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Millet stable isotopes reveal the advance of agricultural practices in the core political regions of early imperial China☆

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ABSTRACT

Recent archaeological research has revealed a significant intensification of agricultural practices in prehistoric China. Traditional historical perspectives suggest that the Han Dynasty also saw notable advancements in agriculture, though supporting evidence from archaeological science, along with comparative studies of farmland management practices between these two critical periods, remains limited. Here, we analyzed carbon and nitrogen stable isotopes from common millets (*Panicum miliaceum*) and foxtail millets (*Setaria italica*) recovered from four Han Dynasty tombs (Longzaocun, 2002CSX, 2008XJG, and Sanyaocun) and one Late Neolithic site (Ziweitianyuan) in the Guanzhong Basin, Central China. Our results integrate previously published millet isotope data spanning the Late Neolithic to Han Dynasty, reveal a long-term trajectory of agricultural management practices in the Guanzhong Basin under changing climatic conditions from about 3625 BCE to AD 220. Compared to the Late Neolithic period, the δ^{13}C values of common and foxtail millets in the Han capital and its surrounding areas decreased by 3.4 ‰ and 3.8 ‰, respectively, while the δ^{15}N values increased by 6.5 ‰ and 2.7 ‰, indicating an intensification of fertilization strategies. Combined with historical records, this study provides direct evidence of how farmland management in the Han Dynasty maintained soil fertility and agricultural productivity in response to the progressively arid and cold climate of the Holocene, thereby deepening our understanding of soil memory.

1. Introduction

Agriculture is a key subject in the study of human-environment interactions, with its long-term evolution shaped by climate, soil conditions, and human activities (Carleton and Collard, 2020, McLauchlan, 2006). The Guanzhong Basin, located in central Shaanxi Province, China, is an important region for investigating agricultural development and soil management. As a typical fault depression basin, it has accumulated substantial Quaternary loess and alluvial deposits. The region is characterized by a relatively flat terrain and a warm temperate, semi-humid monsoon climate, which provides favorable conditions for agriculture since the Holocene. Additionally, the region preserves high-resolution Holocene soil and sedimentary records (Huang, et al., 2002), offering crucial scientific data for reconstructing ancient agricultural activities and environmental changes.

Recent archaeological research argues that a sustainable and intensive agricultural system had developed in northern China by the Late Neolithic period, around 5,500 years ago (Dong, et al., 2016, Ma, et al., 2023, Rosen, et al., 2017, Yang, et al., 2022). Yet the latest quantitative studies suggest that such sustainable, intensive practices developed at an extremely slow pace. Wu, et al. (2019) identify the Late Neolithic period as a "pre-developmental" stage in agricultural intensification, defining the Qin-Han period as the starting point for a technological take-off and acceleration which continued through the Sui to Yuan Dynasties

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Table 1
Chronology of the Guanzhong Basin in this study.

Period		Date	Age
Yangshao Culture		*ca.* 5000–3000 BCE	Neolithic
Longshan Culture		*ca.* 3000–2000 BCE	Neolithic
Erlitou Culture (Xia Dynasty)		*ca.* 1750–1520 BCE	Bronze
Shang Dynasty		1600–1046 BCE	Bronze
Zhou Dynasty	Western Zhou	1046–771 BCE	Bronze
	Eastern Zhou	770–256 BCE	Bronze
Qin Dynasty		221–207 BCE	Iron
Han Dynasty	Western Han	202 BCE – AD 8	Iron
	Eastern Han	AD 25–220	Iron

(Table 1). To some extent, this supports the traditional argument that the Han Dynasty was a key point of intensive cultivation (Hsu, 1980) under a unified Empire and a more “rational”, market-oriented organization of production (Bray, 1979).

As the core agricultural and political center of the Western Han Dynasty, the Guanzhong Basin serves as an ideal case for examining the development of agricultural practices. Previous studies on Han Dynasty agriculture have primarily relied on historical texts and archaeological remains. Historical records indicate that Han agricultural innovations focused on farmland management and practice (Hsu, 1980, Huang, 2007, Wu, et al., 2019). For example, farmers could learn farming techniques from specialized books (one example is the late Western Han *Book of Fanshengzhi氾胜之书*). Meanwhile, the government ordered expert officials to manage agricultural affairs and construct large-scale irrigation infrastructure. Iron farming tools and ox-plows were also gradually popularized during this period. Improvement of production tools and knowledge altered tilling patterns, leading to the emergence of the ridge-furrow method (*代田法*) and crop rotation system (Fig. 1). However, these historical descriptions lack direct quantitative evidence, particularly in relation to soil fertility and water management.

Over the past two decades, stable nitrogen isotope ratio studies on plant remains have been proven effective in identifying fertilization practices within the context of agricultural activities (Bogaard, et al., 2007, Fraser, et al., 2011, Kendall et al., 2007, Simpson, et al., 1999, Styring, et al., 2014), while stable carbon isotope ratios have been shown to reflect water supply during plant growth (Ferrio, et al., 2020, Ferrio, et al., 2005, Flohr et al., 2011, Wallace, et al., 2013). These parameters have been widely used to scientifically reconstruct prehistoric crop growth conditions, soil fertility, and water status in farmland (Bogaard, et al., 2013, Gron, et al., 2017, Gron, et al., 2021, Kanstrup, et al., 2014). Recently, carbon and nitrogen stable isotope analysis on foxtail millet (*Setaria italica*), common millet (*Panicum miliaceum*), rice (*Oryza sativa*), and soybean (*Glycine* max) unearthed from 14 archaeological sites in the Late Neolithic of north China have demonstrated the presence of fertilization techniques in Chinese agriculture as early as 5500 years ago. Different management methods may have been adopted for different crops, which drove the expansion of millet agriculture and population growth (Tao, et al., 2022, Wang, et al., 2018, Wang, et al., 2022, Yang, et al., 2022). The most recent results from modern cultivation experiments supplement documented changes in isotope values of foxtail and common millet, two of the most important crops in northern China, under different manuring and watering regimes (Christensen, et al., 2022, Dong, et al., 2022, Lightfoot, et al., 2020, Yang, et al., 2024). These previous findings provide an important basis for us to explore the development of farmland management in the Han Dynasty.

Here, we report carbon and nitrogen stable isotopic values of foxtail and common millet remains excavated from four Han Dynasty tombs in the Guanzhong Basin. We obtain direct evidence for farmland management practices in this core area of the Han Dynasty. In addition, we also tested ^{14}C dating and carbon and nitrogen isotope values for common millet grains excavated from one Late Neolithic site in the same area. We combined all new data with published data in an attempt to further investigate whether agricultural production activities in the Han Dynasty constituted an improvement over previous eras from an archaeological science perspective. It should be noted that millet was chosen as the object of study because it was the most important and dominant crop in the Guanzhong Basin from the Neolithic to the Han Dynasty (Liao, et al., 2022).

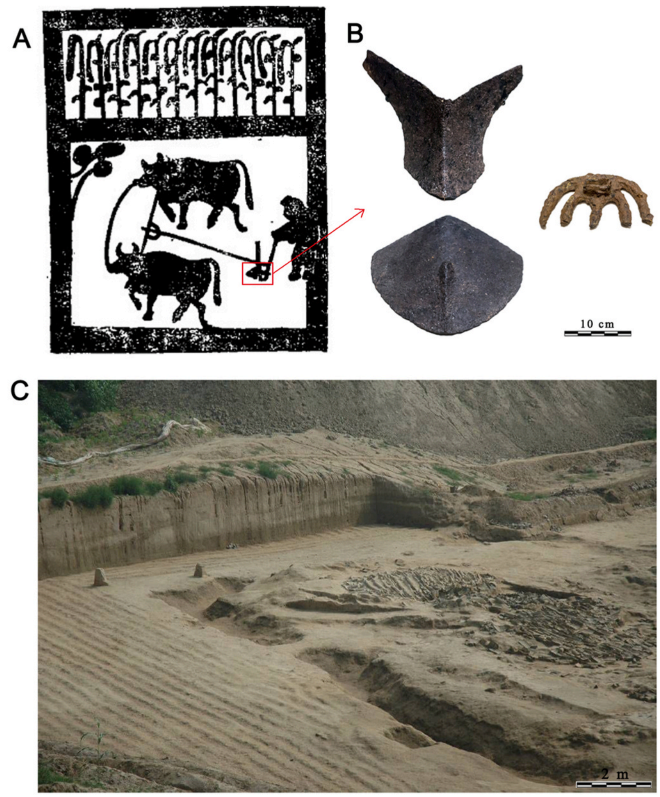

Fig. 1. Agricultural remains of the Han Dynasty. (A) A stone relief describing an ox plow, found in a Han tomb, Mizhi, Shaanxi (Shaanxi Provincial Museum, 1972), (B) Iron agricultural tools collected in the National Museum of China. The two iron tools pictured on the left are known as “*Hua*” (*铧*) and would have mounted on the lower end of the plow to break the ground. The iron tool pictured on the right, known as a “*Pa*” (*耙*), was attached to a wooden shaft, which is mainly used for turning, breaking up and leveling the ground. (C) Farmland remains from archaeological excavations at the Sanyangzhuang Site, Henan, showing the ridge-furrow method (Liu, 2015).

2. Materials and methods

2.1. Materials

Chang’an, the capital city of the Western Han Dynasty, was located in the Guanzhong Basin, in the northwest corner of modern-day Xi’an, Shaanxi Province (Fig. 2). The Guanzhong Basin, lying between the Loess Plateau and the Qinling Mountains, was the political and economic core area from the pre-Qin to the Han Dynasty. The materials used for this paper were obtained from four Han tombs (Longzaocun, 2002CSX, 2008XJG, and Sanyaocun) and one Late Neolithic site (Ziweitianyuan) excavated by the Shaanxi Provincial Institute of Archaeology around Chang’an City. Comparative samples were collected from four Late Neolithic sites (Beishantou, Nanshantou, Xiahe, and Hanzhai sites) (Wang, et al., 2018) and one Pre-Zhou site (Zhouyuan site, provided by Dr. Pengfei Sheng), and were dated *ca.* 3625–1046 BCE.

(1) Longzaocun Cemetery.

Located in Weicheng District, Xianyang City, Shaanxi Province, north of Xi’an (34°27′26.8″N , 108°48′21.7″E, Fig. 2(1)). Five well-

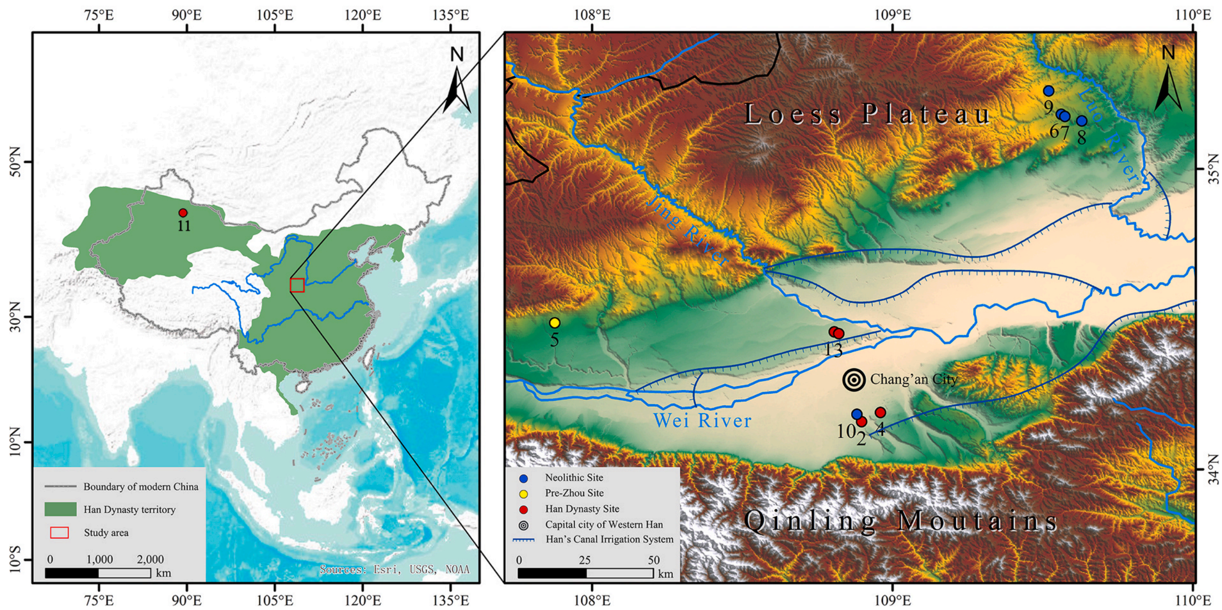

Fig. 2. Location of the Guanzhong Basin and ten sites used in this study (the routes of canal irrigation were redrawn after Dai (1977)). 1: Longzaocun, 2: 2002CSXM68, 3: 2008XJGM22, 4: Sanyaocun, 5: Zhouyuan, 6: Beishantou, 7: Nanshantou, 8: Xiahe, 9: Hanzhai, 10: Ziweitianyuan, 11: Shichengzi.

preserved pottery model granaries containing foxtail millet husks (Fig. 3B) and common millet husks (Fig. 3C) were found in the brick tomb M111 (Fig. 3D) (Liao, et al., 2022). Considering the overall burial structure and the characteristics of the unearthed artifacts, we inferred that the Longzaocun Cemetery dated to the Western Han Dynasty.

(2) 2002CSX Cemetery.

Located in the New Campus of Shaanxi Normal University, Chang'an District, Xi'an City, Shaanxi Province (34°9′30.0″N, 108°53′45.0″E, Fig. 2(2)). The earthen cave tomb M68 consists of an entrance passage and a tomb chamber. The tomb chamber is 3.30 m long, 1.15 m wide and 1.40 m tall. M68 contained three pottery model granaries (Fig. 3E) with foxtail millet husks (Fig. 3B), 10 pottery items, one bronze, and two other cultural artifacts ascribable to the Han Dynasty.

(3) 2008XJG Cemetery.

Located in the eastern part of Xianyang International Airport in Shaanxi Province (34°27′5.5″N, 108°49′14.9″E, Fig. 2(3)). The earthen cave tomb M22 consists of an entrance passage, a covered corridor, and a tomb chamber. The entrance passage is 7.3 m long and 1.05–1.10 m wide. The corridor is 2.6 m long and 1.0 m wide. The chamber is 4.40 m long and 1.40–1.52 m wide. The M22 tomb featured four pottery model granaries containing common millet husks (Fig. 3C), seven other potteries, 17 bronze items, and seven bronze coins, dateable to the Han Dynasty.

(4) Sanyaocun Tomb.

Located in the southern suburbs of Xi'an City, Shaanxi Province (34°11′20.6″N, 108°57′35.1″E, Fig. 2(4)). This brick chamber burial consists of an entrance passage, a covered corridor, and four tomb chambers, dateable to the Eastern Han. The entrance passage is 1.30 m wide. The covered corridor is 0.34 m long, 0.92 m wide, and 1.66 m high. The four chambers are 2.98, 1.84, 1.48, and 1.2 m wide, 2.80, 2.7, 2.7, 1.2 m long, and 3.00, 1.66, 1.24, and 1.1 m high, respectively. A total of 69 artifacts were unearthed, including pottery, glazed pottery, copper coins, bronze mirrors, copper ornaments, iron swords, jade, lead-ware, and glazed ware. Common millet husks (Fig. 3C) were found in the tomb.

(5) Ziweitianyuan Site.

Located in Chang'an District, Shaanxi Province (34°10′58.5 N,108°52′52.7″E, Fig. 2(10)). Charred common millet seeds (Fig. 3A)

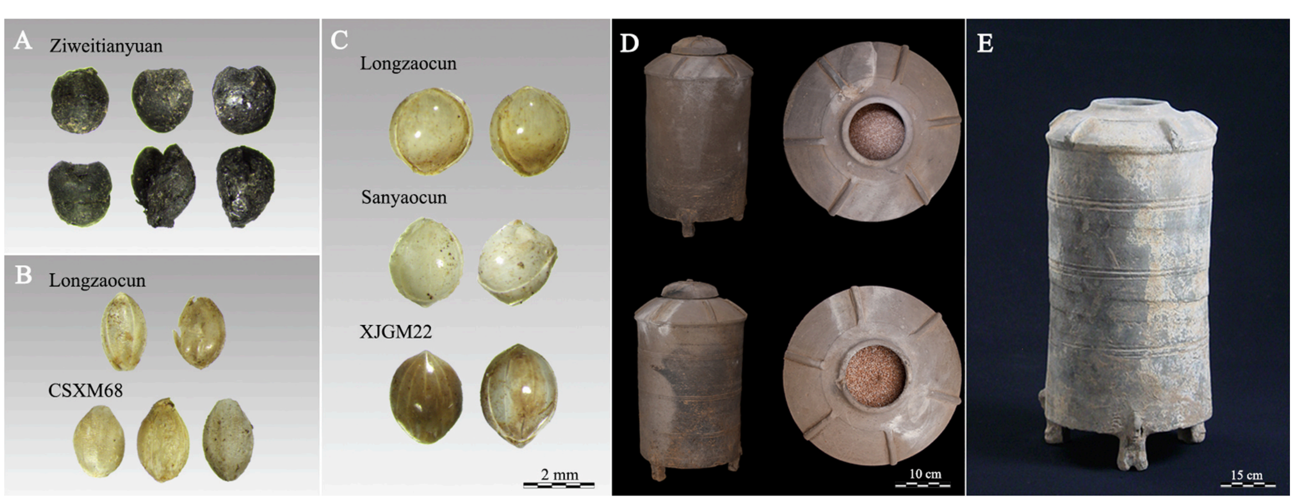

Fig. 3. Samples collected in this study. A: Common millet seeds from Ziweitianyuan Site. B: Foxtail millet husks from Longzaocun and 2002CSXM68. C: Common millet husks from Longzaocun, Sanyaocun, and 2008XJGM22. D: Two pottery model granaries from Longzaocun M111. E: Pottery model granary from 2002CSXM68.

were obtained by flotation from an ash pit (relics unit is H13) of the Late Neolithic Ziweitiantuan Site.

2.2. Methods

2.2.1. Carbon and nitrogen isotopic measurement

Nine samples of uncharred foxtail millet husks and 10 samples of uncharred common millet husks from the Longzaocun Cemetery (LZC), 10 samples of uncharred foxtail millet husks from the 2002CSX Cemetery, 10 samples of uncharred common millet husks from the 2008XJG Cemetery, 10 samples of common millet husks from the Sanyaocun Tomb (SYC), and five samples of charred common millet seeds from Ziweitianyuan Site (ZWTY) were selected for further study.

The δ^{15}N values of wild herbivores are generally 3–5 ‰ higher than natural forage (Hedges and Reynard, 2007). Since no wild animal bones were excavated from Longzaocun, 2002CSX, 2008XJG, Sanyaocun, and Ziweitianyuan, we cited the isotopic data from wild deer bones (n = 12) found at the Wayaogou (*ca.* 4550–4050 BCE) and Dongying sites (*ca.* 3950–3650 BCE, 2650–2050 BCE) in the Guanzhong Basin (Chen, et al., 2016), and subtracted their average δ^{15}N value by 4 ‰ to estimate the nitrogen isotopic baseline of local natural vegetation. However, we acknowledge that wild deer dietary habits exhibit seasonal variation, incorporating a mixture of herbaceous plants in spring and summer, and additional food sources such as nuts, tree branches, and bark in autumn and winter. These dietary shifts could influence the δ^{15}N values of their bone tissues and should be considered as a potential source of variation when interpreting the estimated nitrogen isotopic baseline.

In addition, considering that silkworm manure and silkworm molt could have been added to organic fertilizers applied in the fields during the Han Dynasty (Zhang, 1989), we also used the isotopic data from Han Dynasty silk textiles recovered from the Shichengzi site in Xinjiang (43°36′59.1″N, 89°45′43.2″E, Fig. 2(11)), subtracting 4 ‰ from their average δ^{15}N value to estimate the nitrogen isotopic baseline of natural vegetation. Shichengzi was a Han Dynasty military garrison along the Silk Road, inhabited by agro-pastoralist peoples and Han migrants (Allen, et al., 2022, Sheng, et al., 2020). Therefore, the silk textile should be produced in the Han heartland and brought to the frontier by Han migrants.

The sampled archaeological plant remains and one silk textile were measured using equipment at the Environmental Stable Isotope Laboratory (ESIL), Institute of Environment and Sustainable Development of Agriculture, Chinese Academy of Agricultural Sciences (CAAS). First, 0.5 M HCl at 80 °C was added to the seed samples, and left until the effervescence stopped. The plant samples were then washed three times with the Milli-Q water. The dried seeds were ground into powder with a pestle and then prepared for isotopic analyses (Vaiglova, et al., 2014). We used an IsoPrime 100 IRMS (Elementar, UK) coupled with an Elementar Vario (Elementar, UK), and calibrated with USGS40 ($\delta^{13}C_{VPDB}$ = −26.39 ± 0.04 ‰, $\delta^{15}N_{air}$ = -4.52 ± 0.06 ‰), USGS41a ($\delta^{13}C_{VPDB}$ = 36.55 ± 0.08 ‰, $\delta^{15}N_{air}$ = 47.55 ± 0.15 ‰) as reference materials. We inserted a laboratory reference-Gelatin from bovine skin ($\delta^{13}C_{VPDB}$ = −14.7 ± 0.2 ‰; δ^{15}N = 7.1 ± 0.2 ‰) for every twelve samples. The isotope results were analyzed as the ratio of the heavier isotope to the lighter isotope (^{13}C/^{12}C or ^{15}N/^{14}N) and expressed as ‘δ’ in parts per 1000 or per mil (‰) relative to internationally defined standards (Lee-Thorp, 2008) for carbon (Vienna Pee Dee Belemnite, VPDB) and air nitrogen. The measurement errors were under ± 0.2 ‰ for both δ^{13}C and δ^{15}N values. Simulation experiments show that carbonization will not significantly change the δ^{13}C and δ^{15}N values of foxtail and common millet, so the test results are directly used for analysis (Dong, et al., 2022, Yang, et al., 2011). Further statistical data analysis was performed by the one-way ANOVA, with the significance level set at $p < 0.05$.

2.2.2. Accelerator mass spectrometry radiocarbon dating

To determine the date of the Ziweitianyuan Site, one sample of charred common millet seed recovered from the site was sent to Beta Analytic Inc., Miami, Florida, United States, for radiocarbon analysis. The date was calibrated using the IntCal 20 calibration curve (Reimer, et al., 2020) and OxCal v4.4.4 (http://c14.arch.ox.ac.uk/oxcal).

3. Results

3.1. Isotopic results of archaeological millets

δ^{13}C and δ^{15}N values for common millet (n = 35) and foxtail millet (n = 19) from the five sites are presented in Fig. 4, with detailed results presented in Sup. Table S1. Based on the analysis of wild deer samples from the Late Neolithic Wayaogou and Dongying sites and one Han Dynasty silk textile from the Shichengzi site, the nitrogen isotopic baseline of natural forage was estimated at ~ 0.7 ‰ and ~ 4.8 ‰, respectively (Sup. Tables S2 and S3). The isotopic distribution of plant remains at each occupation site ranged in different intervals, the δ^{13}C and δ^{15}N values at Ziweitianyuan were significantly lower than those at the other four sites. All δ^{15}N values were higher than the natural forage nitrogen baseline estimated from wild deer samples in the Guanzhong region, while the δ^{15}N values from Ziweitianyuan were lower than the baseline estimated from Han Dynasty silk textile.

δ^{13}C values of common millet samples during the Han period (n = 30) ranged from −16.7 ‰ to −10.7 ‰ (mean value ± SD = −13.4 ± 1.8 ‰). The δ^{13}C values of common millet samples during the Late Neolithic period (n = 5) ranged from −10.5 ‰ to −10.3 ‰ (mean value ± SD = −10.4 ± 0.1 ‰). δ^{13}C values of foxtail millet samples during the Han Dynasty period (n = 19) ranged from −14.6 ‰ to −11.6 ‰ (mean value ± SD = −13.1 ± 1.0 ‰).

The δ^{15}N values of common millet samples during the Han Dynasty period (n = 30) ranged from 8.0 ‰ to 15.3 ‰ (mean value ± SD = 11.6 ± 2.6 ‰). δ^{15}N values of common millet samples during the late Neolithic period (n = 5) ranged from 2.9 ‰ to 4.4 ‰ (mean value ± SD = 3.7 ± 0.7 ‰). δ^{15}N values of foxtail millet samples during the Han Dynasty period (n = 19) ranged from 2.1 ‰ to 10.0 ‰ (mean value ± SD = 7.7 ± 2.3 ‰).

In addition, carbon and nitrogen stable isotope data collected for common and foxtail millet seed from the Late Neolithic to Pre-Zhou periods (*ca.* 3625–1046 BCE) of the Guanzhong Basin are plotted in Fig. 5 along with new data from this study, as detailed in Sup. Table S4. One-way ANOVA showed significant differences in the isotope data for common and foxtail millet from all sites (p value < 0.05). Compared with the Late Neolithic period, the δ^{13}C values of common and foxtail millet in the Han Dynasty decreased by approximately 3.4 ‰ and 3.8 ‰ respectively, and the δ^{15}N values increased by approximately 6.5 ‰ and

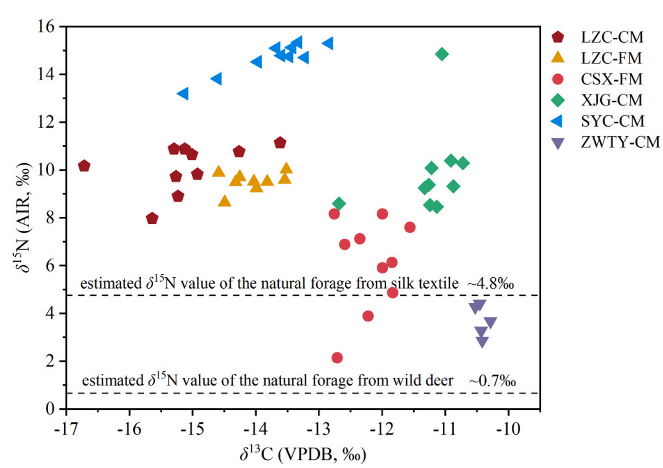

Fig. 4. δ^{13}C and δ^{15}N raw data of archaeological millets from the four Han period tombs and one Late Neolithic Ziweitianyuan site located in the Guanzhong Basin (CM: common millet, FM: foxtail millet, LZC: Longzaocun tomb, SYC: Sanyaocun tomb, ZWTY: Ziweitianyuan site).

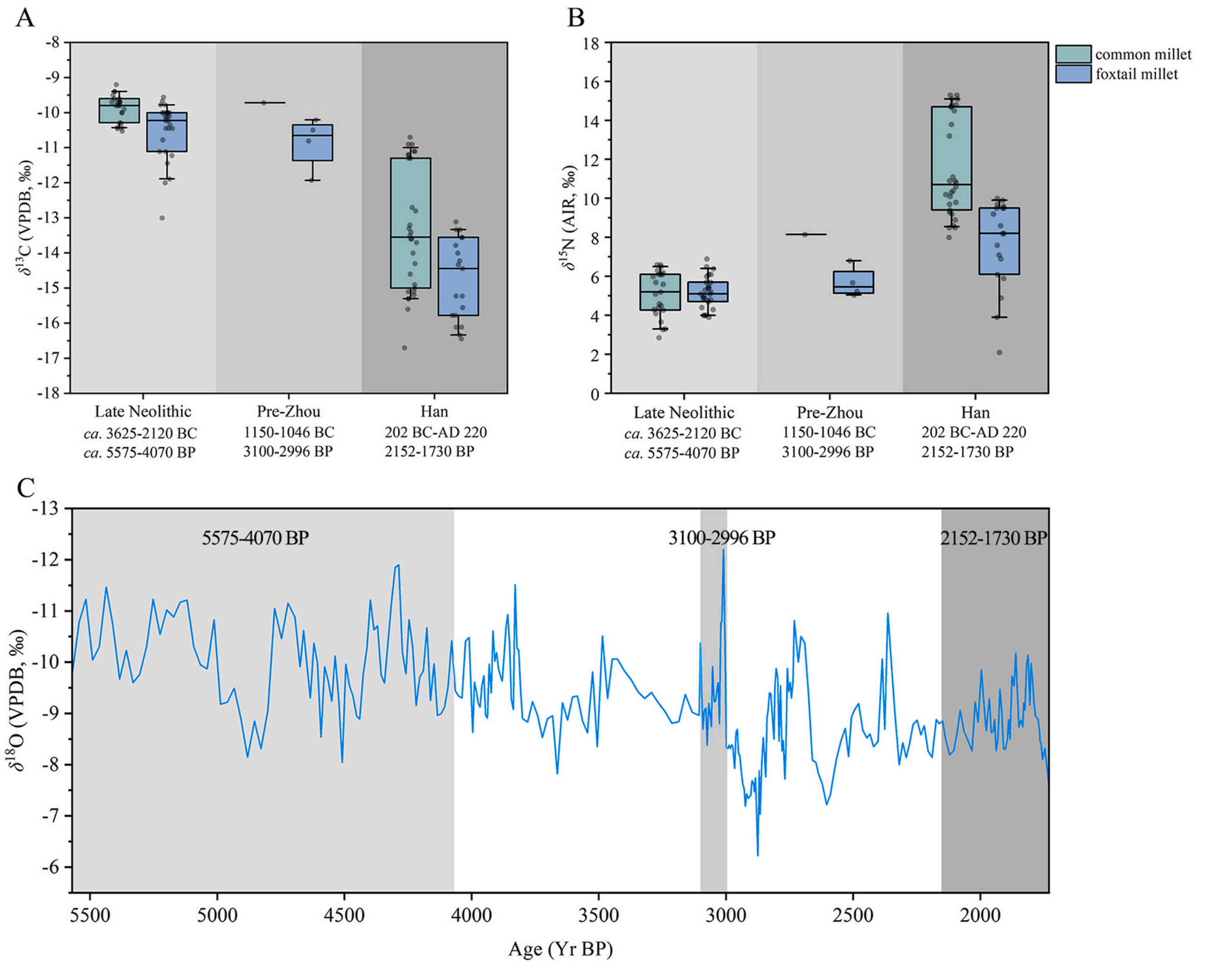

Fig. 5. Stable isotope values of millet and climate records across the Late Neolithic, Pre-Zhou and Han periods. A: $\delta^{13}C$ values of foxtail and common millet from 10 sites, grouped by period. B: $\delta^{15}N$ values of foxtail and common millet from 10 sites, grouped by period. C: $\delta^{18}O$ record from the Jiuxian Cave stalagmites, Shaanxi, China, reflecting monsoonal precipitation variability (Cai, et al., 2010). Shaded regions represent the Late Neolithic (light grey), Pre-Zhou (grey), and Han periods (dark grey).

2.7 ‰ respectively, reflecting the obvious changes in the soil conditions in the Guanzhong Basin over three millennia.

3.2. Radiocarbon dating

Radiocarbon ages for the charred common millet seeds from the Ziweitianyuan site are listed in Sup. Table S5. According to the data, the site dates from 3130 to 3005 cal. BC, i.e., the Late Neolithic period.

4. Discussion

From the early-mid Holocene, the Guanzhong basin emerged as one of the core farming areas of ancient China. High-resolution soil profile studies in Guanzhong indicate that forest clearance and cultivation began approximately 7,500 years ago, a process likely associated with the expansion of agriculture during the Holocene humid period (Huang, et al., 2002). As human activities intensified, soil erosion and fertility loss gradually increased, driving the evolution of farmland management strategies across different historical periods (Vanwalleghem, et al., 2017). Fertilization, farming systems, and water resource management exhibited distinct developmental characteristics at various stages (Li, 1989, Sun, 1984). Carbon and nitrogen stable isotope data from millet crops during three occupation periods in the Guanzhong Basin reveal long-term changes in farmland conditions, providing direct evidence for understanding the sustained management of soils under different historical contexts.

Climate fluctuations have a significant impact on agricultural practices, particularly on long-term timescales (Anderson, et al., 2020). Studies indicate that climate change in the Guanzhong Basin has exhibited distinct phases throughout the Holocene. Paleoclimate data (Liu, et al., 2018) from the Luochuan loess section show that between approximately 5500 and 3000 years ago, annual precipitation in the region increased from around 600 mm to 728 mm, while the mean annual temperature rose from about 10 °C to 12.8 °C; From around 3000 years ago, both precipitation and temperature have gradually declined, approaching modern levels (currently 622 mm and 9.2 °C). Additionally, oxygen isotope records from speleothems at Jiuxian Cave (Fig. 5C) indicate a decreasing trend in summer monsoon precipitation from the Late Neolithic to the Han Dynasty (Cai, et al., 2010). Although the overall climate during the Han Dynasty remained relatively warm and humid, providing favorable conditions for agricultural development (Zhu, 1972), the influence of climatic fluctuations during this period cannot be overlooked.

From an eco-environmental perspective, a fundamental prerequisite for agricultural intensification is the long-term input and management of soil nutrients (Rockström, et al., 2017). This is particularly crucial against the backdrop of Holocene climatic shifts from humid to relatively drier conditions (Cai, et al., 2010, Liu, et al., 2018). Our findings reveal a significant increase in the $\delta^{15}N$ values of millet crops from the Han Dynasty, which reflects, at least in part, the changes in soil management practices implemented to counteract soil nutrient depletion and climate change.

Specifically, compared with the Late Neolithic and Pre-Zhou periods, the $\delta^{15}N$ values of common and foxtail millet samples in the Guanzhong Basin in the Han Dynasty increased by about 6.5 and 2.7 ‰, respectively. We believe that this data indicates a more intensive and effective fertilization practice for millet cultivation by the Han population, based on both modern experimental studies looking at the effect of fertilizer on millet isotope values, and the historical record. Field experiments (Christensen, et al., 2022) show that animal manure application raised $\delta^{15}N$ values of common and foxtail millet by 5.3–7.3 ‰ whereas $\delta^{15}N$ was only slightly affected by the addition of phosphorus and potassium (simulating soil fertility following a slash-and-burn regime). A greenhouse experiment (Dong, et al., 2022) revealed that $\delta^{15}N$ values of millets increase by 1.7 ‰ − 5.8 ‰ under fertilization conditions from 1 % (common in naturally occurring or low manuring level soils in northern China) to 5 % (common in soils in northeastern China or high manuring level soils). Furthermore, historical evidence indicates that the accessibility of fertilizers and the prevalence of artificial fertilization were much higher in the Han Dynasty than in earlier period. First, the scale of domestic animal husbandry in Guanzhong was expanded and people managed pigs on a household system (Liu, 2014, Wang, et al., 2023), which made animal manure more easily available to farmers. An interesting finding is that people in the region tended to build latrines together with pigsties (Fig. 6) (Cao, 1999, Liu, 2014, Liu, 2005). The purpose of such structures was to mix pig manure, human manure, and feed scrap to obtain well-decomposed manure with higher organic content. The "well-decomposed manure from the pigsty (溷中熟粪)" mentioned in the *Book of Fan Shengzhi* refers to this. The most recent research has pointed out the $\delta^{15}N$ value of manure and amount of manure are key factors determining the extent of change in plant $\delta^{15}N$ values (Yang, et al., 2024), and that pig manure has the higher nitrogen availability (Choi, et al., 2006).

Second, more species of fertilizers were available during the Han Dynasty. In addition to human and animal manures, plant ashes, and wild plants, we also find mention of mud, silkworm manure, silkworm molt (Zhang, 1989). A poem contained in the *Book of Han* reads: "Mud from the Jing River, used for irrigation and fertilization, makes my crops grow more abundantly" (泾水一石,其泥数斗,且溉且粪,长我禾黍). The *Book of Fan Shengzhi*, published in the Han, recorded a variety of methods for composting and fertilizing (Deng and Zeng, 2005), implying the importance of fertilization at that time. Therefore, it can be argued that more advanced fertilization practices were available and indeed had been adopted in the core political region of the Han Empire.

It has been confirmed that the carbon isotope ratio of plants is closely related to the water availability in the growth environment, and that water input has different effects on the $\delta^{13}C$ values of different crop species and different parts of the same crop (An, et al., 2015, Lightfoot, et al., 2016, Reid, et al., 2018). Compared to C_3 plants, C_4 plants (such as millet crops) generally exhibit a smaller response in $\delta^{13}C$ values to water availability, as their carbon fixation mechanism minimizes the impact of CO_2 limitation (Bowman, et al., 1989, Ferrio, et al., 2020, O'Leary, 1988). This enhances water use efficiency, allowing C_4 plants to grow in drier conditions. However, the response of C_4 plants to environmental conditions, as reflected in $\delta^{13}C$ values, is complex and varies depending on species and physiological traits (Ferrio, et al., 2020). Additionally, the relationship between carbon isotope values and water availability in millet has been viewed differently. An, et al. (2015) concluded that the $\delta^{13}C$ value of foxtail millet is positively correlated with precipitation when annual precipitation is less than 450 mm, with no significant correlation at levels above 450 mm, but that precipitation and isotopic levels are not related in $\delta^{13}C$ levels of common millet. Experiments by Dong, et al. (2022) and Lightfoot, et al. (2020) on the other hand, showed that watering was positively correlated with the $\delta^{13}C$ value of foxtail millet and negatively correlated with common millet. In a separate study, Yang and Li (2015) found that the $\delta^{13}C$ value of common millet correlated positively with precipitation. These studies highlight the limitations of using millet $\delta^{13}C$ values alone to reconstruct past water conditions.

Compared with the Late Neolithic and Pre-Zhou periods, both species of millet in the Han Dynasty exhibited lower $\delta^{13}C$ values, suggesting that the agricultural environment of the Guanzhong Basin may have undergone changes during this period. Historical records explicitly document the presence of a well-developed irrigation network during the Han Dynasty. Especially in the Guanzhong Basin, large-scale irrigation projects (Fig. 2) such as the Liufu Canal, Cao Canal, Longshou Canal, Bai

Fig. 6. Two pottery model latrine-pigsty-connected buildings excavated from Han period tombs. These were collected in the Hunan Museum and the National Museum of China. The pigsty consisted of a circular wall. A latrine was built on a high platform outside the pigsty, and the lower part was connected to the pigsty.

Canal, Lingzhi Canal, and Chengguo Canal expanded the area of irrigated farmland (Li, et al., 2004). In addition to these hydraulic endeavors, the introduction of new cropping patterns served to mitigate water loss from soil during cultivation, thereby enhancing the sustainability of crop production (Guo, 2001). Furthermore, the observed relationship between elevated nitrogen values and the fertilization of millet crops at four Han Dynasty archaeological sites has been previously discussed as an indicator of advancements in anthropogenic land management. In general, the enrichment of nitrogen values in soils is positively correlated with the organic matter content, and the higher the organic matter content, the higher the available water capacity of the soil (Hudson, 1994). We argue, therefore, that millets in the Guanzhong during the Han Dynasty enjoyed more favorable water conditions in comparison to the Late Neolithic and Pre-Zhou periods, which may have indirectly influenced the observed variations in δ^{13}C values. Nevertheless, we re-emphasize that interpreting water conditions based on C_4 crop δ^{13}C values has limitations. Future research should incorporate more systematic carbon isotope data from wheat and other C_3 crops to further clarify changes in Han Dynasty water management.

Located in the heart of the Han Empire, the pressure on agricultural production in Guanzhong was self-evident. The advance of fertilization and water supply practices, influenced by Holocene climate changes, along with other emerging production technologies, largely maintained intensive agriculture in the core area of the Han Empire. The process of farmland management required continuous investment in substantial material and labor resources. Correspondingly, the individuals interred in the four Han tombs, going by the quality of burial goods and the complexity of tomb structures, were likely to have belonged to the landlord class. Given that agriculture served as the primary means of tax payment and a source of additional profits during the Han Dynasty, landlords could exert their absolute economic advantage and more flexibly utilize more agricultural resources (e.g., access to more fertilizers and water) to maximize their interests. From this perspective, the success of intensive irrigation and fertilization strategies in the Han Dynasty not only fostered advances in farmland management practices but also helped elites accumulate more wealth. This may have accelerated social divisions and unequal economies within the empire.

5. Conclusion

Our study provides carbon and nitrogen stable isotope values for common millet and foxtail millet recovered from four Han Dynastic tombs and one Late Neolithic site in the Guanzhong Basin. Combining related published data and historical information, this study offers direct evidence of agricultural management practices in the core region of the Han Dynasty. Our findings are consistent with historical records of agricultural development in the Han Dynasty, further supporting that this period was a key stage in the intensification of farmland management. Future research should expand the scope of isotope analysis, including systematic studies on wheat crops, to gain a more comprehensive understanding of temporal trends in manure application and water supplies.

An unstable political situation and mobile population are objective factors affecting agricultural productivity. In the years leading up to 202 BCE, northern China was mired in warfare following the collapse of the Qin. It has been first major agricultural revolution in China's imperial era occurred in the powerful Han Empire that followed the peace. However, this view still needs to be treated with caution, as limited availability of crops data for the pre-Qin period. Overall, intensive agricultural practice was one of the cornerstones of maintaining the longevity of China's feudal dynasties. On the other hand, the processes of intensification from the archaeological standpoint remain underappreciated and poorly understood. We look forward to exploring the evolution of farmland management in ancient China over a larger area and a larger time span in the future.

CRediT authorship contribution statement

Jingwen Liao: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis. **Edward Allen:** Writing – review & editing, Investigation. **Amanda G. Henry:** Writing – review & editing, Supervision. **Jason E. Laffoon:** Writing – review & editing, Supervision. **Ming Li:** Resources. **Daiyun Liu:** Resources. **Pengfei Sheng:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2025.109148.

Data availability

C, N stable isotope data and radiocarbon data from the Longzaocun tomb, 2002CSX tomb, 2008XJG tomb, Sanyaocun tomb, Ziweitianyuan site, and Shichengzi site (Original data)

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