Sustainable intensification of millet-pig agriculture in Neolithic North China

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The emergence of complex societies represents one of the major developments of human prehistory. Diverse agricultural strategies were implemented to produce the increased grain surplus necessary to allow the development of complex societies across the world. Little is known, however, about the millet-pig system that developed in Neolithic North China and ultimately underpinned the more complex societies, such as cities and states, in this region. Our data from studies of phytoliths and starches from pig dental residues and stable isotopes of millet grains excavated from the Dadiwan site demonstrate that an intensive crop-livestock system was in practice by at least 5500 years ago. This novel system, characterized by the feeding of millet crop residues to pigs and the fertilization of millet fields with pig and/or human dung, enabled sustainable intensification in agriculture and fed the early complex societies in North China.

After the establishment of agriculture during the Neolithic period, the growth of human populations and surplus food production ultimately underpinned the scaling up of human societies, including an increase in numbers of non-farmers, the development of centres of urbanization and an increase in social complexity[1-4]. How agricultural innovations supported this growth has received increasing attention. In northern Mesopotamia, for example, agricultural extensification involved expanding farmland with lower intensity agriculture[5-6], while controlled irrigation became more important in southern Mesopotamia[7]. Other post-Neolithic land use changes include diversification in long-lived perennial commodity crops like fruit trees and vines[8]. In South China, the Yangtze basin, where highly productive rice agriculture was established in the Neolithic period, continued intensification of a rice monoculture supported the emergence of urban centres like Liangzhu by 5300 calendar years before present (cal yr BP) (Fig. 1)[9,10].

Agricultural strategies that were prominent in the shift from Neolithic village societies to complex societies in North China, however, are less well understood. In this region, social complexity represented by Banpo and Jiangzhai started to appear during the early Yangshao period[11] and significantly increased in some sites like Dadiwan, Xiahe, Xipo and Shuanghuaishu during the late Yangshao period, characterized by wide and rapid emergence of large settlements, large-scale ritual buildings and hierarchical tombs[4,12,13], with urban centres like Shimao and Taosi emerging by ~4500 cal yr BP across parts of the Chinese Loess Plateau and Yellow River basin, and state (Erlitou) formation occurring by 3800 cal yr BP (Fig. 1)[4,11,15].

From at least 8000 to 4000 BP, populations across North China grew reliant on cultivation of the millets (*Setaria italica* (L.) P. Beauv. and *Panicum miliaceum* L.)[16]. Millets tend to have low productivity with traditional yields half or less than that of rice[17], and one third or less than the estimated productivity of Neolithic wheat and barley[18]. A particular challenge with millets was, therefore, to increase production, which can be expected to have involved either an expansion of cultivation over a much greater land area, or reduction of fallow periods, which are expected in loess cultivation[19]. Therefore, key issues are in understanding how production was increased and how utilization of crops was enhanced. These activities would then support the growth in population that eventually underpinned the development of urbanization and state formation in this region surrounding Dadiwan.

Dadiwan and chronology

The Dadiwan site (105°54′14″E, 35°0′54″N, 1460 meters above sea level) is located in the upper reaches of the Wei River, the largest tributary of the middle Yellow River regions in Northwest China (Fig. 1). The site was occupied from 7800 to 4800 cal yr BP. and includes five successive cultural phases from the pre-Yangshao (Phase I), Yangshao Culture (Phase II, III and IV) and Changshan Culture (Phase V)[13] (Extended Data Fig. 1). The Dadiwan site is famous for both the early appearance of millet (*Panicum miliaceum* L.) agriculture in the pre-Yangshao period (7800-7200 cal yr BP)[13,20-21], and its developed millet-pig-based agricultural system[22] and associated developed settlements[13]. During Phase I, both millet agriculture and the population at Dadiwan are limited. In the early Yangshao period (Phase II, 6500-5900 cal yr BP), a well-organized hierarchical settlement emerged, and social complexity reached a high level in the late Yangshao period (Phase IV, 5500-4800 cal yr BP) exemplified by enormous enlargement of the site, more hierarchical house features with large ritual buildings, and rich delicate pottery which could only made by specialized craftsmen[13].

To better understand the agricultural economy during the rise of societal complexity, we focused on the integration of the two core elements of millet-pig-based agriculture at Dadiwan: the dominant plant crops, including foxtail millet and common millet, and the key livestock animal, the domesticated pig (*Sus scrofa domesticus* L.). Dental residues from the excavated pig teeth were studied for phytolith and starch remains to reconstruct pigs' diets, and stable isotopic analyses of charred millet grains were completed to evaluate potential field manuring practices.

Thirty-five pig jawbones unearthed from Dadiwan during the excavations in the 1970s and 1980s (Extended Data Table 1) were chosen for dental residue studies, ten of which were directly dated by accelerator mass spectrometry (AMS) (Methods). Although obvious dental calculus was not commonly observed in our samples, food residues can stick to the mucosa on the surfaces of pig teeth during feeding[23], and analysis of these deposits can provide information regarding pig diet[24]. We obtained 35 residue samples for phytolith and starch analyses. The pig mandibles were either brushed or washed of any clinging dust, and one sample of dust from the storeroom was analyzed to make certain there was no potential contamination from the storage environment. Ten samples of the contemporaneous sediments from the insides of the pig mandible medullary cavities were analyzed to judge the potential contamination from the original, buried site contexts (Extended Data Table 1 and Methods).

According to the phase assignments of archaeological features in the original archaeological reports, the sampled jawbones were all assigned to the earlier four cultural phases at Dadiwan, including one from the pre-Yangshao phase, twelve from the early Yangshao phase, and eleven from each of the middle and late Yangshao phases (Extended Data Table 1). Direct AMS ^{14}C dating on ten of them, however, reveal that their original phase assignments are problematic (Extended Data Table 2). Only the dating results from the single pre-Yangshao sample is consistent with its original phase assignment. The remaining nine dated samples, three purportedly from each of the early, middle and late Yangshao phases, all dated to the late Yangshao phase (5500-4800 cal yr BP). As the remaining 34 jawbones were all archaeologically assigned to the Yangshao period during excavation, to be conservative, we here assume that the 25 undated samples used in this study are also from the late Yangshao phase, as those directly dated (Extended Data Fig. 1 and Extended Data Table 2).

Feeding pigs by millet husks

A total of 6834 phytoliths and 59 starch granules were recovered from the extracted teeth residues (Methods), including phytolith morphotypes from millet husks (η- and Ω-type phytoliths), and those from the leaves and stems of grasses (Poaceae) (Fig. 2, Extended Data Table 3 and Supplementary Fig. 1). Identifiable starch granules from millets, the grass tribe Triticeae, and underground storage organs (USOs) are present as well (Fig. 2 and Supplementary Fig. 2).

In the single pre-Yangshao sample, only one out of 275 phytoliths (lower than 0.5%) is from the husk of common millet (Extended Data Table 3). By contrast, 3764 millet husk phytoliths were identified in the late Yangshao samples (n=34), making up over 57.4% (even as much as 80% in six samples) of all the identified phytoliths in these assemblages (Fig. 2 and Extended Data Table 3). Only 15 millet starch grains, however, were identified among the late Yangshao samples, and these occur at a very low frequency of 17.6% of the assemblage (Fig. 2). These data are notably in contrast with the high occurrence frequency of 91.2% for the millet husk phytoliths among these samples (Fig. 2 and Extended Data Table 3). In the sediment control samples, no starch was recovered and the percentage of millet husk phytoliths is much lower than the studied residue samples (Extended Data Fig. 2), indicating that the microfossil remains in the dental residue samples are not derived from the associated sediments. No starch or millet phytoliths were detected in the store-room dust sample, thus eliminating the possibility of contamination during storage.

The high frequency of millet husk phytoliths and low occurrence of millet starches on late Yangshao pig teeth in the Dadiwan site suggest that the animals may have been fed predominantly with millet husks, crop residues, together with some geophytes and weeds as supplementary forage. This dietary pattern, based on fiber-rich husks rather than high-starch grain, may explain why there is no obvious dental calculus on our samples, as only high carbohydrate consumption can facilitate calculus formation on teeth[25]. Previous studies of stable isotopes on Neolithic pig bones have revealed that pig husbandry relied heavily on millets in North China and that the proportion of millets in pig diets appears to reach more than 90% in late Neolithic sites[22,26-30]. In this study, our microfossil data from pig dental residues provide more in-depth study and specific details of the pig raising practice than can be revealed by isotope studies on their own.

Manuring millet plots with pig dung

For the isotopic analyses, 12 samples of charred millet seeds (totaling 355 individual grains) floated from deposits in six Yangshao house and pit features unearthed during the recent 2014-2015 excavation. Their δ^{15}N values were obtained (Extended Data Table 4). Four of these samples were dated directly by AMS (Methods).

The direct dates derived from millet grains support their original cultural phase assignments during excavation, which cover the entire Yangshao period (6500-4800 cal yr BP) (Extended

Data Fig. 1 and Extended Data Table 2). δ^{15}N values of charred millet grains at the Dadiwan site range from +4.4‰ to +6.6‰ (Fig. 3, Extended Data Tables 4), significantly higher than the estimated δ^{15}N values of the contemporary local herbivore forage (+2.5±1.2‰, n=9) (Fig. 3, Extended Data Tables 5) which represent an approximation of the local δ^{15}N value of nonarable vegetation[31,32]. In accordance with the results from the manuring experiment for common and foxtail millets in Europe[33], our data from modern millet plot investigation suggest that the δ^{15}N value baseline of modern C_4 and C_3 plants is low, approximately –1.5‰ and –1.0‰ (Methods, Extended Data Figs. 3, 4 and Extended Data Table 6), respectively, in northern China. And manuring can significantly enhance the δ^{15}N values of foxtail millet and C_4 weeds (Extended Data Fig. 4 and Extended Data Table 6). The elevated δ^{15}N values of millet from the Dadiwan site, compatible with the δ^{15}N values of modern foxtail millet manured by pig dung (Extended Data Fig. 4), therefore, indicate that a sustained manuring practice was undertaken in the millet fields at the Dadiwan site during the Yangshao period. Comparing the nitrogen isotopic results of herbivore forage, millet grains, pigs and humans, it is very likely that the high δ^{15}N values of pigs, as well as high δ^{13}C (ref. [22]), as elevated as humans, at Dadiwan during the late Yangshao period, was induced by the consumption of ^{15}N-enriched millet residues (Fig. 3). Contemporary sites in the lower regions of the Wei River have also yielded charred millet grains with high δ^{15}N values[29]. Thus, field manuring practices appear to have been widespread during the Late Neolithic in North China (Fig.1).

Zooarchaeological studies of the faunal assemblage from the late Yangshao period at Dadiwan indicate that pigs were the dominant domesticated animals at the site during this time[13], thus, it would follow that pig dung was a likely source of manure for fertilizing fields. Human feces and/or leftovers could also contribute. The large number of pig bones found in the late Yangshao period at the Dadiwan site (Number of Identified Pieces (NISP): 1999, 55% in the faunal assemblage)[13], indicate a large population of pigs that could provide a stable source of organic fertilizer for millet fields if at least some of them were captive and fed with millet husks as suggested above, and as is now a common practice in modern smallholding production in the region[34].

An intensive millet-pig system

In combination, our data sets indicate that millet-pig-based agriculture at the Dadiwan site evolved into an intensive and integrated agricultural system by the late Yangshao period at the latest, about 5500 years ago (Fig. 4). Previous isotopic analysis of human and animal bones from the site demonstrated that millet grains became humans' staple food at Dadiwan by at least 5900 years ago[22]. Our data indicate that, subsequently, millet husks, crop residues remaining after harvesting and winnowing, were used to feed pigs, resulting in both the high $\delta^{13}C$ values of the pig bones[22] and quantities of millet husk phytoliths in the pig dental residues. This strategy of pig husbandry avoided the problem of dietary overlap and food competition between human and pigs[28,35,36]. Further, the deliberate control of pig diet implies an intensive pig management strategy such as sty-raising[37]. Finally, pig dung, which could have been collected in the pens, in combination with night soils, would have been a readily available resource for manuring millet fields to produce higher yields, and reduce the need for fallows. Thus, a crop-livestock system with the core values of sustainable agricultural intensification[38-40] which increased productivity through an increase in crop utilization and soil fertilization was in place during the later Neolithic in North China, facilitating population density growth (Fig. 4).

The large quantities of pig remains recovered from the late Yangshao at the Dadiwan site and contemporary archaeological sites across North China indicate that more pigs were raised during this time than previously[41,42], as human populations increased[43]. With increasing crop yields capable of feeding both more people and more pigs, this initial millet-pig-based agriculture evolved into a more efficient, productive, and sustainable economic system. This new system not only provided the necessary foundation for the development of complex societies in ancient China, but also is one of the key components of the complex societies with essential high work specialization and communal management, and is directly comparable with the intensive crop-livestock system which is still flourishing in the region today[38-40].

Methods

Pig dental residue collection and contamination control

As the pig jawbones were unearthed more than 40 years ago, associated sediments around them, which are optimal for assessing potential contamination after burial, are impossible to acquire. Instead, we collected and analysed the sediments preserved in the jawbone medullary cavities. After excavation, the jawbones were stored in the storeroom for decades. Thus, we also collected the dust in the storeroom for analysis for further contamination control. During sampling, we used ultra-pure water to clean the outside of the jawbones to remove the dust that had accumulated during storage. To obtain adhering dental residues, the teeth in pig jawbones were placed in an ultrasonic cleaner for 5 minutes. During laboratory analysis, all implements such as knives, test tubes, glass stirring rods, etc. were sonicated and then boiled 15 min to prevent any lab contamination.

Charred millet grain sampling

Systematic flotation was carried out during the recent excavation in the Dadiwan site in 2014-2015. Twelve samples (a total of 355 millet grains) of intact charred millet grains were obtained from six Yangshao cultural features, houses or pits (Extended Data Table 4). Two taxa—foxtail millet and common millet—were collected from each of the features for $\delta^{15}N$ analysis.

Extraction and identification of starch grains

The dental residue samples were processed based on the protocol modified from the references[44]. First, a solution of 6% H_2O_2 was used to oxidize and remove some of the organic matter. Second, a solution of 10% HCl was used to remove the carbonates. Third, a 5% Sodium metaphosphate solution [$(NaPO_3)_6$] was used to disperse the clay to release the microfossils. Finally, a heavy liquid solution of CsCl (1.8 g/cm^3) was added to isolate the starch grains.

The materials recovered from the flotation of CsCl were mounted in 10% glycerine and 90% water on a clean glass slide and scanned with both white and cross-polarized light at a magnification of 400× using a Leica microscope. Starch grains were classified based on their morphological features, including size, shape, position and form of the hilum and fissure, number and characteristics of pressure facets, presence or absence of demonstrable lamellae and extinction cross[45,46]. The numerous previously published studies available on starch grain morphology were consulted[47-50]. Except 10 unidentifiable starch grains, the remaining were classified into three general groups conservatively in this study: 18 polyhedral or spherical starch grains, ranging 7.7-20.3 μm in size, are identified as millets (Supplementary Fig. 2a); 22 lenticular or circular granules, ranging 18.1-36.0 μm, are derived from the Triticeae (Supplementary Fig. 2b); and 9 oval or spherical starch grains with bent extinction crosses, ranging 9.6-35.9 μm, are from some underground storage organs (USOs) (Supplementary Fig. 2c to f).

Extraction and Identification of phytoliths

The dental residue samples which were previously analyzed for starches were processed based on the protocol modified from the references[51-53]. A heavy liquid solution of $ZnBr_2$ (2.35 g/cm^3) was added to the samples to isolate the phytoliths. The recovered material from the flotation of $ZnBr_2$ was mounted with Canada balsam.

Identification was performed using a Leica microscope with phase-contrast and microscopic interferometer at 400× magnification. All phytoliths recovered from pig dental residues were counted. Phytoliths were classified based on the system proposed by previous study[53] and the International Code for Phytolith Nomenclature (ICPN1.0)[54]. The phytolith types (η-and Ω-type phytolith) from millet husks were identified according to the criteria established by previous studies[55,56].

Stable isotope analysis of charred millet grains

A modified method was used to pretreat the charred millet samples[57]. First, the millet grains were soaked with 0.5M HCl at 80°C for 60 min. Second, we rinsed the millet grains with ultra-pure water six times. Third, we freeze-dried the grains and crushed them into a homogeneous powder. Finally, we weighed 2.5-3.0 mg samples into tin containers for isotopic measurement. The δ^{15}N values of all samples were measured in the Key Laboratory of Western China's Environmental Systems (Ministry of Education), Lanzhou University. The isotope ratios were measured in a Finnigan MAT 253 mass spectrometer and expressed as δ in per mil (‰) relative to the internationally defined standards for nitrogen (Ambient Inhalable Reservoir, AIR). The analytical precision for nitrogen isotopes was 0.1‰[58]. Given that there are no significant isotopic changes of δ^{15}N values (Δ=–0.02‰) of millet grains after charring[58], no isotopic correction was carried out on these grains for the effect of charring. The δ^{13}C values of remaining powder samples were measured at the Environmental Stable Isotope Laboratory (ESIL), Institute of Environment and Sustainable Development of Agriculture, Chinese Academy of Agricultural Sciences.

Estimating the δ^{15}N value of herbivore forage at Dadiwan

It is important to estimate the nitrogen isotope baseline of the local vegetation before considering possible manuring effects on the crops. It is common practice to calculate the δ^{15}N values of herbivore forage based on the isotopic data of wild herbivores[31,32,59,60]. Here, the mean δ^{15}N value of the Yangshao period herbivore forage is estimated to be equal to 2.5‰, calculated by subtracting 4‰ (the mean isotopic trophic level increase)[31] from the mean δ^{15}N value of the bones of wild herbivores (+6.5±1.2‰, n=9) excavated from Dadiwan (Extended Data Table 5)[22].

Investigation and sampling of modern millet plot

In order to confirm the manuring impact on the δ^{15}N values of millet grains in northern China, we found a millet plot (113°10′33″E, 36°45′31″N), being manured by pig dung without chemical fertilizers, and without irrigation, in Malantou village, Wuxiang County, Shanxi Province, on the Chinese Loess Plateau, in October 2020 (Extended Data Fig. 3). The annual rainfall in this area is 400-600 mm (Extended Data Fig. 3)[61], which is similar to the reconstructed annual precipitation (500-600 mm) during the Yangshao period in North China (reconstructed by pollen assemblages in Gonghai Lake, Central Loess Plateau.)[62]. Through interviewing the owner of this farmland, we learned that the area of this farmland is about 1000 m^2, about 1000 kg of manure is applied annually, millet (*Setaria italica* (L.) P. Beauv.) and corn (*Zea mays* L.) are planted in turn every year, and the annual manure amount is roughly remained the same. An experimental study involving different kinds of modern manure composts shows that the distribution of δ^{15}N values is relatively concentrated within the same type, and there is little difference among different types of manure composts—the maximum difference in mean value is only +1.5‰ (ref. [63]). Therefore, the influence of animal diets on manure δ^{15}N values is very small.

In order to know whether manure can improve the δ^{15}N values of millet and whether there is a difference in the baseline of δ^{15}N values between C_3 and C_4 plants, 23 samples of millet grains and 2 samples of C_4 weed seeds were collected in the farmland, and 4 samples of C_4 weed seeds and 2 samples of C_3 weed seeds were collected in the area outside of the plot, which was not affected by manuring (Extended Data Table 6), in 2020.

Isotopic analysis of modern plant samples

Subsamples of 1 g (approx. 400) dried millet grains were ball milled for isotopic analysis and the modern samples were measured at the Environmental Stable Isotope Laboratory (ESIL), Institute of Environment and Sustainable Development of Agriculture, Chinese Academy of Agricultural Sciences , using an IsoPrime 100 IRMS (Elementar, UK) coupled with an Elementar Vario (Elementar, UK), and calibrated with USGS 40 ($\delta^{13}C_{VPDB}$=–26.39±0.04‰, $\delta^{15}N_{AIR}$=–4.52±0.06‰） and USGS41a ($\delta^{13}C_{VPDB}$=+36.55±0.08‰, $\delta^{15}N_{AIR}$=+47.55±0.15‰) reference materials. For every 12 samples, a laboratory reference-Gelatin from bovine skin ($\delta^{13}C$=+14.7±0.2‰; $\delta^{15}N$=+6.9±0.2‰) was inserted for calibration and to monitor stability. 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 for carbon (Vienna Pee Dee Belemnite, VPDB) and air nitrogen. The measurement errors were less than ±0.2‰ for both $\delta^{13}C$ and $\delta^{15}N$ values.

AMS ^{14}C radiocarbon dating

Ten pig jawbones were dated directly at Peking University in Beijing. Four millet samples were dated directly by Beta Analytic, Miami, Florida, USA. The IntCal20 curve[64] and the Libby half-life of 5568 yr were used in the tree-ring calculation of all dates, with the calibration performed using the OxCal 4.4 program[65]. All ages are reported as "calendar year before present (cal yr BP)", relative to 1950 CE (Extended Data Table 2).

Data availability:

The data that support the findings of this study are available in the Article and Extended Data.

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Author Contributions Statement

D.Z., F.C. and X.Y. designed the study; J. Yang, W.W., H.W., Y.Y., D.Z., H.L., J.W., L.R., X.S. and J. Yao collected dental residue samples; J. Yang, X.Y. and W.W. performed microfossil analysis; J. Yang, D.Z., X.Y., F.C., L.P., W.W., D.Q.F. and Y.G. analyzed data; J.W. and L.R. identified the faunal remains; H.L. identified the millet grains; J. Yang, D.Z. and J. Yao carried out stable isotope analysis; H.X., H.L. and J.Y. processed dating samples; J. Yang performed modern field survey and sampling; J. Yang, D.Z., X.Y., F.C., D.Q.F. and L.P. wrote the paper with contributions of all authors.

Competing Interests Statement

The authors declare no competing interests.

Figure Legends

Fig. 1 | Geographic location of the study area and the spatial pattern of millet-pig-based agriculture along the Yellow River valley, Late Neolithic North China. 1, Dadiwan. 2, Banpo. 3, Jiangzhai, 4, Xiahe. 5, Shimao. 6, Xipo. 7, Taosi. 8, Erlitou. 9, Shuanghuaishu. 10, Liangzhu. The base map was obtained from the Natural Earth public domain map dataset (https://www.naturalearthdata.com/downloads/10m-raster-data/).

Fig. 2 | Diagram showing the percentage of millet husk phytoliths and the number of starch grains from pig dental residues at Dadiwan. The symbol "*" indicates that the total number of phytoliths is less than 50, not large enough for calculating the percentage of millet husk phytoliths. "USOs" is the abbreviation for underground storage organs. Red bars represent the samples from the Pre-Yangshao period, and blue bars represent the samples from the Late Yangshao period.

Fig. 3 | The comparison of δ^{15}N values of herbivore forage, millet grains, pigs and human at Dadiwan during the Yangshao period. The δ^{15}N values of pigs and humans at Dadiwan are from ref.[22]. The box-plot elements are defined as: white square, mean; center line, median; box limits, upper and lower quartiles; whiskers, minimum and maximum.

Fig. 4 | Schematic drawing of the intensive millet-pig system in Neolithic North China.

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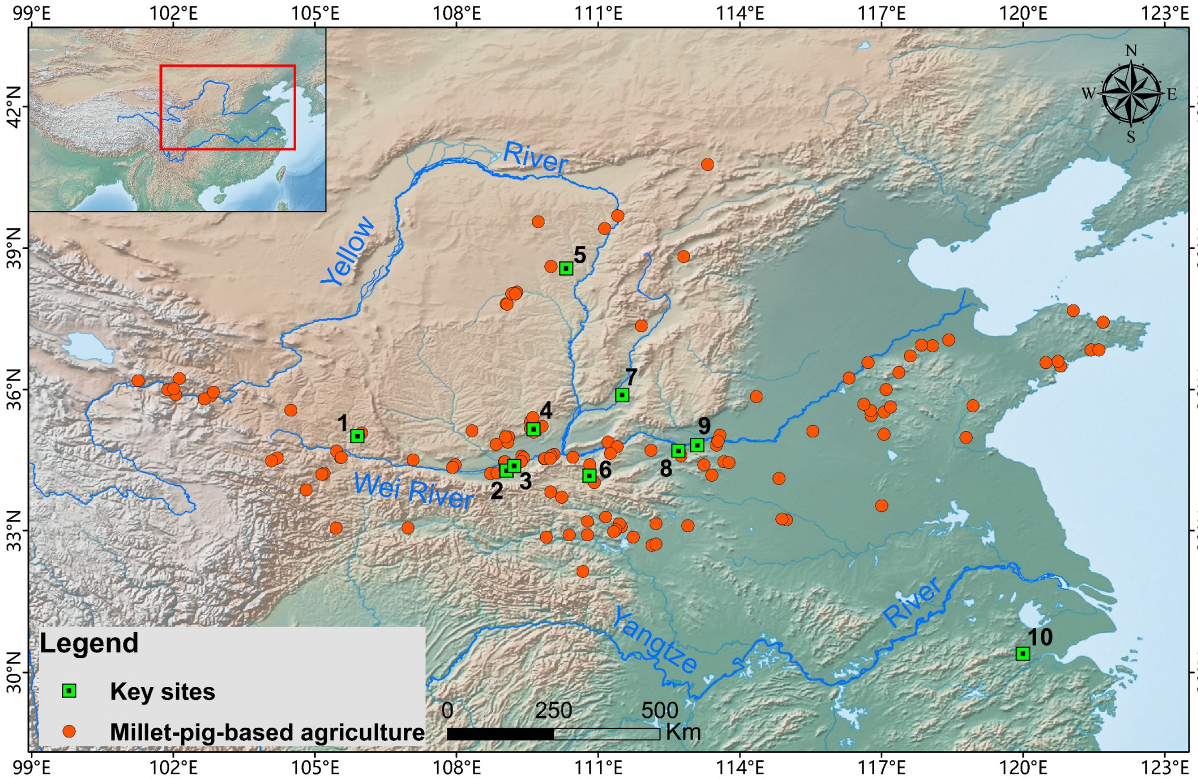
99°E
102°E
105°E
108°E
111°E
114°E
117°E
120°E
123°E
42°N
39°N
36°N
33°N
30°N
N
S
W
E
Yellow
River
Wei River
Yangtze
River
1
2
3
4
5
6
7
8
9
10
Legend
Key sites
Millet-pig-based agriculture
0
250
500
Km

Figure 1

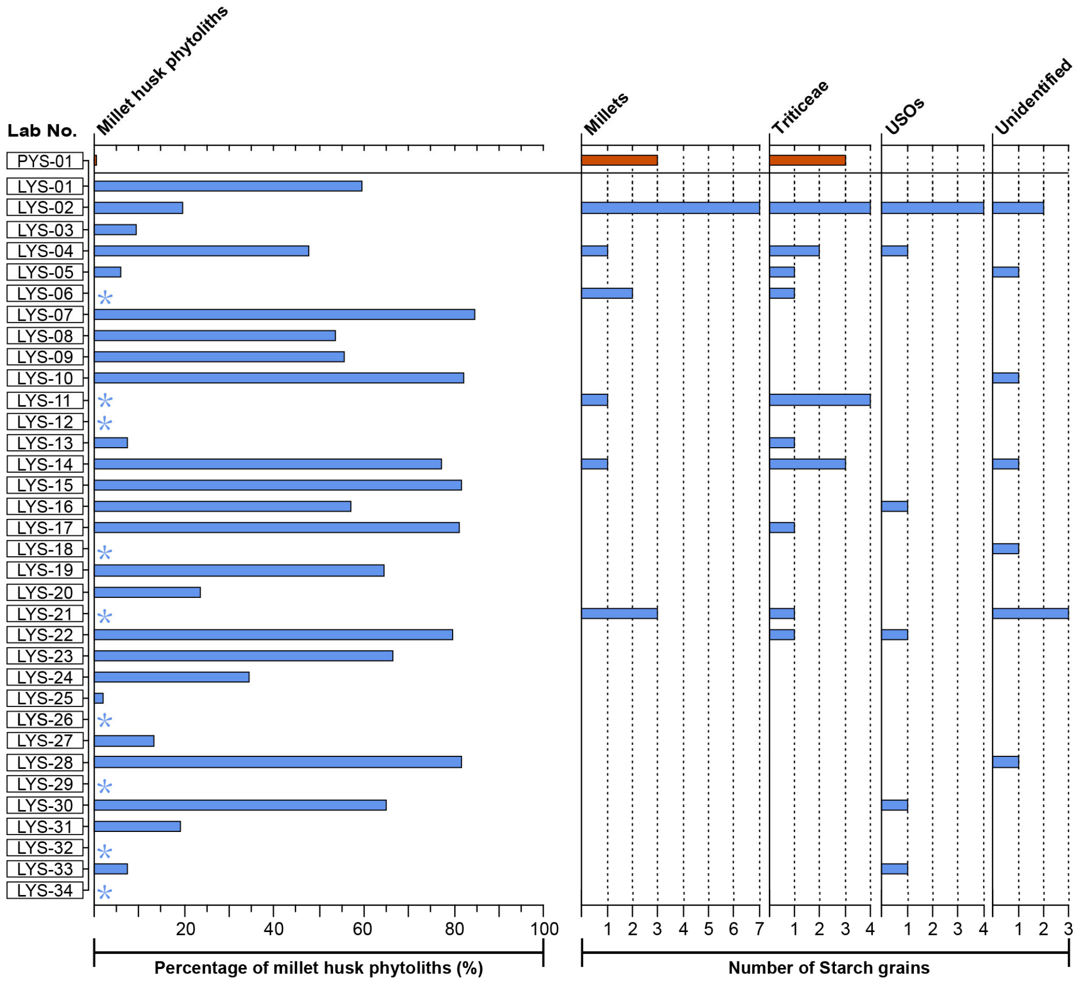
Lab No.
Millet husk phytoliths
Millets
Triticeae
USOs
Unidentified
PYS-01
LYS-01
LYS-02
LYS-03
LYS-04
LYS-05
LYS-06
LYS-07
LYS-08
LYS-09
LYS-10
LYS-11
LYS-12
LYS-13
LYS-14
LYS-15
LYS-16
LYS-17
LYS-18
LYS-19
LYS-20
LYS-21
LYS-22
LYS-23
LYS-24
LYS-25
LYS-26
LYS-27
LYS-28
LYS-29
LYS-30
LYS-31
LYS-32
LYS-33
LYS-34
20 40 60 80 100
1 2 3 4 5 6 7
1 2 3 4
1 2 3 4
1 2 3
Percentage of millet husk phytoliths (%)
Number of Starch grains

Figure 2

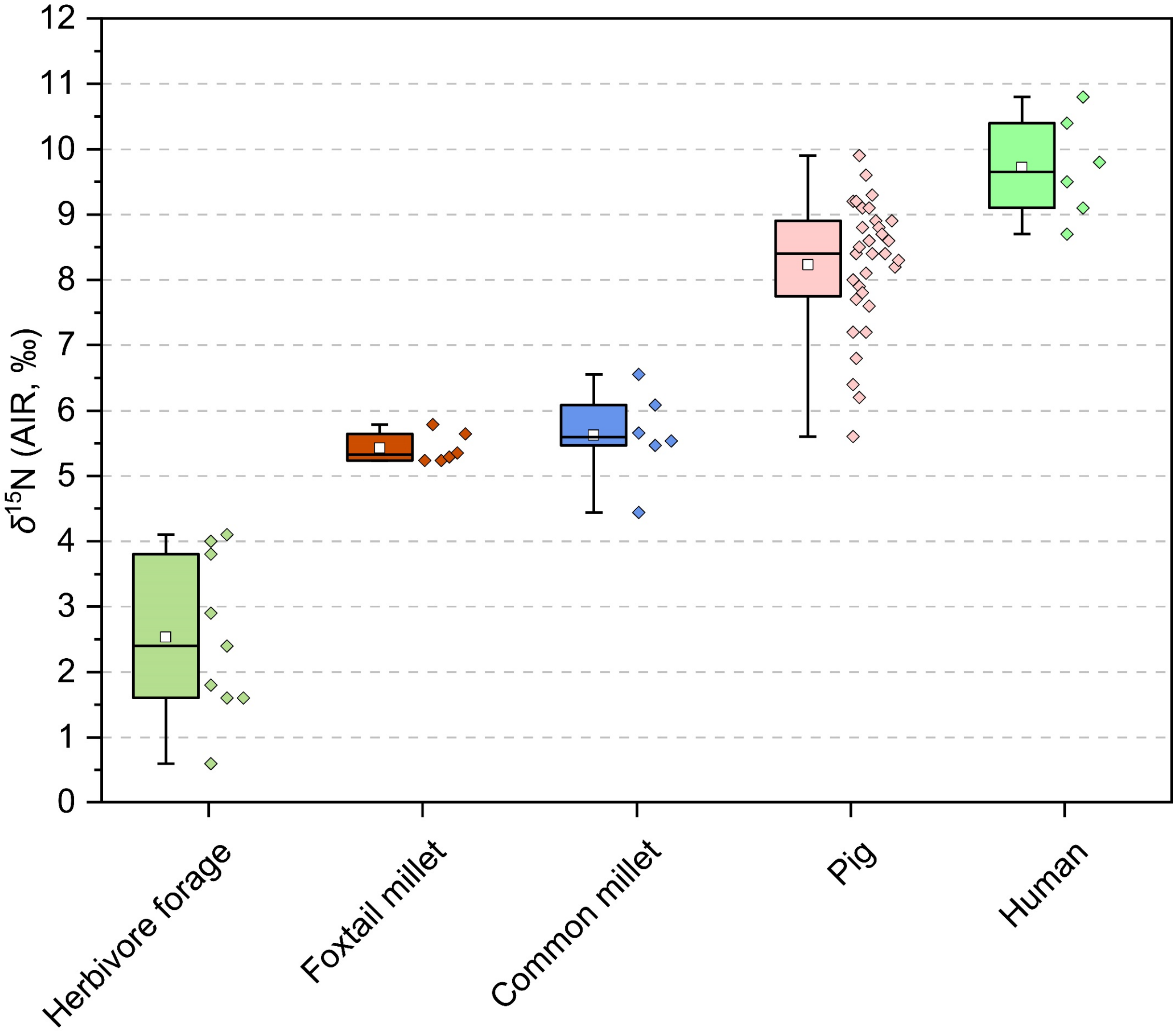
δ15N (AIR, ‰)
12
11
10
9
8
7
6
5
4
3
2
1
0
Herbivore forage
Foxtail millet
Common millet
Pig
Human

Figure 3

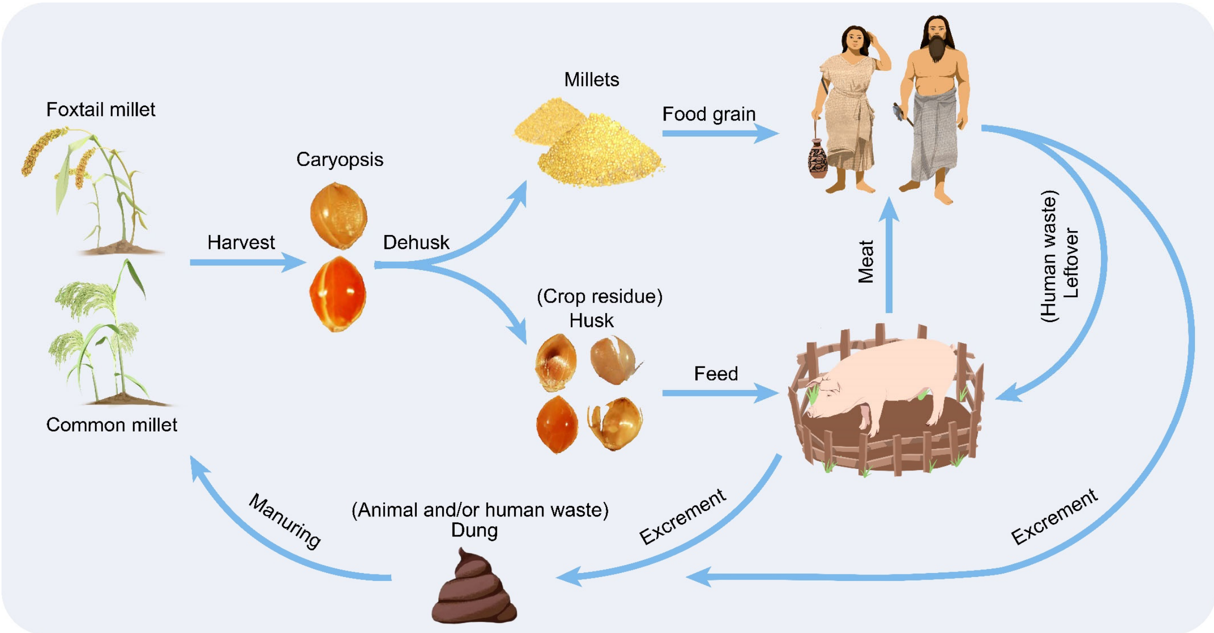
Foxtail millet
Common millet
Harvest
Caryopsis
Dehusk
Millets
Food grain
(Crop residue)
Husk
Feed
Meat
(Human waste)
Leftover
Manuring
(Animal and/or human waste)
Dung
Excrement
Excrement

Figure 4