020; Li, 2018), Guangzhong Basin (Jin et al., 2024; Tang et al., 2022; Wang, 2014) and Yiluo Basin (Tao et al., 2022a; Liu and Fang, 2010; Zhao and Fang, 2007; Zhong et al., 2016, 2018).

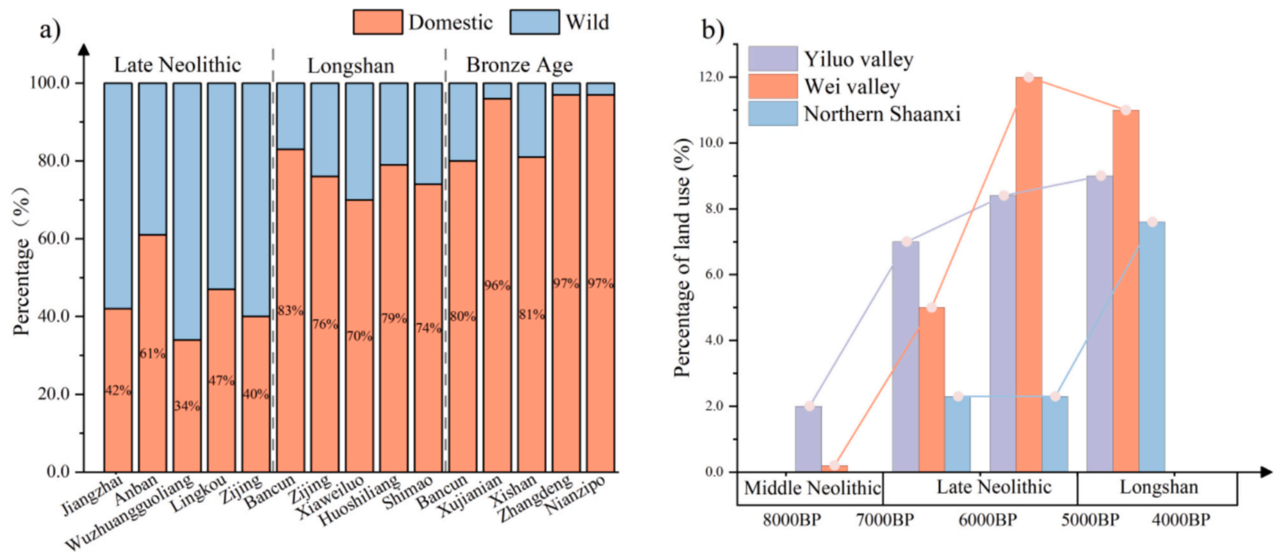

Fig. 8. Intensive agricultural practices in the Yellow River valley. (a) Comparison of domestic and wild animals unearthed from sites in the Yellow River region from the Late Neolithic to the Bronze Age (data from Yuan (1999, 2014)); (b) The percentage of land use in Yiluo valley, Wei valley and Northern Shaanxi at 8–4 ka BP revealed by the PLUM model (redrawn from Luan et al. (2024)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

significantly across temporal and spatial scales, indicating that the two crops were grown in comparable soil conditions and likely received consistent manuring intensity from ancient farmers.

Jin et al. (2024) reported that around 5000 BP, there was a significant shift from broomcorn millet to foxtail millet as the dominant crop in northern China, likely due to differences in environmental adaptability and yield between the two crops. Our findings indicate that, despite changes in the proportions of foxtail and broomcorn millet in the crop assemblage before and after this transition, manuring practices remained consistent. Broomcorn millet, although its proportion decreased, continued to be a key component of dryland farming systems. Ancient farmers may not have differentiated manuring inputs between the two millet types. Modern planting experiments have demonstrated that under similar water, heat conditions, and land management practices, the growth efficiency, management requirements, and labor input for both crops are relatively comparable (Ouyang et al., 2024; Yang et al., 2024a). This suggests that ancient farmers might have cultivated both foxtail and broomcorn millet in the same fields with identical manuring management. However, further research into the nitrogen absorption mechanisms of these crops is necessary to verify this hypothesis.

Agricultural intensification and extensification represent two non-mutually exclusive ways in agricultural development. In the northern Mesopotamian plain, extensification primarily involved expanding farmland with lower intensity agricultural practices (Styring et al., 2017). In contrast, studies conducted in the Bai Shui valley (Wang et al., 2018) and at the Dadiwan site (Yang et al., 2022) in northern China have revealed an intensive agricultural system involving humans, millet, and pigs. Yu et al. (2012, 2016) and Luan et al. (2024) developed the PLUM model to reconstruct land use percentages in the Yiluo River Basin, Wei River Basin, and the northern Loess Plateau in the Yulin area between 8 and 4 ka BP. Their findings reveal a long-term trend of increasing land use efficiency since 8 ka BP (Fig. 8b). From the overall temporal trends, as land use efficiency increased, the δ^{15}N values of millet in the Tianshui Basin, Guanzhong Basin, and Yiluo Basin either remained stable or even increased, indicating intensified agricultural practices characterized by higher labor and resource inputs. In contrast, in the northern Loess Plateau, the δ^{15}N values of millet showed a roughly negative correlation with increasing land use efficiency, suggesting an extensification strategy similar to that observed in northern Mesopotamia, where farmland expansion was accompanied by cultivation of larger areas of land with relatively lower manure application intensity.

4.2. Diachronic changes in manuring practices in millet agriculture

Given that the nitrogen isotopic composition of plant seeds reflects the soil ^{15}N enrichment conditions in which they grow, the significant fluctuations in δ^{15}N values of millet across a broad range in the northern Loess Plateau (Fig. 3) suggest that these crops were likely cultivated in fields with diverse soil nutrient conditions. A clear decrease in δ^{15}N values is observed from the Late Neolithic period to the Bronze Age. Previous studies have indicated that around 4000 BP, cultural prosperity led to a doubling of sites in northern Shaanxi (State Administration of Cultural Heritage, 1998), suggesting that prehistoric millet farmers may have needed to increase crop production to support larger and potentially more economically specialized populations in this arid region on the Loess Plateau. Despite this, millet δ^{15}N values reached one of their lowest points during this period, indicating the decrease in nitrogen availablity. The northern Loess Plateau is characterized by large topographic variation, relatively limited water resources, and a fragile ecological environment. Long-standing challenges for local agriculture include nutrient depletion and soil erosion of loess. The downward trend of millet δ^{15}N values, on the one hand, may result from the gradual exhaustion of loess nutrient due to sustained cultivation. On the other hand, it may reflect the adaptive adjustment of farming strategies to regional characteristics in response to demographic shifts in the northern Loess Plateau. When the profits obtained from increasing fertilizers fail to meet expectations, reducing manure input per unit area and expanding the planting area may become a better option. In combination with the research on lake sediments in the nearby Daihai Lake, the δ^{15}N values of black carbon—respresenting the nitrogen availibility of natural vegetation burned during regional fire events—show an upward trend since 6700 BP (Wang et al., 2019). The oppsite trend further supports that the decline in millet δ^{15}N values, as well as those in weeds that accompanied the farmland or were intentionally obtained by humans at the site (Sheng et al., 2021), is more plausibly attributed to anthropogenic activities. The influence of natural factors also warrants attention. Studies have shown that soil nutrients such as nitrogen and organic matter are easily depleted due to erosion on the Loess Plateau, especially in cultivated land (Meena et al., 2017; Moisa et al., 2021).

Regional climatic and environmental conditions may also have partially contributed to increased soil erosion and nutrient loss during that period (Xu, 2006b; Liu, 2009), although further research is required to support this.

The Qijia culture sites were extensively distributed in the Tianshui Basin during the Longshan period. Archaeobotanical evidence indicates that millet farming dominated in this region from the Neolithic through the Qijia culture period (Ma et al., 2016). During the Qijia culture period, domesticated animals included dogs, pigs, cattle, and sheep, reflecting a more diverse range of livestock species (Ren, 2017). These animals, primarily fed on human food leftovers or by-products of millet cultivation, produced substantial amounts of manure, which served as an ideal organic manure for the loess region. This suggests that the significantly higher δ^{15}N values observed in millet during this period compared to other periods, may reflect increased use of organic manure. Similarly, the elevated δ^{15}N values in wheat during the same period also indicate the practice of crop manuring (Li et al., 2022). The Qijia culture exhibited extensive spatial distribution and numerous sites in the Gansu-Qinghai region. Notably, a large number of pig mandibles were found as burial goods in some Qijia tombs, suggesting an uneven distribution of wealth and the emergence of private property, reflecting a relatively advanced level of social development (Yan, 2000). This implies that the inhabitants of the Tianshui Basin likely enhanced agricultural productivity through increased labor and resource inputs to support a growing population, particularly those groups requiring surplus agricultural products due to social stratification. Pollen records indicate relatively humid climatic conditions in this region during the Longshan period (Xu, 2006a), which may also provide a crucial foundation for the agricultural and cultural prosperity of the Qijia culture prior to the 4.2 ka BP cold and dry climate event (Liu et al., 2010).

The preference for areas near river systems during human land expansion (Luan et al., 2024) made the Guanzhong Basin and the Yiluo Basin ideal locations for human settlement. Since the middle-late Yangshao culture period in the late Neolithic period, these regions witnessed a notable increase in both the number and size of archaeological settlements, along with the emergence and acceleration of social stratification (Liu and Chen, 2017), thereby becoming a core area for the origin of Chinese civilization. Agricultural development was integral to the emergence of states and civilizations. The widespread use of agricultural tools such as sickles and knives during this period (An et al., 2019), coupled with the discovery of substantial crop remains at multiple sites, underscores the flourishing of agricultural production. The temporal changes in δ^{15}N values of millet observed in this study suggest that early farmers enhanced crop yields through manuring practices, particularly during the Longshan and Bronze Ages. This agricultural surplus enabled support for non-productive populations and non-agricultural sectors (Brewer, 2011), providing a robust foundation for social division of labor and state formation. An et al. (2019) collected specific arable weeds that thrive exclusively or preferentially in nutrient-rich soil conditions. Their results showed a significant increase in the proportion of these weeds from the Longshan to the Bronze Age, suggesting an improvement in soil fertility likely due to manuring practices. Additionally, archaeological evidence indicates that around 4000 BP, in regions such as Guanzhong and the Central Plains, foxtail and broomcorn millet were the dominant crops, with wheat, rice, and other crops gradually being integrated into the agricultural system (Liu and Fang, 2010; Qu et al., 2018). These findings suggest that early inhabitants of the middle and lower Yellow River employed diversified strategies, including intensive manuring and crop diversification, to support urbanization and the development of civilization, which differed from those in northern Mesopotamia (Styring et al., 2017).

4.3. Spatial differences in manuring in millet agriculture

The diverse topography, climate, and intensity of human activities have resulted in significant spatial heterogeneity and complexity in soil conditions across the Loess Plateau (Song et al., 2023). In this study, after accounting for the influence of drought, the δ^{15}N values of millet crops across different regions exhibited substantial variation (Fig. 4). This suggests that such differences may not only be attributed to variations in manure input but also influenced by inherent differences in local soil substrates. Typically, subtracting the trophic level enrichment value (4 ‰) from the δ^{15}N values of wild herbivores within a region can provide the δ^{15}N values of their food sources—wild plants—thereby reflecting information about the natural environment. Consequently, this study compiled existing data on wild herbivores from the late Neolithic to the Bronze Age (Fig. 9). The results indicated that during the Longshan period, the natural vegetation in the Tianshui Basin exhibited significantly lower δ^{15}N values. However, during this time, the δ^{15}N values of millet were notably higher than those in other regions. This suggests that the elevated δ^{15}N values of crops during this period were likely due to the early farmers of the Qijia Culture employing a more intensive manuring strategy compared to other regions.

During the late Neolithic period, the millet δ^{15}N values in the prosperous Yangshao culture regions of the Guanzhong Basin and the Yiluo Basin were significantly lower. However, based on the δ^{15}N values of wild herbivores, no significant difference was found in the δ^{15}N levels of vegetation growing on natural soils across these regions. This suggests that the lower isotopic values in the Guanzhong Basin and the Yiluo Basin may reflect relatively lower manure input, possibly due to the inherent differences in soil nutrient supply capacity. These regions possess relatively deep and fertile soils with better nutrient retention capabilities (Song et al., 2011; Wang et al., 2013), making them ideal for long-term agricultural cultivation compared to other regions. In contrast to the northern Loess Plateau, the farmers in the Guanzhong and Yiluo Basins likely achieved satisfactory yields without excessive manure application. Additionally, the significantly lower δ^{15}N values of millet in the northern Loess Plateau during the Bronze Age, as previously mentioned, may be due to nutrient depletion from sustained cultivation or adaptive adjustment of planting strategies due to demographic shifts.

4.4. Manuring in millet agriculture as a driving factor of social complexity

Millet agriculture has a long and rich history in ancient China, with numerous historical documents since the Bronze Age recording the wisdom of the ancient farmers in increasing crop yields. A variety of farmland management strategies are employed to maintain and improve soil fertility, including fertilization with dung, legume-cereal rotation, fallowing practices, etc. As early as the Shang Dynasty (1600–1046 BCE) during the Bronze Age, there were oracle bone inscriptions such as "*屎有足，乃贵田*", which referred to the practice of applying human excrement before plowing the fields (Hu, 1981). The use of human waste in agriculture was also frequently recorded in later agricultural-related documents. By the Ming-Qing dynasties, the recycling of human excrement, referred to as "*金汁*" (golden liquid), even evolved into a specialized industry (Du, 2018). The artificial cultivation of green manure crops and their rotation with cereals also have long been regarded as significant agricultural practices. From the introduction of alfalfa during the Western Han dynasty (202 BCE-8 CE) to the statement in Qi Min Yao Shu (*齐民要术*) around the 6th century CE that "*凡美田之法，绿豆为上;小豆、胡麻次之*" (the best way to improve soil fertility is to plant mung beans; followed by adzuki beans and flax) (Jia, 2015), historical records demonstrate that early farmers in the dryland regions of the middle and lower reaches of the Yellow River, had already recognized the varying fertilizer efficiencies among different green manure crops based on their long-term cultivation experience. The rotation systems between green manure crops (e.g., nitrogen-fixing legumes) and cereals to sustain soil fertility became increasingly sophisticated. Moreover, fallowing practices were also an important option when the relationship between humans and the land was not yet under significant pressure, which has already been recorded in books written during the Eastern Zhou Dynasty (770–256 BCE), such as Zhou Li (*周礼*)

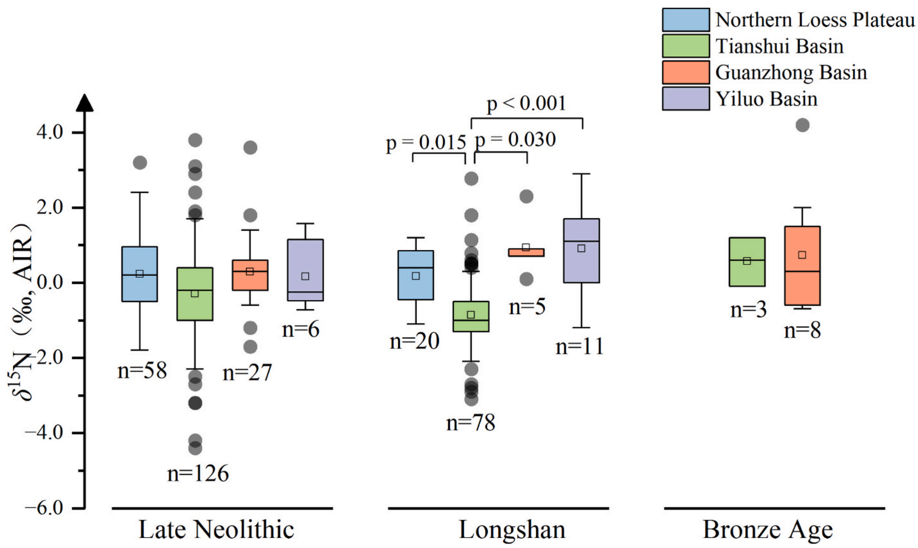

Fig. 9. Comparison of δ^{15}N values of wild herbivores in different regions.

and Lü Shi Chun Qiu (*吕氏春秋*). Collectively, these texts indicate the diverse manuring strategies employed by ancient farmers since the Bronze Age, with the utilization of animal manure or human waste being the most extensively and commonly recorded and offering valuable references for understanding the sustainability of early millet agriculture in China. Animal manure, human excrement, the rotation of cereal crops with green manure crops (e.g., legumes), and fallowing practices may have all played crucial roles in enhancing the agricultural productivity along with the societal evolution. While systematic experimental studies examining the impact of different fertility management strategies on specific indicators of crops remain limited, recent modern planting experiments of foxtail and broomcorn millet in China have revealed that millet δ^{15}N values effectively reflect the application of ^{15}N-rich fertilizers (Wang et al., 2022a; Ouyang et al., 2024; Yang et al., 2024a), providing critical clues for investigating past field management practices.

The long-term climate trend from the late Neolithic to the Bronze Age showed a gradual shift towards colder and drier conditions (Cai et al., 2010), posing substantial challenges to successful crop production (Fig. 10c). Despite these climatic adversities, settlement areas expanded, populations grew significantly, and social stratification at large sites became progressively more complex (Fig. 10b) (Hosner et al., 2016). As a result, ancient communities in northern China faced growing demands for food to sustain their survival. Stable isotope data from our study

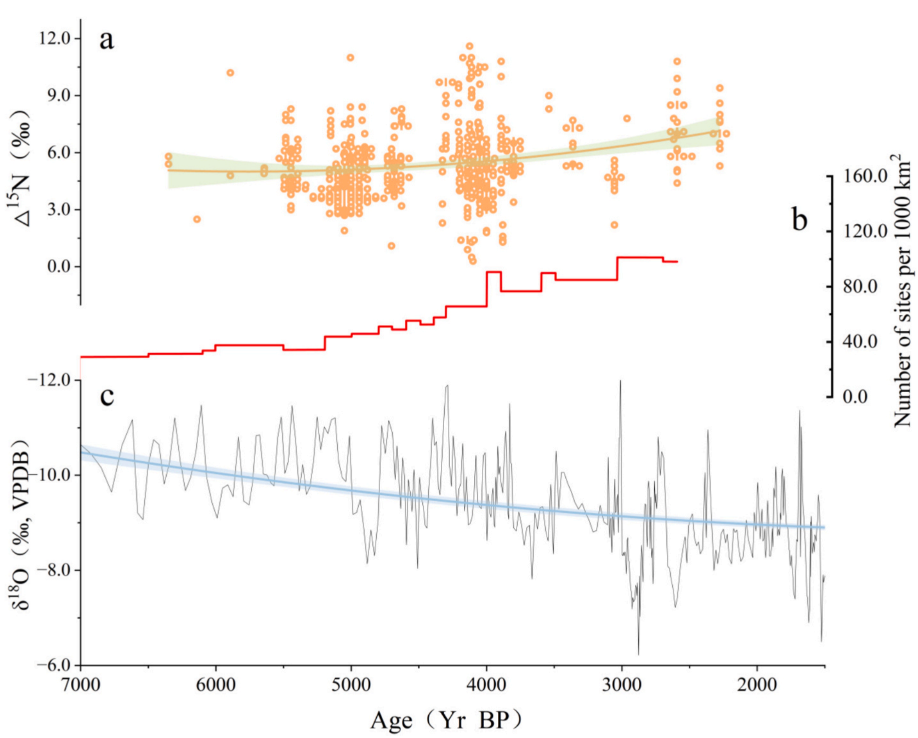

Fig. 10. Climate change and social complexity from the late Neolithic Age to the Bronze Age related to this study. (a) Δ^{15}N values of millet in this study; (b) Density average estimates for the archaeological sites (number of sites per 1000km^2) calculated for northern China (Hosner et al., 2016); (c) Jiuxian Cave speleothem δ^{18}O records in North China (Cai et al., 2010).

revealed a consistent upward trend (Fig. 10a), suggesting the widespread adoption of ^{15}N-rich fertilizers, possibly collected from easily accessible livestock manure, in millet agriculture across the Yellow River valley of China. The advancement of manuring techniques and associated agricultural technologies enabled the adaptation of ancient societies to their changing environment, significantly enhancing crop production and establishing a material foundation for population growth and urbanization. Once population growth exceeded the carrying capacity of the natural environment, it prompted communities to expand into larger areas, particularly plains, thereby greatly increasing their living space (Fig. 8b). The ongoing advancements in agricultural technology and the expansion of cultivated areas have been crucial to the evolution of Chinese agriculture over more than ten millennia, establishing a robust economic foundation for the sustained development of Chinese civilization while reinforcing its distinct continuity (Zhao and Fan, 2024).

The uneven distribution of manuring across different regions and times periods is profoundly influenced by natural environment, climate change, and human activities, reflecting underlying cultural patterns and developmental trajectories. Isotopic studies on plant remains in Europe, West Asia and other regions have shown that manuring not only promoted the adaptation of human communities to diverse environments, but also, due to its delayed yet long-lasting effects, could be perceived as a valuable investment. This practice may have played a role in shaping the worldview of ancient societies, contributing to the emergence of land property concepts and the concentration of wealth. The expansion and consolidation of landholdings intensified social inequality, facilitating the formation of political power and bureaucratic systems (Bogaard et al., 2013; Styring et al., 2017), and also sowed the seeds for later social conflicts—a fact that has been repeatedly proven in the development process of successive dynasties in China (Yu et al., 2020). Moreover, in the pre-industrial era, the primary challenge in farmland manuring was the labor required to transport manure from production sites to application sites, which led to its localized application near residential areas or livestock pens (Gur-Arieh and Madella, 2024). As a result, manuring practices were constrained by resource allocation capabilities. More intensive manuring likely indicates increased cooperation and coordination among people in managing land, resources, and labor, with surplus food production facilitating the emergence of non-agricultural classes, thus laying the foundation for social complexity.

5. Conclusion

This study compiles existing stable isotope data of millet from the Yellow River Basin to investigate the manuring characteristics of early dryland farming in northern China during the Pre-Qin period. Combining multiple lines of evidence, including soil nutrient characteristics, zooarchaeological and archaeobotanical data, as well as environmental archaeological findings, this study demonstrates that widespread manuring practices likely emerged in the Yellow River valley of China since the late Neolithic Age. Manuring, rather than slash-and-burn agriculture, was pivotal to the sustainable development of early millet farming in China. Under the pressures of population growth and climatic variability, the inhabitants of the Yellow River regions intensified land use while maintaining a long-term strategy of cultivation and manuring. Nevertheless, influenced by diverse factors such as soil properties, environmental degradation, and varying levels of cultural development, there were notable diachronic and regional variations in the intensity of fertilization practices. Overall, as a cornerstone of agricultural advancement, these practices not only reflected but also facilitated broader progress of agricultural technology and the expansion of agricultural regions, reinforcing the continuity of Chinese civilization. The intensification of manuring practices underscores the capacity of ancient societies to manage resources efficiently, thereby laying the groundwork for early urbanization and the evolution of Chinese civilization.

CRediT authorship contribution statement

Huiyong Ouyang: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Xue Shang:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization.

Funding

This work was supported by the National Social Science Fund of China (Grant No. 21BKG040), the National Natural Science Foundation of China (Grant No. 42277441) and the Fundamental Research Funds for the Central Universities (Grant No. E2ET0910X2).

Declaration of competing interest

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

Acknowledgement

We would like to thank all anonymous reviewers of this article. We also appreciate Mengjie Cui, Dan Jin, Ruixue Li, Xin Sun and Xiaoyang Yu for their constructive discussion during the process of manuscript preparation.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.palaeo.2025.113283.

Data availability

All data and/or code is contained within the submission.

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