

Temporal changes of mixed millet and rice agriculture in Neolithic-Bronze Age Central Plain, China: Archaeobotanical evidence from the Zhuzhai site

The Holocene
1–17
© The Author(s) 2017
Reprints and permissions:
sagepub.co.uk/journalsPermissions.nav
DOI: 10.1177/0959683617744269
journals.sagepub.com/home/hol


Can Wang,¹ Houyuan Lu,^{1,2,3} Wanfa Gu,⁴ Xinxin Zuo,¹
Jianping Zhang,^{1,2} Yanfeng Liu,⁴ Yingjian Bao⁵ and Yayi Hu⁴

Abstract

Mixed millet and rice agriculture is a unique agricultural style of China, and is distributed in a broad band between the Yangtze and Yellow River basin. However, the development of this style during the Neolithic-Bronze Age has not been comprehensively clarified, owing to limited archaeobotanical data and imprecise chronology for most of the regions. Here, the Central Plain, a location where mixed agriculture may have first appeared, was selected as the area for research. Phytolith and microfossil analyses from the Zhuzhai site, together with the accelerator mass spectrometer (AMS) radiocarbon dating of samples, reveal information about the temporal changes of mixed agriculture as well as the domestication and cultivation of crops in this region. The results indicate that mixed millet and rice agriculture formed in the Central Plain about 8000 years ago. Common millet was the principal crop in the Peiligang and Yangshao periods, with the domestication process beginning in the Peiligang period and continuing up to the Shang period, at which time it was replaced by foxtail millet. Foxtail millet may have gone through a significant degree of domestication by ca. 6000 cal. BC, but its domestication process was still unclear. Rice had appeared since the Peiligang period, but its proportions were always low. Rice assigned to the Peiligang and Yangshao Cultures was the domesticated *japonica*, and its cultivation was always performed in dry field systems through the Neolithic-Bronze time. Within the subsistence economy, mixed agriculture was a minor component during the Peiligang period, but has been dominant since the Yangshao period.

Keywords

Central Plain, China, mixed agriculture, Neolithic-Bronze Age, phytolith, plant macroremains

Received 5 June 2017; revised manuscript accepted 24 October 2017

Introduction

It is generally accepted that China is an independent center where the domestication of millets and rice took place (Larson et al., 2014). This domestication is regarded as a protracted process that eventually led to the appearance of millet and rice agriculture in the Yellow River and Yangtze River valleys, respectively (Fuller et al., 2014; Gross and Zhao, 2014; Zhao, 2011a). The development and interplay of these two agricultural systems during the Neolithic-Bronze Age not only facilitated prehistoric cultural evolution and demographic expansion in China (Wang et al., 2014) but also was fundamental to the formation of ancient Chinese civilization (Liu and Chen, 2012). Hence, in view of their profound impacts on human societies, the timing, location, processes, dispersals, and spatial-temporal distribution patterns of millet and rice agriculture have been subjected to intensive research in China within the past two decades (Cohen, 2011; Jones and Liu, 2009; Lu, 1999; Qin, 2012; Zhao, 2014).

At present, archaeobotanical evidence has certainly suggested that the origin of Chinese agriculture can be traced back to the early Holocene, with the earliest domesticated millets and rice dating between 8000 and 6000 cal. BC (Deng et al., 2015; Lu et al., 2009a; Yang et al., 2012; Zheng et al., 2016; Zuo et al., 2017). Meanwhile, a north-south pattern for the development and distribution of millet and rice farming was confirmed (Crawford, 2006;

Lu, 2006). However, this division was not distinct, as there was a large area of millet and rice mixed agriculture that existed between the Yellow and Yangtze Rivers. This was a result of the bidirectional spread between both kinds of agricultural systems (Qin, 2012; Wang and Xu, 2003). Furthermore, regional differences of

¹Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, China

²Center for Excellence in Tibetan Plateau Earth Science, Chinese Academy of Sciences, China

³University of Chinese Academy of Sciences, China

⁴Zhengzhou Municipal Institute of Archaeology, China

⁵The School of History and Culture, Henan Normal University, China

Corresponding authors:

Can Wang, Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, No. 19, Beitucheng Western Road, Beijing 100029, China.
Email: shandawangcan@163.com

Houyuan Lu, Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, No. 19, Beitucheng Western Road, Beijing 100029, China.
Email: houyuanlu@mail.iggcas.ac.cn

mixed millet and rice farming have been recognized, with the relative importance of millets versus rice varying among the Hanjiang River valley (Deng et al., 2015; Weisskopf et al., 2015a), Huaihe River valley (Yang et al., 2016a), Weihe River valley (Zhang et al., 2010b), Shandong Highland (Crawford et al., 2016; Jin et al., 2016), Chengdu Plain (d'Alpoim Guedes et al., 2013), and Central Plain (Lee et al., 2007). Even within the same region, the agricultural preferences on millets or rice were likely to make a temporal change throughout different cultural periods. Previous studies have provided some sequences of agricultural development in different mixed farming regions (e.g. Deng et al., 2015; Lee et al., 2007; Yang et al., 2016a); however, excellent plant-remains data with accurate chronology for most regions is still limited, particularly with respect to the early stages of the establishment of mixed millet and rice agriculture (Liu et al., 2008). Thus, the diachronic development of mixed agriculture in China during prehistoric times cannot be comprehensively clarified at this point. More archaeobotanical evidence and radiocarbon dates from Neolithic-Bronze Age sites in the mixed farming regions, especially those key areas previously mentioned in this section, are needed to resolve this problem.

One of the ideal regions for addressing the above problem by means of archaeobotanical research is the Central Plain region. Given that early plant remains of common millet (*Panicum miliaceum*), foxtail millet (*Setaria italica*), and rice (*Oryza* sp.) were recovered from the Central Plain (Lee and Bestel, 2007; Pang and Gao, 2006; Wu, 1994; Zhang, 2011a; Zhang et al., 2012; Zhao, 2011b), this region is acknowledged as a home to the millet agriculture in North China and one of the major regions for the northward spread of rice agriculture from South China (Qin, 2012; Wang, 2013). The meeting of millet and rice in the Central Plain is not only significant to the origin and spread of agriculture, but it also coincided with the population migration and technical interchange between North and South China (Zhang and Hung, 2013; Zhang, 2011b). This facilitated great socioeconomic development, as well as the emergence of the City State, making the Central Plain a cradle of Chinese civilization (Liu, 2007; Yan, 1987).

Evidence of ancient agriculture in the Central Plain is mainly based on plant macroremains. Numerous assemblages of charred plant remains have been collected from the Yiluo valley (Lee et al., 2007), upper Ying valley (Fuller et al., 2007b; Zhang et al., 2010a), Luoyang basin (Zhang et al., 2014), and some single sites (Qin, 2009; Zhao, 2007, 2011b) of the Central Plain, which span from the Neolithic to Shang-Zhou Dynasties. Quantitative analysis of these plant macrofossils indicated that millets were consistently the principal crops, and while rice was introduced by the late Yangshao period (ca. 3500–3000 cal. BC), it was not always a stable component of agricultural economy (Lee et al., 2007; Qin, 2012; Zhao, 2011b). Nonetheless, data on plant macroremains for this region are limited to the early Neolithic, that is, Peiligang period (ca. 6500–5000 cal. BC), because of poor preservation conditions. Only few charred millet grains have been discovered from Peiligang Culture sites, and rice is absent (Lee et al., 2007; Yang et al., 2015; Zhang et al., 2014). Recently, studies of plant microremains have filled this gap. Residue analyses of stone tools and potteries from eight Peiligang Culture sites have found abundant millet starch grains (Liu et al., 2013; Yang et al., 2015; Zhang, 2011a), especially at the Tanghu site, where both millets and rice starch grains and phytoliths were excavated (Yang et al., 2015; Zhang et al., 2012). This implies that the Central Plain might be the place in which mixed millet-rice farming first appeared around 8000 years ago, parallel to that of the western Shandong area (Crawford et al., 2006, 2016; Jin et al., 2014). Since the time of origin is basically confirmed, the present study raises critical questions about the temporal changes of mixed millet and rice agriculture in Neolithic-Bronze Age Central Plain: How did the relative

proportion of millets versus rice in crop assemblages and foxtail millet versus common millet in dry farming change over time? What was the specific domesticated status of millets in different periods and how did the process of millet domestication occur? How did the nature (wild or domesticated/*japonica* or *indica*), as well as the arable systems (wetland or dryland) of rice change through time?

In order to answer these questions, the Neolithic-Bronze Age site of Zhuzhai was investigated. The Zhuzhai site (113°30'19"E, 34°49'31"N) is located in Zhengzhou City, Henan Province, bordered by the Yellow River to the north and the Songshan Mountains to the south (Figure 1). The site is named after the nearby Zhuzhai village situated 0.5 km to the west, and occupies the tableland at the confluence of the Xushui River and its tributary with an altitude of about 105 m a.s.l. The site has various phases of occupations, with the earliest one being the Peiligang Culture, followed by another seven cultural periods: Yangshao Culture, Shang Dynasty, Western Zhou Dynasty, Warring States, Han Dynasty, Tang Dynasty, and Song Dynasty. In 2011 and 2012, the site was excavated by Zhengzhou Municipal Institute of Archaeology, and a total of 5000 m² in settlement occupations were uncovered (Liu and Bao, 2012). During the excavations, 340 archaeological contexts were found, including ash pits, house foundations, burials, pottery kilns, ditches, and a large number of artifacts such as stone tools, bone implements, and ceramics. These remains mainly belong to the Peiligang Culture, Yangshao Culture, and Shang Dynasty, with few remains originating from other periods (Bao, 2017; Liu and Bao, 2012). The Zhuzhai site is considered as an ordinary settlement without central function during all phases of occupations, and only the Yangshao remains have clear function zoning; the eastern part of excavated area includes living, production, and burial areas, while high-hierarchy buildings, including a big house foundation (30 m²) and a wide drainage ditch, occurs in the western part (Liu and Bao, 2012).

Based on phytolith and macrofossil analyses, together with AMS radiocarbon dating, the development process of mixed millet-rice agriculture in the Central Plain during the Neolithic and Bronze Age was determined. Moreover, statistical analysis of morphotypes and morphological parameters was conducted on archaeological phytolith assemblages to shed light on the nature of crop remains and whether rice was cultivated in a wet or dry field at the site. The study provides new data for clarifying the formation and progress of mixed millet-rice farming in China from a regional perspective, and has implications for understanding the cultivation, domestication, and spread of the two crops in prehistoric periods.

Materials and methods

A total of 40 soil samples for phytolith analysis were collected from the Zhuzhai site, including 12 samples from the Peiligang period (ca. 6500–5000 cal. BC), 21 samples from the Yangshao period (ca. 4500–3000 cal. BC), four samples from the Shang Dynasty period (ca. 1600–1000 cal. BC), and three samples from the Warring States period (deposits from a pottery *fu* caldron in M36; 475–221 cal. BC) (Table 1). Systematic flotation work was not applied to the Zhuzhai site because of the fact that it was a salvage excavation project and was only given a short amount of time for investigation. However, archaeologists excavating the site still collected 49 L of soil from six flotation samples for plant macroremain analysis. These samples were taken from six ash pits, in which four pits (H158, H208, H218, H226) were assigned to the Peiligang Culture and two pits (H202, H225) were assigned to the Yangshao Culture.

The method used for phytolith extraction from the soil was wet oxidation, as described by Wang and Lu (1993) and Piperno

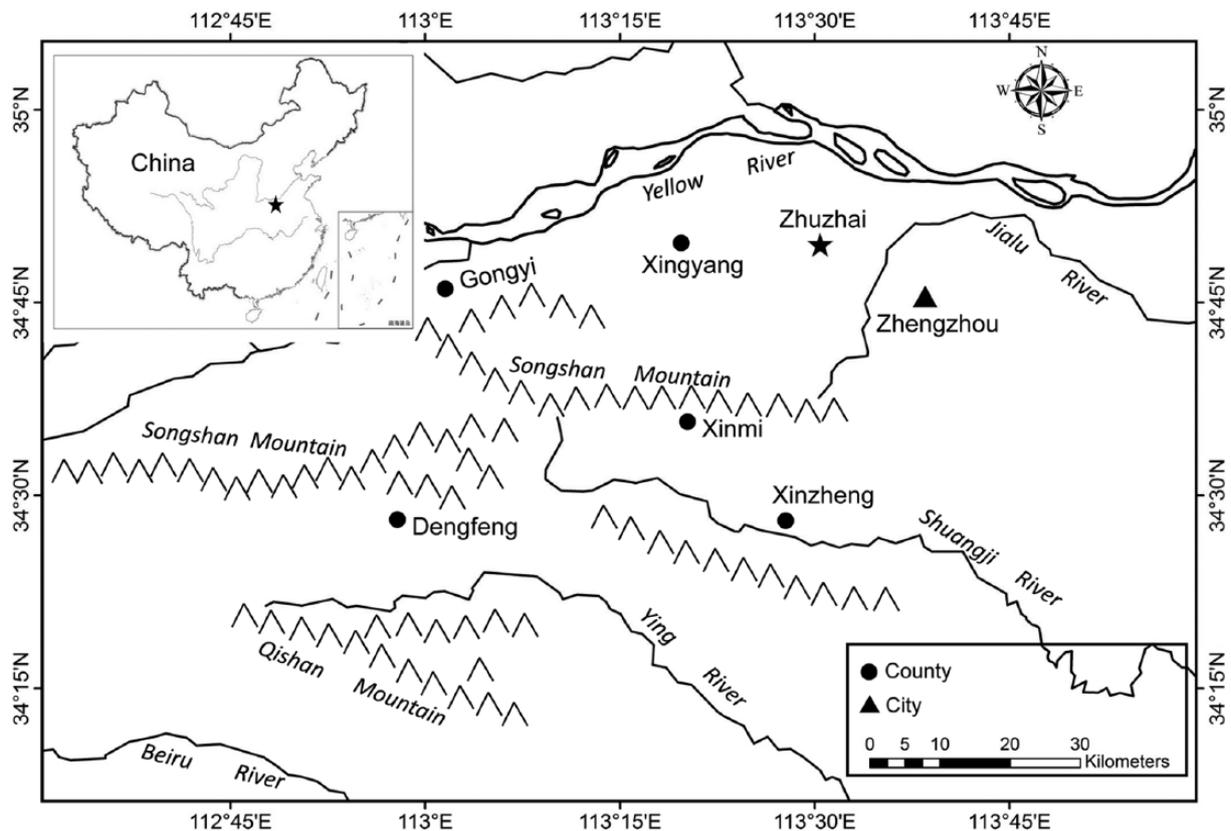


Figure 1. Location of the Zhuzhai site.

Table 1. Summary of samples collected for phytolith analysis from the Zhuzhai site.

Period	No. of samples	Ash pits	House foundations	Pottery Kiln	Ditches	Burials	Cultural layers
Peiligang	12	12					
Yangshao	21	7	3	2			
Shang	4	3					
Warring States	3						
Total	40	22	3	2			

(2006). The procedure consisted of weighing out 2 g of soil and adding 30% hydrogen peroxide (H_2O_2) and 10% cold hydrochloric acid (HCl) to each sample to remove organic matter and carbonates. Meanwhile, a Lycopodium Spore tablet (27,637 grains/tablet) was added to detect the concentrations of phytoliths for each sample, while separating with zinc bromide ($ZnBr_2$, density 2.35 g/cm^3) heavy liquid. The sample was ultimately mounted on a slide with neutral resin and fixed with a cover glass. Phytolith identification, counting, and photographing were conducted using a Leica DM750 light microscope at 400 \times magnification. More than 400 phytoliths were counted in each sample. Phytolith identification and classification was aided by the use of published references (Lu et al., 2006; Wang and Lu, 1993). Millet phytoliths were identified by reference to Lu et al. (2009b), and the identification of double-peaked, bulliform, and parallel-bilobe rice phytoliths was performed with reference to Fujiwara (1993) and Lu et al. (1997). Phytolith abundance was quantified using frequency expressed as a percentage of all phytoliths counted.

In order to determine the extent to which the millets were domesticated, the morphological parameters of millet husk phytoliths from the site by period were measured, as described in the work of Lu et al. (2009b), Zhang et al. (2011), and Ge et al. (2016). Then, these data were compared with that of modern millets obtained from a previous study (Lu et al., 2009b) in order to

determine the morphological variations of phytoliths in millet domestication. For the determination of the nature of rice phytoliths, the number of scale-like decorations of rice bulliform phytolith and the morphometric parameters of both double-peaked and bulliform phytoliths were determined based on previous works (Gu, 2009; Gu et al., 2013; Huan et al., 2015; Lu et al., 2002; Wang and Lu, 2012; Wu et al., 2014b; Zhao et al., 1998; Zheng et al., 2003). The measurement of phytolith morphological parameters and data procurement was performed on images using ImageJ software. Then, a sensitive/fixed phytolith morphotype model defined by Weisskopf et al. (2015b) was applied to sediment samples from cultural contexts (i.e. ash pits) to track degrees of wetness in rice arable systems. Because the samples for this analysis should contain a substantial concentration of rice (6900 grains/g \sim 600 \times 10⁴ grains/g) (Weisskopf et al., 2015b), the subsequent number of selected samples is 2, 10, and 3, assigned to the Peiligang Culture, Yangshao Culture, and Shang Dynasty, respectively.

For the extraction of charred plant remains, the six samples were floated by bucket with a 0.2 mm mesh screen at the site. After drying, the light fraction samples were sent to the Paleontology Lab of the Institute of Geology and Geophysics CAS for sorting. These samples were first sifted in sample sieves (2, 1, 0.7, 0.5 mm), and the <0.5 mm fractions were excluded because no charred seeds or

Table 2. Results of AMS ^{14}C dates from the Zhuzhai site.

Lab no.	Material dated	Feature	Cultural period	^{14}C date (BP)	Calibrated date (cal. BC)	
					1 σ (68.2%)	2 σ (95.4%)
Beta-346756	Charcoal	H185	Peiligang	7100 \pm 40	6020 (45.6%) 5977 5948 (22.6%) 5921	6050 (95.4%) 5899
Beta-346759	Charcoal	H226	Peiligang	7080 \pm 40	6009 (33.1%) 5973 5953 (35.1%) 5915	6032 (95.4%) 5882
Beta-346758	Charcoal	H158	Peiligang	7000 \pm 40	5977 (17.5%) 5948 5920 (50.7%) 5842	5986 (95.4%) 5786
Beta-346761	Charcoal	H235	Peiligang	6940 \pm 40	5873 (6.5%) 5861 5847 (61.7%) 5757	5966 (1.2%) 5957 5905 (94.2%) 5730
Beta-346760	Charcoal	H225	Yangshao	4490 \pm 30	3332 (30.2%) 3264 3245 (13.7%) 3214 3187 (13.0%) 3156 3128 (11.3%) 3101	3348 (95.4%) 3090
Beta-346762	Charcoal	H202	Yangshao	4490 \pm 30	3332 (30.2%) 3264 3245 (13.7%) 3214 3187 (13.0%) 3156 3128 (11.3%) 3101	3348 (95.4%) 3090
Beta-346757	<i>Charcoal</i>	<i>H218</i>	<i>Peiligang</i>	<i>2990 \pm 30</i>	<i>1266 (54.9%) 1192 1176 (6.0%) 1163 1144 (7.3%) 1131</i>	<i>1374 (2.6%) 1356 1301 (92.8%) 1118</i>
Beta-346763	<i>Charcoal</i>	<i>H214</i>	<i>Yangshao</i>	<i>2950 \pm 30</i>	<i>1215 (68.2%) 1118</i>	<i>1260 (3.2%) 1241 1236 (92.2%) 1051</i>

Abnormal dates are shown in italics. AMS: accelerator mass spectrometer.

fruits were found in these tiny remains. The remaining samples were sorted under a Leica L2 binocular stereomicroscope. Charred seeds, fruits, and plant remains were moved from charcoal and stored in plastic tubes with the context number. These charred plant remains were then sent to the State Key Laboratory of Systematic and Evolutionary Botany, Institute of Botany CAS, and identified by Mr Changjiang Liu with reference to modern plant specimens and published identification keys (Liu et al., 2008).

A total of eight charcoal samples were selected for radiocarbon dating with an AMS at Beta Analytic Radiocarbon Dating Laboratory. All ^{14}C dates were reported in years before present (BP, meaning from 1950 CE) and based on the Libby half year of 5568 with a 1 σ standard deviation. Then, the ^{14}C dates were calibrated using the OxCal 4.2.3 program (Ramsey, 2009) and IntCal13 curve (Reimer et al., 2013) with ranges expressed both at 1 σ (68.2%) and 2 σ (95.4%) confidence level. All calibrated dates reported were referred to as 'cal. BC'.

Results

Chronology

The eight AMS dates obtained from the Zhuzhai site are shown in Table 2. Except for two abnormal dates from H218 and H214, the dates are in line with the cultural ages. The available dates can be grouped into two sets. The first set contains four dates covering the time interval 6050–5730 cal. BC (95.4% range) which falls within the age of the Peiligang Culture. The second set covers the period from 3348 to 3090 cal. BC (95.4% range), which corresponds to the late Yangshao Culture. The chronology of the samples from the Shang Dynasty and Warring States period is based on the archaeological ages inferred from archaeological stratigraphy and unearthened objects because of the absence of available materials for radiocarbon dating.

Phytoliths

Phytoliths from the Zhuzhai site were mostly well preserved with distinct features for correct identification (Figure 2). The

phytolith contents of all samples were abundant, with a mean concentration of phytoliths reaching approximately 695×10^4 grains/g. Finally, a total of 24,174 phytoliths were counted in 40 samples and assigned to 29 types according to the classification system of Wang and Lu (1993) and Lu et al. (2006). Crop phytoliths were found in 30 samples, including double-peaked, bulliform, and parallel-bilobe types for rice (Figure 2d–f) and millet husks (η -type from common millet: Figure 2a and b; Ω -type from foxtail millet: Figure 2c). Other main phytolith types are short saddle, long saddle, bilobate, cross, reed bulliform, smooth-elongate, sinuate-elongate, rondel, trapeziform sinuate, square, and so forth.

Phytoliths from the Peiligang Culture period. A total of 5845 phytoliths were counted from 12 samples belonging to the Peiligang Culture, of which nine samples contained crop phytoliths (Figure 3). Present in these samples were 448 pieces of common millet husks, 32 rice phytoliths (including 29 double-peaks and three rice bulliforms), and only four pieces of foxtail millet husks. The highest percentage of common millet was 40%, while the highest percentages of rice and foxtail millet were 5% and 0.6%, respectively (Figure 3). Using all 12 samples as basic analytical units, the ubiquity of both common millet and rice was 50%, while that of foxtail millet was 17%.

Phytoliths from the Yangshao Culture period. A total of 13,874 phytoliths were encountered in 21 samples belonging to the Yangshao Culture, of which 17 samples contained crop phytoliths (Figure 3). In these samples, 592 phytoliths from common millet husks, 261 phytoliths from foxtail millet husks, and 133 rice phytoliths (including 115 double-peaks, 15 rice bulliforms, and three parallel-bilobes) were found. The common millet phytoliths were dominant in most samples with the highest percentage reaching 27.5%, while those of foxtail millet and rice were 25% and 6%, respectively (Figure 3). Using all 21 samples as basic analytical units, the ubiquity of common millet and foxtail millet was, respectively, 71.4% and 61.9%, while that of rice was 47.6%.

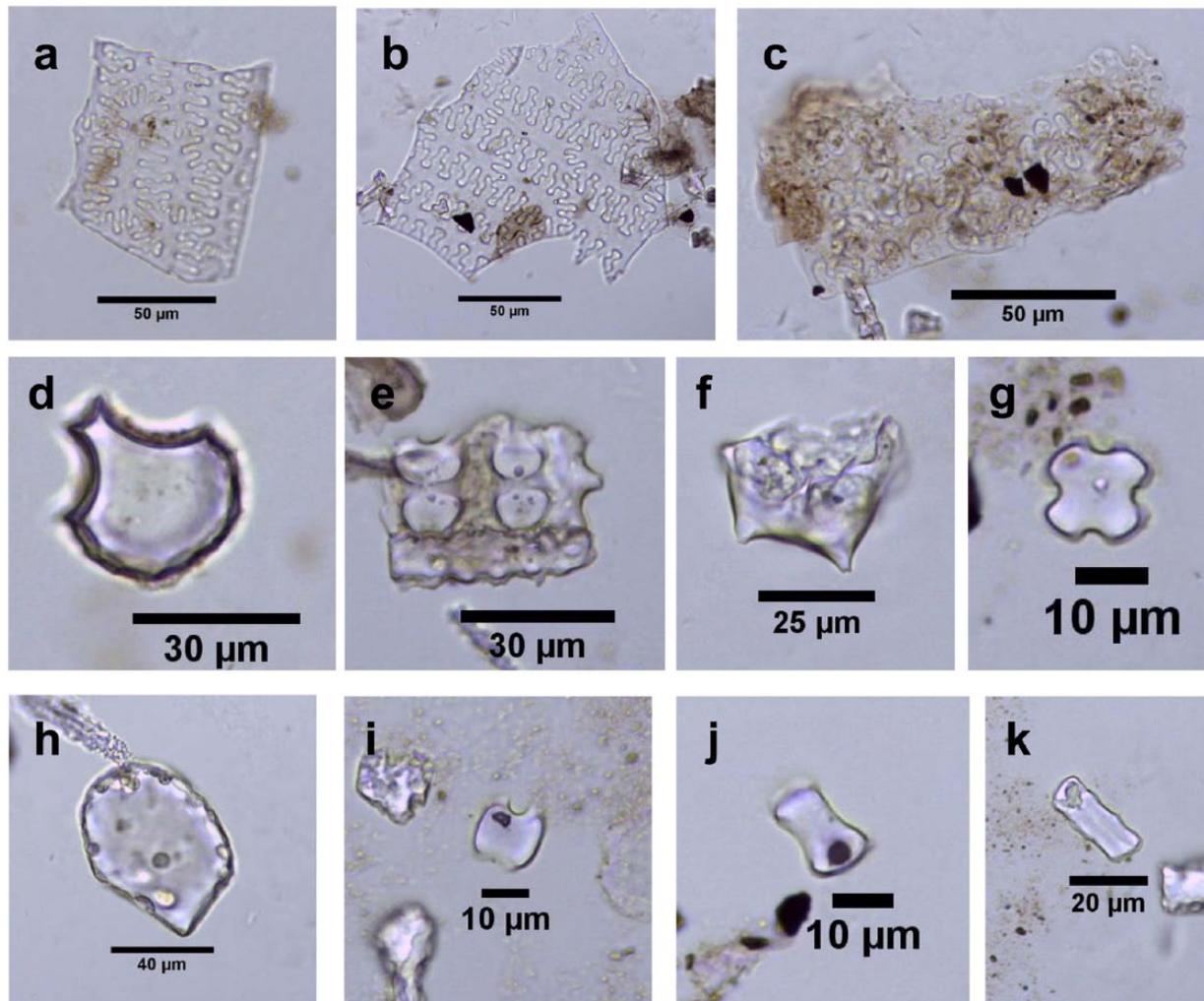


Figure 2. Main phytolith types from the Zhuzhai site. (a, b) η -type from husks of common millet, (c) Ω -type from husks of foxtail millet, (d) bulliform from rice leaf, (e) parallel-bilobe from rice leaf/stem, (f) double-peaked from rice husk, (g) cross, (h) scutiform-bulliform from reed, (i) short saddle, (j) long saddle, and (k) trapeziform sinuate.

Phytoliths from the Shang Dynasty period. A total of 3109 phytoliths were identified from the four samples assigned to the Shang Dynasty period that contained crop phytoliths (Figure 3). Among these crop types, the most abundant was phytolith from the husks of foxtail millet (101 pieces), followed by common millet phytolith (66 pieces). Rice phytoliths (double-peaked and bulliform) were found in small quantities (15 pieces). The highest percentage of foxtail millet was 10.4%, while those of common millet and rice were 4.9% and 0.8%, respectively (Figure 3).

Phytoliths from the Warring States period. In total, 1346 phytoliths were counted in three samples from a burial (M36) belonging to the Warring States period. Unfortunately, no crop phytoliths were found in M36.

Figure 4 shows the temporal changes of relative proportions of phytolith from common millet, foxtail millet, and rice at the Zhuzhai site, indicating an evolution of mixed farming of millet and rice in the Central Plain. During the Peiligang and Yangshao Culture periods, common millet dominated all other crop types, with 92% and 60% proportions, respectively. Rice appeared in the Peiligang Culture period, but its proportions were always low (7–14%) during the three periods. Foxtail millet was present in the Peiligang Culture period in the fewest proportions (1%), but increased significantly to 26% in the Yangshao Culture period, exceeding that of rice. In the Shang Dynasty period, the proportions of foxtail millet further increased to 56%, replacing common millet (36%) as the dominant crop.

Morphometric analysis of millet phytolith showing millet domestication at the Zhuzhai site. According to observations, the Ω -type husk phytoliths from the foxtail millet in the samples were too broken to perform morphometric analysis. Therefore, information cannot be provided about the domestication of foxtail millet. Instead, η -type (which can be subdivided into η I, η II, and η III) husk phytoliths from common millet were more intact than those in the foxtail millet at the Zhuzhai site. In order to characterize the morphological variations of the structures of the η -type undulated patterns, four parameters were used: (1) W = width of ending interdigitation of the η -type undulated patterns, (2) H = length of undulation amplitude of the η -type undulated patterns, (3) R = ratio of the width of ending interdigitation to undulation amplitude ($R = W/((H1 + H2)/2)$), and (4) $W1$ = length of undulation amplitude and ending interdigitation of the η -type undulated patterns (Figure S1, available online). The measured average values of the parameters of the η -type undulated patterns are shown in Table 3. Figure 5 shows the bivariate biplots of above W , H , and R values by period, which all overlap in the data distribution of modern common millet within the limit of error, indicating that there is no statistically significant difference in phytolith morphology between the modern domesticated common millet and the ancient species. Moreover, the values of H and $W1$ both show an increasing trend from the Peiligang Culture to the Shang Dynasty (Figure 6), indicating the average size of the η -type undulated patterns of common millet gradually gets larger over time at the Zhuzhai site.

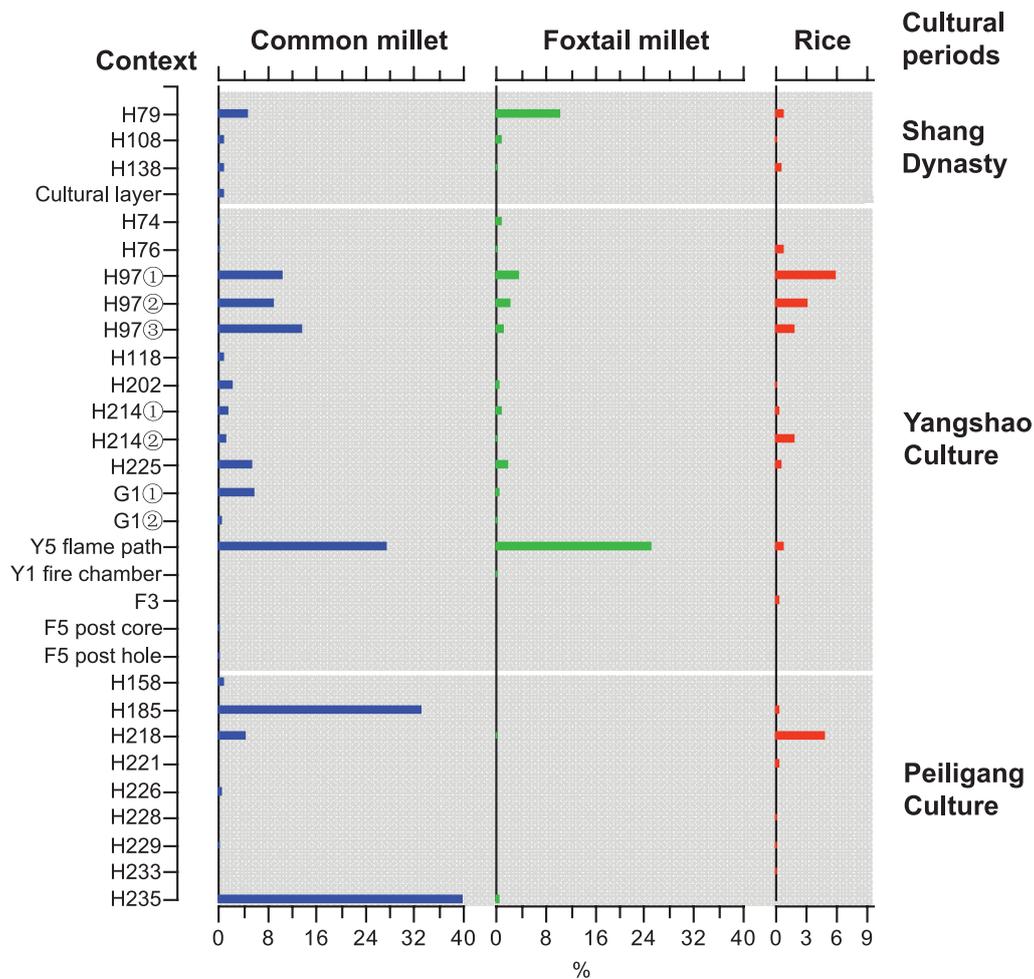


Figure 3. Variations in percentages of crop phytoliths among different periods at the Zhuzhai site.

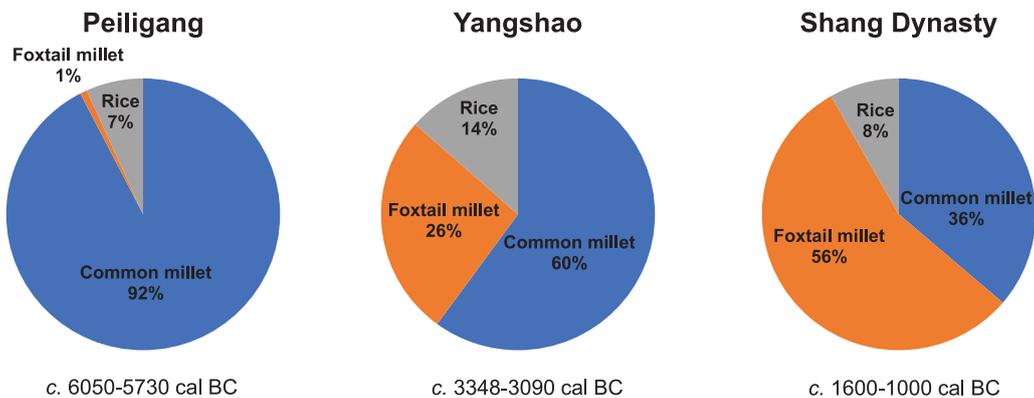


Figure 4. Proportions of phytolith from common millet, foxtail millet, and rice in different periods at the Zhuzhai site.

Measurement of early rice phytoliths showing the nature of rice at the Zhuzhai site. The presence of rice phytoliths assigned to the Peiligang and Yangshao Culture periods is an important finding at the Zhuzhai site, though the contents of the samples are relatively low. Previous studies have suggested that the morphological characteristics of rice phytolith appear to be under genetic control, and therefore reflect taxonomical significance (Gu et al., 2013; Ma and Yamaji, 2006; Zheng et al., 2003), making their nature (wild/domesticated or *japonica/indica*) determination feasible. In the last 20 years, scholars have established several criteria for determining the nature of rice phytoliths. Such methods have played a vital role in the identification of rice remains from archaeological sites (Ball et al., 2016). In the present study, three methods were

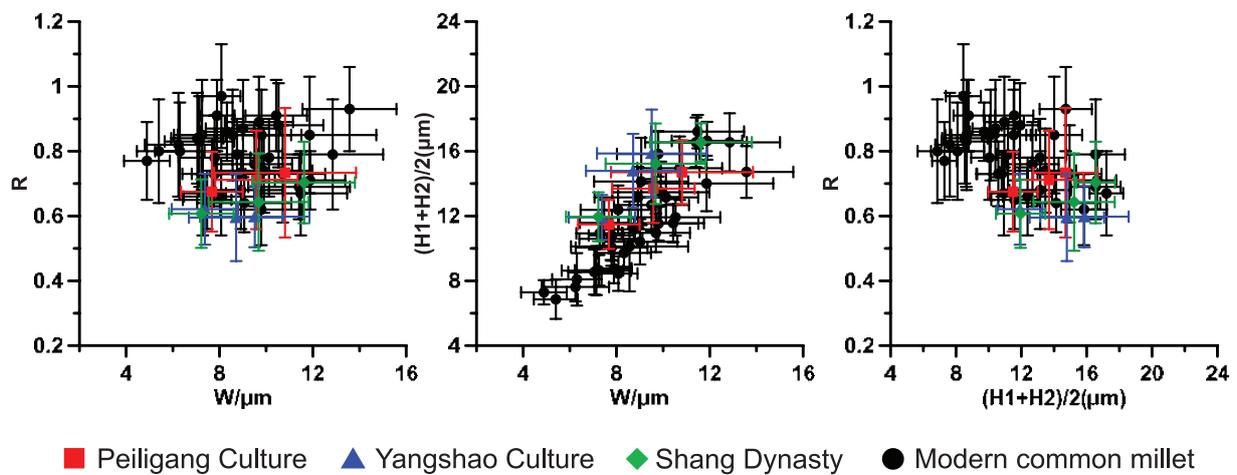
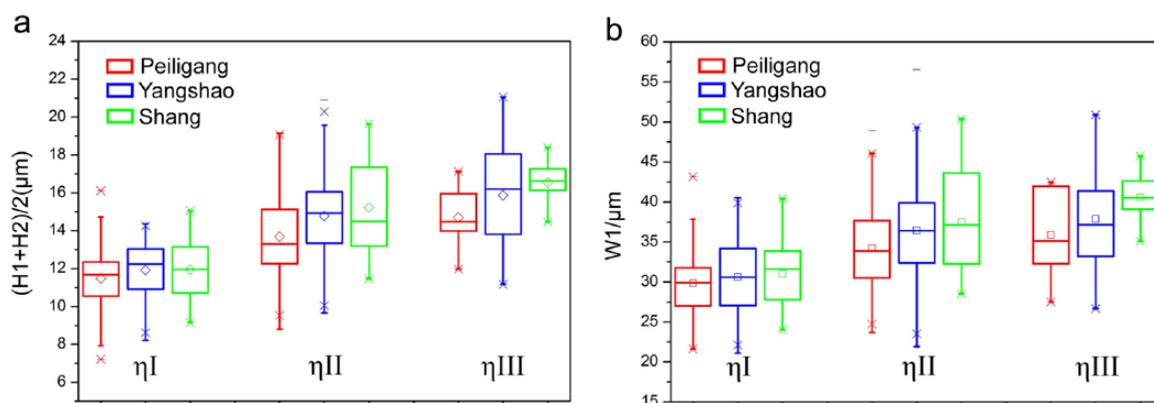
applied for this identification: (1) morphometrics of rice double-peaked phytolith (Gu, 2009; Zhao et al., 1998), (2) morphometrics of rice bulliform phytolith (Wang and Lu, 2012; Zheng et al., 2003), and (3) number of scale-like decorations of rice bulliform phytolith (Lu et al., 2002; Huan et al., 2015) (Figure S2, available online). Although there existed some doubt as to the effectiveness of these methods (Fuller and Castillo, 2014; Fuller et al., 2010), they were used as an alternative methodology aside from using rice macroremains.

For the Peiligang Culture period, the double-peaked glume cell was a relatively abundant morphotype of rice phytolith, and thus was used as the main material for determination. A total of 12 double-peaked phytoliths were selected, and their shape measurements

Table 3. Measured data of the parameters of the η -type undulated patterns of common millet from the Zhuzhai site.

Samples	W (μm)		$(H1 + H2)/2$ (μm)		R		$W1$ (μm)		Count number
	Average	SD	Average	SD	Average	SD	Average	SD	n
P-1	7.67	1.32	11.48	1.51	0.68	0.12	29.87	3.97	96
P-2	9.58	1.77	13.69	2.12	0.71	0.15	34.25	5.11	109
P-3	10.81	3.04	14.70	1.97	0.73	0.20	35.86	6.42	5
Y-1	7.37	1.42	11.91	1.38	0.62	0.11	30.61	4.36	127
Y-2	8.71	2.02	14.79	2.28	0.60	0.13	36.43	6.08	141
Y-3	9.51	2.35	15.86	2.71	0.60	0.09	37.89	6.58	25
S-1	7.22	1.38	11.95	1.51	0.61	0.11	31.00	3.87	45
S-2	9.68	2.14	15.23	2.49	0.64	0.15	37.48	5.91	44
S-3	11.62	2.18	16.55	1.18	0.70	0.13	40.56	3.19	10

P = Peiligang Culture, Y = Yangshao Culture, and S = Shang Dynasty; 1, 2, 3 correspond to η I, η II, and η III types, respectively.

**Figure 5.** Comparison of η -type undulated patterns for common millet between three periods and modern time. Data of modern common millet (domesticated species = 12) are adapted from Lu et al. (2009b).**Figure 6.** Box plot of (a) H and (b) $W1$ values of η -type undulated patterns in three periods at the Zhuzhai site. η I, η II, and η III represent three levels of the undulation amplitude.

were incorporated into the formula used to distinguish wild from domesticated rice, derived from Zhao et al. (1998). The results indicate that the predicted values of the 12 double-peaked phytoliths for domesticated rice are greater than those for the wild rice (Table 4), thus deducing that these phytoliths are from domesticated rice. Additionally, although only three pieces of rice bulliform phytolith with clear scale-like decorations were found in the Peiligang Culture period, the number of scale-like decorations is 9, 10, and 12, respectively. This concurs with the diagnostic feature of the domesticated *Oryza* species observed by Lu et al. (2002) (Figure S2c, available online).

Given that the double-peaked phytoliths in the Peiligang period are determined to be a domestic type, further investigation into what subspecies of domesticated rice, *Oryza sativa* L. *indica* or *Oryza sativa* L. *japonica*, was cultivated can be performed. Four parameters (TW, CD, α_1 , and α_2 ; Figure S2a, available online) of the above-mentioned 12 double-peaked phytoliths were measured. The observed data were inserted into a discrimination formula established by Gu (2009), and the scores (Y) of *japonica* and *indica* were obtained. If $Y_{japonica} > Y_{indica}$, the phytolith was identified as *japonica*, and vice versa. The results show that seven pieces are determined to be *japonica*, accounting for 58.3% of the

Table 4. The values of morphometric parameters of double-peaked rice husk phytoliths from the Zhuzhai site belonging to the Peiligang period and the discriminant results (unit: μm).

No.	TW	MW	H1	H2	CD	A-Score	B-Score	C-Score	D-Score	Results
1	22.325	42.308	21.112	17.483	3.318	17.399	12.139	12.983	18.092	A > B, D > C Domestic
2	38.331	56.087	29.318	26.311	5.272	8.736	2.942	5.028	9.429	A > B, D > C Domestic
3	27.407	37.504	17.578	16.132	3.352	17.044	12.389	12.823	17.737	A > B, D > C Domestic
4	20.034	37.442	16.802	14.755	4.440	17.904	13.656	14.010	18.597	A > B, D > C Domestic
5	23.980	36.050	18.669	18.187	4.185	18.221	13.217	13.770	18.914	A > B, D > C Domestic
6	34.120	39.913	18.669	18.669	3.863	17.278	12.079	12.631	17.971	A > B, D > C Domestic
7	21.717	41.330	24.881	21.986	3.748	15.234	9.601	10.965	15.927	A > B, D > C Domestic
8	28.107	44.509	21.486	22.978	2.968	15.972	9.134	10.026	16.665	A > B, D > C Domestic
9	32.831	39.269	20.816	21.244	5.583	17.133	11.969	12.776	17.826	A > B, D > C Domestic
10	23.819	38.413	13.735	17.597	4.077	19.438	13.604	13.677	20.131	A > B, D > C Domestic
11	35.406	41.040	18.669	22.853	1.609	14.996	7.901	8.454	15.689	A > B, D > C Domestic
12	37.124	42.278	19.742	13.090	4.721	13.877	11.200	11.876	14.570	A > B, D > C Domestic

Table 5. The values of morphometric parameters of double-peaked phytoliths in Peiligang period for *japonica/indica* determination and the discriminant results (unit: μm).

No.	TW	CD	$\alpha 1$	$\alpha 2$	$\alpha 1 + \alpha 2$	$Y_{japonica}$	Y_{indica}	Results
1	22.325	3.318	132.607	148.556	281.163	135.155	126.280	$Y_{japonica} > Y_{indica}$ japonica
2	38.331	5.272	82.735	99.647	182.382	92.939	92.219	$Y_{japonica} > Y_{indica}$ japonica
3	27.407	3.352	84.806	98.830	183.636	75.726	75.059	$Y_{japonica} > Y_{indica}$ japonica
4	20.034	4.440	70.393	85.836	156.229	60.095	63.374	$Y_{japonica} < Y_{indica}$ indica
5	23.980	4.185	52.337	88.103	140.440	50.820	54.916	$Y_{japonica} < Y_{indica}$ indica
6	34.120	3.863	68.749	86.090	154.839	64.312	65.751	$Y_{japonica} < Y_{indica}$ indica
7	21.717	3.748	73.101	83.541	156.642	57.272	59.922	$Y_{japonica} < Y_{indica}$ indica
8	28.107	2.968	123.861	89.774	213.635	93.160	89.491	$Y_{japonica} > Y_{indica}$ japonica
9	32.831	5.583	105.683	107.103	212.786	111.002	108.363	$Y_{japonica} > Y_{indica}$ japonica
10	23.819	4.077	84.596	133.678	218.274	100.129	97.176	$Y_{japonica} > Y_{indica}$ japonica
11	35.406	1.609	84.382	85.264	169.646	61.230	59.893	$Y_{japonica} > Y_{indica}$ japonica
12	37.124	4.721	65.772	79.019	144.791	64.765	67.253	$Y_{japonica} < Y_{indica}$ indica

selected double-peaked phytoliths (Table 5). Therefore, the subspecies of *Oryza sativa* cultivated at the Zhuzhai site in the Peiligang Culture period is most likely *japonica*.

For the Yangshao Culture period, although double-peaked phytoliths were abundant, there were few morphotypes with distinguishable form available for morphometric analysis. Instead, rice bulliform phytoliths were used as the major material for the determination. A total of 50 bulliform phytoliths were measured. The number of scale-like decorations on them ranged from 5 to 14, and 27 individual phytoliths had nine or more scale-like decorations (Figure S3, available online), accounting for 54% of the selected phytoliths. This proportion of bulliform phytoliths with ≥ 9 decorations is similar to the proportion found in modern domesticated rice soil (63.70% \pm 9.22%) (Huan et al., 2015), and therefore, these microfossils are designated as domesticated rice. Moreover, the morphological characteristics (VL and HL; Figure S2b, available online) of over 50 rice bulliform phytoliths (VL: $44.91 \pm 7.82 \mu\text{m}$, HL: $39.16 \pm 8.28 \mu\text{m}$) are not only larger in size than those from the Tanghu site (VL: $39.3 \pm 5.0 \mu\text{m}$, HL: $33.9 \pm 4.4 \mu\text{m}$) (5800 cal. BC) and the Majiabang Culture (VL: $36.11 \mu\text{m}$, HL: $30.68 \mu\text{m}$) (5000–4000 cal. BC), but also exceed those from the Songze (VL: $41.58 \mu\text{m}$, HL: $35.34 \mu\text{m}$) (4000–3300 cal. BC) and Liangzhu cultures (VL: $41.79 \mu\text{m}$, HL: $34.28 \mu\text{m}$) (3500–2200 cal. BC) (Zhang et al., 2012; Zheng et al., 1999). The large size of the bulliform phytoliths further confirms the domestic nature of the rice in the Yangshao Culture period.

Two methods, including *b/a* ratio and discriminant analysis (Wang and Lu, 2012), were applied to the above-mentioned bulliform phytoliths to distinguish between *japonica* and *indica* through the measuring of six parameters (Figure S2b, available

online). Generally, the mean *b/a* ratio of *japonica*-type bulliforms is < 1 , while that of *indica*-type bulliforms is > 1 . Three discriminants (see Gu (2009), Sato et al. (1990), and Wang et al. (1996) for detailed formula) can reliably identify *japonica* and *indica*, and when the average values of parameters are inserted into these formulas, the discriminant values and results are obtained. In our samples, the mean *b/a* ratio is 0.83 (Table 6), which indicates that the cultivated rice is *japonica*. This is supported by the results derived from three discriminants (Table 6). Thus, the subspecies of rice cultivated at the Zhuzhai site in the Yangshao Cultural period is still *japonica*.

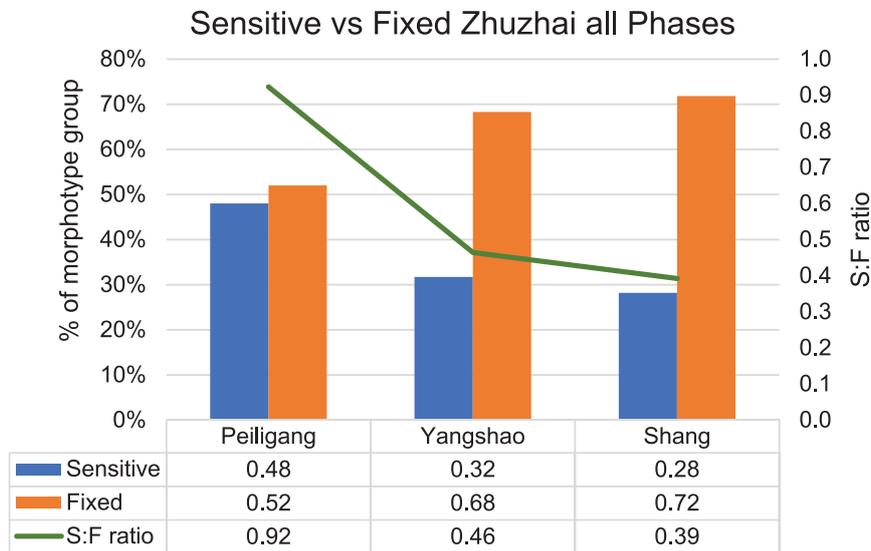
The rice arable systems at the Zhuzhai site reflected by phytoliths. The presence of bulliform and parallel-bilobe phytoliths from rice leaf/stem suggests that the Zhuzhai rice was likely to be grown locally, making the assessment on the cultivation ecology of this rice feasible. The phytoliths from the Peiligang Culture show more than 50% are fixed morphotypes, and the sensitive to fixed ratio is 0.92 (Figure 7). In the later phases, such as the Yangshao and Shang periods, the phytoliths have many more fixed forms and a lower sensitive to fixed ratio than those of the Peiligang Culture (Figure 7). The overall sensitive to fixed ratios at the Zhuzhai site decreased through time (Figure 7), indicating a decrease in water abundance in each arable system.

Charred plant remains

A total of 180 charred plant remains were found from six soil samples (49 L), of which 164 were seeds assigned to 23 plant taxa (Table 7). All of the 164 remains can be classified into three

Table 6. The average values of morphometric parameters of rice bulliform phytolith in the Yangshao period for *japonica/indica* determination and the discriminant results by different discriminants (unit: μm).

Count number	VL	HL	LL	c	a	b	b/a	Discriminant values and results		
								Wang et al. (1996)	Sato et al. (1990)	Gu (2009)
50	44.91	39.16	30.25	8.09	24.97	19.93	0.83	-2.35 <i>japonica</i>	0.81 <i>japonica</i>	84% <i>japonica</i> , 16% <i>indica</i>

**Figure 7.** Percentage of sensitive versus fixed phytolith morphotypes in three periods at the Zhuzhai site; percentages exclude all phytolith types not within the sensitive/fixed classification as defined by Weisskopf et al. (2015b).

categories, comprising three species of crops, eight species of fruits or nuts, and 12 species of weeds (Table 7). The remaining plant remains, such as plant fragments and unknown seeds, were recorded as 'others', and could not be unambiguously identified because of poor preservation or lack of clear identification features. Representative taxa identified from the site are illustrated in Figure 8.

Charred plant remains from the Peiligang Culture period. A total of 64 charred plant remains were found in four pit samples (30 L). Among these, the most important finding was one charred rice grain (Figure 8c) from the H158 pit (5986–5786 cal. BC). This is the first macrobotanical evidence of rice belonging to the Peiligang Culture in the Central Plain. The rice grain is 3.56 mm in length, 1.57 mm in width, and 1.43 mm in thickness, and the length to width ratio is 2.17, which is similar to the rice from the Xihe site located in the western Shandong Province (Jin et al., 2014). The other crops were also present in low quantities, including five grains of common millet and six grains of foxtail millet. The crops made up a small proportion in all remains (18.75%), while fruits and nuts such as *Celtis koraiensis* (Figure 8i), *Broussonetia papyrifera* (Figure 8m), *Vitis* sp. (Figure 8h), *Juglans mandshurica* (Figure 8o), and *Quercus* sp. (Figure 8p) occupied 37.5% of the plant assemblages of the Peiligang Culture period. The assemblage of weeds included *Eleusine indica* (Figure 8e), *Cuscuta* sp., *Setaria viridis*, *Galium* sp., and Cyperaceae, accounting for 31.25% of all plant remains.

Charred plant remains from the Yangshao Culture period. A total of 116 charred plant remains were found in two pit samples (19 L), of which 71 were from foxtail millet and five were assigned to common millet. No rice grains were recovered, and this is possibly because of the limited sample size. The crops became the most abundant type (65.5%) in the plant assemblages of the

Yangshao Culture period, while wild fruits became rare, not only in quantities (1.7%) but also in species (just two types: *Physalis* sp. and *Ziziphus jujuba*) (Figure 8i and n). Weeds, such as Fabaceae, *Setaria* sp., *Chenopodium* sp. (Figure 8g), *Melilotus* sp. (Figure 8k), and *Carex* sp., made up 25.9% of all of the remains.

Discussion

Millet farming at the Zhuzhai site

The results indicate that the millets were staple crops in the Zhuzhai site's mixed farming during the Neolithic-Bronze Age, but the relative proportion of foxtail millet to common millet experienced a temporal change.

For the Peiligang Culture period, there were six foxtail millet seeds and five common millet seeds recovered from the Zhuzhai site (Table 7), but these charred remains were too few to reflect the relative proportion of the two millets. Phytolith analysis provided rich millet remains, and its results showed that the ratio of common millet phytoliths was much more than that of foxtail millet (Figures 3 and 4). This suggests that millet farming in the Central Plain was mainly based on the cultivation of common millet during the Peiligang Culture from 6050–5730 cal. BC. This archaeobotanical evidence, together with other studies from the Xinglonggou (Zhao, 2004), Yuezhuan (Crawford et al., 2006, 2013), Dadiwan (Liu et al., 2004), Cishan (Lu et al., 2009a), Tanghu (Zhang et al., 2012), Zhangmatun (Wu et al., 2014a), Bianbiandong (Sun et al., 2014), and other sites in the central Gansu Province (An et al., 2010), further demonstrates that the whole North China region was dominated by common millet in the early Neolithic stage, while foxtail millet was scarcely present.

Previous macrofossil studies revealed that foxtail millet finally replaced common millet as a staple food in the Yangshao Culture after around 4000 cal. BC in North China (Liu et al., 2008; Qin, 2012; Zhao, 2014), especially in the Central Plain (Fuller et al.,

Table 7. Charred plant remains recovered from the Zhuzhai site.

Category	Plant taxa	Units (Peiligang Culture)				Units (Yangshao Culture)		Total
		H158	H208	H218	H226	H202	H225	
Crops	<i>Oryza sativa</i>	1						1
	<i>Panicum miliaceum</i>	3			2	4	1	10
	<i>Setaria italica</i>		2	4		41	30	77
Weeds	<i>Setaria viridis</i>		1				3	4
	<i>Setaria</i> sp.					7		7
	<i>Eleusine indica</i>		2	4				6
	<i>Chenopodium</i> sp.						1	1
	Fabaceae						6	6
	<i>Melilotus</i> sp.						2	2
	Cyperaceae				1			1
	<i>Carex</i> sp.					1		1
	<i>Cuscuta</i> sp.	10				7		17
	<i>Cuscuta chinensis</i>	1						1
	<i>Galium</i> sp.				1			1
	Urticaceae					3		3
	Fruits or nuts	<i>Celtis koraiensis</i>		1				
<i>Broussonetia papyrifera</i>			5		5			10
<i>Vitis</i> sp.			1					1
<i>Ziziphus jujuba</i>							1	1
<i>Physalis</i> sp.							1	1
<i>Zanthoxylum</i> sp.					1			1
<i>Juglans mandshurica</i>		6						6
<i>Quercus</i> sp.		1			4			5
Others	cf. millets	3						3
	cf. Poaceae					1		1
	cf. <i>Glycine</i> sp.		2					2
	Fragments of kernels					6		6
	Unknown			1			1	2
	Charred stalks	2						2
	Total	27	14	9	14	70	46	180

2007b; Lee et al., 2007; Qin, 2009; Zhang et al., 2014). However, the phytolith results from this research indicate that common millet was still more significant than foxtail millet in the late Yangshao period at the Zhuzhai site (3348–3090 cal. BC), though the ratio of foxtail millet did remarkably increase (Figure 4). Similarly, evidence from numerous sites in this stage such as Gongjiachuan, Wujiapo, and Yanggu in east Gansu (4500–3000 cal. BC) (Zhou et al., 2011); Lijiatai and Hulijia in Qinghai (4000–3000 cal. BC) (Jia, 2012); Gouwan in Henan (5000–3000 cal. BC) (Wang et al., 2011); Beiqian in Shandong (4200–3500 cal. BC) (Jin et al., 2016); and Quanhu, Wangjiazui, Yangguanzhai, Shuigou, Huxizhuang, and Anban in Shaanxi (4000–3000 cal. BC) (Zhang et al., 2010b) also revealed that the content of common millet was larger than that of foxtail millet, suggesting that the common millet-based dry farming not only continued but also widely existed in North China during the Yangshao period. This means that the transformation from a common millet-dominated pattern to a foxtail millet-dominated pattern of millet farming in the North (Liu et al., 2008; Qin, 2012) may not have been very common in the Yangshao period (4000–3000 cal. BC).

Because of the lack of Longshan and Erlitou Culture sediments, the structure of millet cultivation at the Zhuzhai site during these periods was unclear. However, by the last phase of the Shang Dynasty period, foxtail millet had outnumbered common millet according to the phytolith record (Figure 4). This result was in accordance with plant macrofossil evidence from other Shang Dynasty sites in the Central Plain (Fuller et al., 2007b; Lee et al., 2007; Zhang et al., 2014; Zhao, 2011b), suggesting that foxtail millet had certainly become the dominant crop in millet farming during this stage.

In addition, it is necessary to note that in some instances, charred remain and phytolith analyses were both performed in the

same sites or areas, focusing on the relative proportion of foxtail millet versus common millet, but their results were always inconsistent. Usually, the proportion of foxtail millet was much higher than that of common millet in charred plant assemblages, while phytolith records revealed opposite result. An example of this is found in the studies of the Lajia site (Wang et al., 2015; Zhao, 2003) and the Guanzhong Basin (Zhang et al., 2010b; Zhao, 2011a). The same situation also can be observed in samples H202 and H225 from the Yangshao pits at the Zhuzhai site (Figure 3 and Table 7). An experimental study has found that the same weight of common millet and foxtail millet yield almost the same amount of phytoliths within the same experimental approach (wet oxidation or dry ashing) (Zhang et al., 2010b). This means that the foxtail millet and common millet phytoliths have an equal chance of being preserved under the same circumstances, and the quantity of phytoliths reflects the relative production of the two millets, rather than the quantity of individual grains collected by flotation. However, in the Yangshao samples of the Zhuzhai site, even though the flotation results were adjusted, the relative production of foxtail millet ($n = 31$) was still much higher than that of common millet ($n = 5$), which remained different from the phytolith results. A similar case also occurred at the Lajia site (Wang et al., 2015). Thus, the difference between phytoliths and charred remains may be caused by other factors. For example, whether the two millets have different likelihoods of being charred in archaeological contexts has attracted the attention of scholars.

Charring is an ideal and widespread case for the preservation of seeds at archaeological sites (Liu et al., 2008). The charring of seeds requires exposure to heat, and is determined by the consistency and texture of the seeds themselves. Experiments on the charring of the seeds of the two types of millets indicated that the

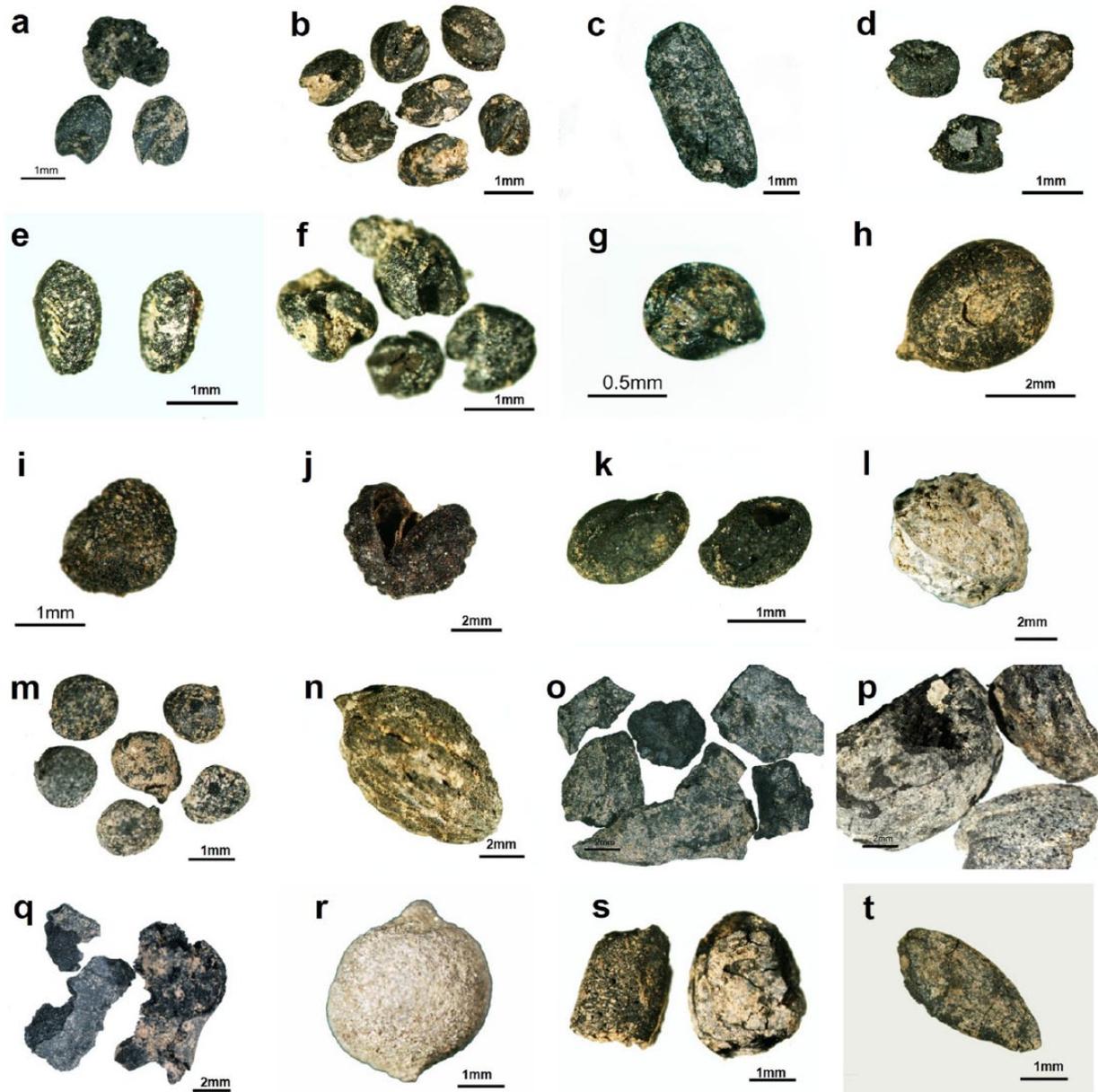


Figure 8. Representative charred plant remains from the Zhuzhai site: (a) *Panicum miliaceum* (H158), (b) *Setaria italica* (H202), (c) *Oryza sativa* (H158), (d) *Setaria viridis* (H225), (e) *Eleusine indica* (H208), (f) *Setaria* sp. (H218), (g) *Chenopodium* sp. (H225), (h) *Vitis* sp. (H208), (i) *Physalis* sp. (H225), (j) *Zanthoxylum* sp. (H226), (k) *Melilotus* sp. (H225), (l) *Celtis koraiensis* (H208), (m) *Broussonetia papyrifera* (H226), (n) *Ziziphus jujuba* (H225), (o) *Juglans mandshurica* (H158), (p) *Quercus* sp. (H226), (q) charred stalks (H158), and (r–t) unknown seeds (H218, H208, H202).

charring temperature range of common millet was lower than that of foxtail millet under any circumstances (Märkle and Rösch, 2008). Thus, the common millet seeds have a lower probability of being preserved than that of foxtail millet at sites during the charring process, and the amount of common millet would be underestimated against foxtail millet in charred plant assemblages. Given this taphonomic bias in charred millet remains, the plant macrofossil analyses may overestimate the ratio of foxtail millet in millet farming and their results may be problematic. Considering the quantity of phytoliths reflects the real relative production of the two millets, the plant macroremain results need to be tested by phytolith analysis when determining the millet farming patterns.

Millet domestication at the Zhuzhai site

Phytolith evidence from the Cishan site in the North China Plain indicated that possibly the earliest domestication of common millet dated back to 8000 cal. BC (Lu et al., 2009a). However, clues for common millet domestication in the start of the Holocene were still rare, especially in the plant macroremains (Qin, 2012).

From 6500 to 4000 cal. BC, an essential stage for millet domestication (Fuller et al., 2014), the size of common millet grains from Xinglonggou (averaging 1.6 mm long, 1.2 mm wide) (Zhao, 2004), Dadiwan (averaging 1.3–2.1 mm long, 1.1–1.9 mm wide, and 0.8–1.9 mm thick) (Liu et al., 2004), Zhangmatun (averaging 1.7 mm long, 1.3 mm wide, and 1.2 mm thick) (Wu et al., 2014a), Yuezhuang (averaging 1.5 mm long, 1.0 mm wide, and 1.0 mm thick) (Crawford et al., 2013, 2016), and the Peiligang samples of the Zhuzhai site (averaging 1.6–1.9 mm long, 1.4–1.9 mm wide) partially overlapped with the modern domesticated specimens that produce a larger, more spherical grain shape (Zhao, 2014), implying that these remains indicate the early morphology of domesticated common millet. Our morphometric analysis of common millet phytoliths also suggested that common millet with domesticated traits have occurred at the Zhuzhai site since the Peiligang Culture period (Figure 5). Additionally, the two phytolith parameters (H and $W1$), as mentioned above, revealed that the average size of η -type undulated patterns of common millet at the Zhuzhai site became increasingly larger from the Peiligang Culture to the Shang Dynasty (Figure 6). This may have

been caused by the increase in grain size, a remarkable result of plant domestication (Fuller, 2007; Fuller et al., 2014; Zhang et al., 2011). Hence, the phytolith data suggested that the process of common millet domestication at the Zhuzhai site began in the Peiligang period and continued up to the Shang period, and the degree of domestication gradually became higher over a long time. However, since the increases in η -type phytolith of ancient common millet fell within the morphological range of modern domesticated varieties (Figure 5), then the increasing trend of η -type undulated patterns of common millet shown in Figure 6 might also be the result of the cultivation of different domesticated varieties in each period.

The earliest plant remains of the domesticated foxtail millet were recovered from the Nanzhuangtou (Yang et al., 2012), Donghulin (Yang et al., 2012; Zhao, 2014), and Zhuannian (Yang et al., 2014) sites in the North China Plain from 9000–7500 cal. BC, suggesting that the beginning of foxtail millet domestication predated that of common millet (Larson et al., 2014). But their phytolith morphology in the early stage of the Cishan site (6700 cal. BC) was still close to the green foxtail (Zhang, 2010), indicating that foxtail millet was still undergoing domestication during the early Holocene. The size of the foxtail millet grain from the Yuezhuang site (averaging 1.2 mm long, 1.2 mm wide, and 0.9 mm thick; 6000–5700 cal. BC) (Crawford et al., 2013, 2016) and the Peiligang samples from the Zhuzhai site (averaging 1.5 mm long, 1.0 mm wide, and 1.0 mm thick; 6050–5730 cal. BC) fell within the range of variation of the later domesticated type (Crawford et al., 2016), while the phytolith and grain morphology of foxtail millet in the late stage of the Cishan site (5500 cal. BC) and the Xinglonggou site of the Xinglongwa Culture (6200–5400 cal. BC) was closer to the domesticated specimens (Zhang, 2010; Zhao, 2004). Both of these facts indicate that foxtail millet had already gone through a significant degree of domestication by 6000–5500 cal. BC. As mentioned above, substantial data could not be provided to illustrate the domestication process of foxtail millet at the Zhuzhai site in detail, but it is speculated that this process may be protracted according to the starch analysis of sites in the West Liaohe region, which have suggested that millet domestication proceeded gradually over a long period from approximately 6500 to 3000 cal. BC (Ma et al., 2016b).

Rice cultivation at the Zhuzhai site

The earliest presence of rice in North China was confirmed by the plant remains from the Jiahu (Zhao and Zhang, 2009) and Baligang sites (Deng et al., 2015) in the southern Henan Province and can be dated to as early as ca. 7000–6500 cal. BC. It subsequently spread into the lower Yellow River Houli Culture at ca. 6000 cal. BC, as suggested by the archaeobotanical studies of the Yuezhuang and Xihe sites in western Shandong (Crawford et al., 2006, 2013, 2016; Jin et al., 2014). Furthermore, the discovery of rice phytoliths and starch grains at the Tanghu site (ca. 5800 cal. BC) provided the sole evidence to date of rice cultivation in the Central Plain during the Peiligang Culture period (Yang et al., 2015; Zhang et al., 2012). The rice remains assigned to the Peiligang Culture (ca. 6050–5730 cal. BC) at the Zhuzhai site confirmed the findings of the Tanghu site. The rice was most likely grown there, rather than being a traded good because of the presence of bulliform and parallel-bilobe phytoliths from rice leaf/stem. This certainly indicated that rice had been cultivated in the Central Plain at ca. 6000 cal. BC, corresponding to the first northward expansion of rice resources in China (Qin, 2012).

There are two different opinions about the source of the 8000-year-old rice cultivated in the dry farming areas of Yellow River valley. The first idea considered that the rice cultivation developed from early regional wild rice collecting (Fuller et al., 2010; Qin, 2012; d'Alpoim Guedes et al., 2015), while the second

idea regarded it as introduced by migrants from other areas such as the middle Yangtze and Huai River valley (Zhang, 2011b; Zhang et al., 2012; Zhang and Hung, 2013). Whether it came from the surrounding wild rice or was brought from different location, this early occurrence of rice cultivation in the Yellow River valley clearly benefited from the Holocene megathermals in China. During this time, the temperature was ca. 2–4°C higher than at present (Ge et al., 2007; Wang and Gong, 2000) and precipitation increased because of the expansion of monsoon circulation (Dykoski et al., 2005; Xiao et al., 2004). The rising temperatures and moisture levels offered favorable conditions for wild rice populations to spread inside the Yellow River valley, (d'Alpoim Guedes et al., 2015) and also provided great opportunities for the technical exchange of rice cultivation.

With regard to the cases at the Zhuzhai and Tanghu sites (Zhang et al., 2012), the selected rice phytoliths of the Peiligang Culture were determined to be a domesticated type, indicating that rice was already in the process of domestication during the Peiligang Culture period. At the same time, rice domestication in the Yangtze had not finished (Fuller et al., 2009). Therefore, the early rice in the Central Plain was unlikely to be brought from the Yangtze, but rather was a result of the exploitation of the surrounding wild rice, as was the case with the Houli Culture (d'Alpoim Guedes et al., 2015). However, it was speculated that this may have been influenced by the Baligang site to the south of the Central Plain, in which the cultural traditions varied between north and south. The domesticated rice spikelet bases dominated in the pre-Yangshao occupation at the Baligang site before 6300 cal. BC, indicating an earlier domestication than in the lower Yangtze (Deng et al., 2015). The utilization experience of rice at the Baligang site could have been introduced into the Central Plain through cultural communications, and such communications could have facilitated the practices of rice domestication in the Central Plain.

Because of the lack of early Yangshao Culture sediments at the Zhuzhai site, it could not be determined whether rice was absent from 5000–4000 cal. BC, which was once considered as the southward retreat of rice cultivation to the Yangtze (Qin, 2012). According to the evidence at the Tanghu site, however, rice continued to be cultivated from 5800 to 2500 cal. BC in the Central Plain (Zhang et al., 2012). During the middle and late Yangshao period (4000–3000 cal. BC), the rice was widely grown in the Yellow River valley (Wu, 1994), while rice farming based on the fully domesticated species began to spread northward from the lower and middle Yangtze (Fuller et al., 2009; Qin, 2012). Considering the temporal-spatial route for the northward spread of rice cultivation as drawn by scholars (Qin, 2012; Zhang et al., 2010, 2012), the indigenous rice agriculture of the Central Plain may have been impacted by the rice-farming culture from the middle Yangtze. This assumption was also supported by the larger rice bulliform phytoliths at the Zhuzhai site in the late Yangshao period, which may reflect a higher degree of rice domestication than from the Songze and Liangzhu Cultures in the lower Yangtze. Its proportion of rice bulliform phytoliths with ≥ 9 scale-like decorations reached 54% during the late Yangshao period, while this proportion just became 59% till the Eastern Zhou Dynasty (770–256 BC) in the lower Yangtze (Huan et al., 2014). Meanwhile, more advanced rice farming in the middle Yangtze is probable in comparison with the lower Yangtze, as some scholars have suggested (Fuller, 2011; Nasu et al., 2012; Qin, 2012).

Although rice had been cultivated at the Zhuzhai site as early as 6000 cal. BC, it was always relatively rare in the sequence (Figure 4). The same situation also occurred in the Yiluo valley (Lee et al., 2007), upper Ying valley (Fuller et al., 2007b; Zhang et al., 2010a), Luoyang basin (Zhang et al., 2014), and the Tanghu site (Zhang et al., 2012), indicating that rice always constituted a negligible proportion of food production in the Central Plain at

least until the Shang period. This means that the dominance of millet farming in the region did not change after the introduction of rice cultivation. Despite this, the occurrence of rice farming in the Central Plain certified that the earliest formation of mixed millet and rice agriculture extended to 8000 years ago, and its birthplace was likely located in North China. No millet has been found at the sites located in South China such as the Shunshanji site in the Huai River valley (Luo et al., 2016; Yang et al., 2016b) and the Xiaohuangshan site in the lower Yangtze (Yao et al., 2016), where rice has been cultivated. The earliest occurrence of mixed agriculture in South China may be 4500 cal. BC, when millets were introduced into the middle and lower Yangtze (Deng et al., 2015; Zhao and Jiang, 2016).

The implication of the nature and arable system of rice at the Zhuzhai site

Lee et al. (2007) have pointed out that the charred rice remains are too few in the Central Plain, and there is no way to determine the nature and arable systems of the rice grown there. In this study, phytolith analysis was used to address these issues. The results showed that (1) the early rice at the Zhuzhai site was domesticated *japonica* type, and (2) rice farming at the Zhuzhai site used consistent dryland systems.

The implication of domesticated *japonica* at the Zhuzhai site lies in two points. First, it provides a new reference for the debate about the origin time of domesticated rice. On one hand, the rice remains from the Shangshan, Kuahuqiao, Xiaohuangshan, Jiahu, and Baligang sites (7000–6000 cal. BC) were identified as domesticated (Deng et al., 2015; Liu et al., 2007; Zheng et al., 2007; Zuo et al., 2017; Zhao and Zhang, 2009); on the other hand, Fuller et al. (2007a, 2008) argued these remains were mostly wild rice, and even that of the Majiabang and Hemudu Cultures after 5000 cal. BC showed few signs of domestication. The 8000-year-old rice remains from the Yellow River region complicates this problem. In the case of the Yuezhuang and Xihe sites, the discoverer did not clearly define the nature of the rice remains (Crawford et al., 2006, 2013; Jin et al., 2014), and therefore whether they were wild or domesticated is controversial (Fuller et al., 2010; Qin, 2012; Zhang, 2011b) and it could not provide valid evidence in defining the origin time of domesticated rice. In contrast, it is certain that domesticated rice assigned to the Peiligang Culture was recovered from the Zhuzhai site, indicating that the Central Plain, a region far away from the Yangtze, had already used domesticated rice 8000 years ago. Hence, the earliest domesticated rice in the Yangtze River valley occurs at least 6000 cal. BC or earlier. Without doubt, the earliest appearance of domesticated rice is only the beginning of the long process of rice domestication, and the rice remains in the Yangshao period at the Zhuzhai site have shown a high degree of domestication, indicating that the rice domestication of the Central Plain may have been completed during 4000–3000 cal. BC. This timeframe is consistent with that of the Yangtze (Fuller et al., 2009; Ma et al., 2016a).

Second, it provides support for the hypothesis that China is the origin of *japonica*. According to new genetic studies, although Asian rice subspecies originated from multiple wild rice populations, the key genomes in domestication occurred only once in *japonica* and introgressive hybridization from early *japonica* to proto-*indica* led to domesticated *indica* rice (Choi et al., 2017). Some scholars further suggested that this early *japonica* originated from China, and that until 3000 cal. BC, *indica* only occurred in India (Fuller, 2011; Fuller and Sato, 2008; Huang et al., 2012; Gross and Zhao, 2014). Therefore, it is speculated that the early domesticated rice in China is only the *japonica* type. In addition, domesticated rice remains from early Neolithic Shangshan, Xiaohuangshan, Kuahuqiao, and Jiahu sites (Chen, 1997; Zheng et al., 2007); middle Neolithic Longqiuzhuang,

Luojiajiao, and Caoxieshan sites (Udatsu et al., 1998; Zheng et al., 2000; Zou et al., 1998); late Neolithic Liangchengzhen site (Jin et al., 2004); and Zhuzhai site in Peiligang and Yangshao periods were all identified as *japonica*, thus supporting the above speculation. Therefore, as long as the rice from Neolithic China is determined to be domesticated, it is certainly *japonica* rather than another subspecies.

Previous studies have demonstrated that rice arable systems can be reflected by a ratio of sensitive versus fixed grass phytolith morphotypes (Weisskopf, 2016; Weisskopf et al., 2014, 2015a, 2015b). The fixed (dry) morphotypes are those which normally silicify and are considered genetically predisposed to form phytoliths. Sensitive types are formed only when much water is available, especially from later in the plant's life cycle (Weisskopf et al., 2015a, 2015b). In the Zhuzhai site, sensitive types were always fewer than fixed types (Figure 7), suggesting the rice cultivation was carried out in a dry field system during the Neolithic-Bronze Age. It is also supported by no or few weed indicators of paddy fields such as *Echinochloa* or Cyperaceae in the samples (Table 7).

This dry field system mainly depends on having enough annual rainfall (>800 mm) (Fuller et al., 2011), so the paleorainfall reconstruction is crucial for understanding the rice arable system in the Zhuzhai site. Phytolith data from the Weinan section on the same latitude as Zhengzhou suggested the reconstructed mean annual precipitation at 10.5–2.8 ka was 745 ± 65 mm (maximum 870 mm) (Lu et al., 2007), which could sustain the dry-cropped rice in the Neolithic-Bronze Age. Moreover, the Zhuzhai site is located where two rivers meet, and its rice may be cultivated alongside the river in order to use the ground water or seasonal flood. Without irrigation, this arable system is less labor-intensive and subsequently gets lower grain yields, accounting for the small ratios of rice in the crop assemblages. It is likely a farming strategy to adapt to the available field where millets were grown, and fortunately, the water status could satisfy the demand, and therefore, it would not be necessary to make an effort to prepare a new wet field for rice. The Zhuzhai site is also an ordinary settlement without complex social organization, large population, and intensive land use practices, providing small opportunity for cultivating rice in paddy fields, which needs sufficient labor force and effective maintenance.

By contrast, the earliest paddy fields in the Central Plain have been found at the Huizui site, dating to the middle Yangshao Period (Rosen et al., 2017). This rice paddy farming facilitated population growth and social complexity, making the Huizui site a regional center in the Yiluo River Basin (Liu et al., 2005; Rosen et al., 2017). At Zhaojiazhuang in Shandong, another Neolithic paddy field in North China was found and dating to ca. 2000 BC (Jin et al., 2007). However, because of the limited research conducted on the determination of rice arable systems in North China, the diversity of ancient rice planting patterns could not be discussed. More studies are needed to complete the picture of rice farming during the Neolithic-Bronze Age.

The place of agriculture in subsistence economy at the Zhuzhai site

In the Central Plain, the Peiligang Culture has long been regarded as having achieved a significant level of agriculture (Li, 2003), but new records show that the gathering of wild plants dominated the subsistence economy and that agriculture was only a minor component during this stage (Liu et al., 2013, 2010; Zhang et al., 2011). At the Zhuzhai site, there were many kinds of wild fruits and nuts recovered from the Peiligang Culture contexts, and their proportion was larger than that of crops (Table 7), which supports the latter opinion. The crops finally dominated the plant assemblages of the Zhuzhai site during the Yangshao period, with wild edible plants

becoming more sporadic and almost disappearing (Table 7), implying that agriculture had replaced gathering and became dominant in subsistence economy at ca. 3300–3000 cal. BC.

The developmental trajectory of agriculture in subsistence economy at the Zhuzhai site was similar to that of farming in the adjacent Yiluo valley (Lee et al., 2007). Taken together, the trend of agricultural development in the Central Plain was completely synchronous to the developmental paths of agriculture in North China (Wang et al., 2016).

Conclusion

The archaeobotanical evidence discussed from the Zhuzhai site verifies that mixed millet and rice agriculture has been established in the Central Plain about 8000 years ago. Common millet was used as the staple crop in the Peiligang and Yangshao periods, and was replaced by foxtail millet in the Shang period. Rice has occurred since the Peiligang Culture, but apparently was not an important crop throughout time. The process of common millet domestication in the Central Plain began at the latest in the Peiligang period and continued up to the Shang period. Foxtail millet may have gone through a significant degree of domestication in this region during ca. 6000–5500 cal. BC, but its domestication process was still unclear. Rice assigned to the Peiligang and Yangshao periods was the domesticated *japonica*, and its cultivation was always carried out in dry field systems during the Neolithic-Bronze Age. In the economic system of the Central Plain, mixed agriculture was a minor component during the Peiligang period, but became dominant beginning in the Yangshao Culture. The findings provide new references for clarifying the developmental process of mixed millet and rice farming in China, by contributing a diachronic and regional perspective to the Central Plain.

Acknowledgements

We appreciate the helpful comments and suggestions provided by two anonymous reviewers. We also thank Editage (<http://online.editage.cn/>) for English language editing.

Funding

This work is supported by the National Basic Research Program of China (Grant No. 2015CB953803), the National Natural Science Foundation of China (Grant No. 41701233 and 41230104), the China Postdoctoral Science Foundation (Grant No. 2016M601124), the National Social Science Foundation of China (Grant No. 16CKG007), and the ‘Macroevolutionary Processes and Palaeoenvironments of Major Historical Biota’ of the Chinese Academy of Sciences (Grant No. XDPB0503).

References

- An CB, Ji DX, Chen FH et al. (2010) Evolution of prehistoric agriculture in central Gansu Province, China: A case study in Qin'an and Li County. *Chinese Science Bulletin* 55: 1381–1386 (in Chinese).
- Ball T, Chandler-Ezell K, Dickau R et al. (2016) Phytoliths as a tool for investigations of agricultural origins and dispersals around the world. *Journal of Archaeological Science* 68: 32–45.
- Bao YJ (2017) The remains of the Peiligang culture in the Zhuzhai site, Zhengzhou city. *Archaeology* 5: 14–24 (in Chinese).
- Chen BZ (1997) Phytolith analysis and study on the origin of cultivated rice (*Oryza Sativa*). *Acta Agronomica Sinica* 23: 114–118 (in Chinese).
- Choi JY, Platts AE, Fuller DQ et al. (2017) The rice paradox: Multiple origins but single domestication in Asian rice. *Molecular Biology and Evolution* 34: 969–979.
- Cohen DJ (2011) The beginnings of agriculture in China: A multi-regional view. *Current Anthropology* 52: S273–S293.
- Crawford GW (2006) East Asian plant domestication. In: Stark M (ed.) *Archaeology of Asia*. Oxford: Blackwell, pp. 77–95.
- Crawford GW, Chen XX and Wang JH (2006) Houli culture rice from the Yuezhuang site, Jinan, Shandong. In: Oriental Archaeology Center of Shandong University (ed.) *Oriental Archaeology* (vol. 3). Beijing: Science Press, pp. 247–251 (in Chinese).
- Crawford GW, Chen XX, Luan FS et al. (2013) A preliminary analysis on plant remains of the Yuezhuang site in Changqing District, Jinan City, Shandong Province. *Jiangnan Archaeology* 2: 107–116 (in Chinese).
- Crawford GW, Chen XX, Luan FS et al. (2016) People and plant interaction at the Houli Culture Yuezhuang site in Shandong Province, China. *Holocene* 26: 1594–1604.
- D'Alpoim Guedes J, Jiang M, He K et al. (2013) Site of Baodun yields earliest evidence for the spread of rice and foxtail millet agriculture to south-west China. *Antiquity* 87: 758–771.
- D'Alpoim Guedes J, Jin GY and Bocinsky RK (2015) The impact of climate on the spread of rice to north-eastern China: A new look at the data from Shandong Province. *PLoS ONE* 10: e0130430.
- Deng ZH, Qin L, Gao Y et al. (2015) From early domesticated rice of the middle Yangtze basin to millet, rice and wheat agriculture: Archaeobotanical macro-remains from Baligang, Nanyang basin, central China (6700–500 BC). *PLoS ONE* 10: e0139885.
- Dykoski CA, Edwards RL, Cheng H et al. (2005) A high-resolution, absolute-dated Holocene and deglacial Asian monsoon record from Dongge Cave, China. *Earth and Planetary Science Letters* 233: 71–86.
- Fujiwara H (1993) Research into the history of rice cultivation using plant opal analysis. In: Pearsall DM and Piperno DR (eds) *Current Research in Phytolith Analysis: Applications in Archaeology and Paleocology*. Philadelphia, PA: University of Pennsylvania, pp. 147–158.
- Fuller DQ (2007) Contrasting patterns in crop domestication and domestication rates: Recent archaeobotanical insights from the old world. *Annals of Botany* 100: 903–924.
- Fuller DQ (2011) Pathways to Asian civilizations: Tracing the origins and spread of rice and rice cultures. *Rice* 4: 78–92.
- Fuller DQ and Castillo C (2014) Rice: Origins and development. In: Smith C (ed.) *Encyclopedia of Global Archaeology*. Berlin: Springer, pp. 6339–6343.
- Fuller DQ and Sato Y-I (2008) Japonica rice carried to, not from, Southeast Asia. *Nature Genetics* 40: 1264–1265.
- Fuller DQ, Harvey E and Qin L (2007a) Presumed domestication? Evidence for wild rice cultivation and domestication in the fifth millennium BC of the Lower Yangtze region. *Antiquity* 81: 316–331.
- Fuller DQ, Qin L and Harvey E (2008) Rice archaeobotany revisited: Comments on Liu et al. (2007). *Antiquity* 82. Available at: <http://antiquity.ac.uk/projgall/fuller1/index.html>.
- Fuller DQ, Zhang H and Fang YM (2007b) A preliminary report of the survey Archaeobotany of the upper Ying Valley (Henan Province). In: School of Archaeology and Museology, Peking University and Henan Provincial Institute of Cultural Relics and Archaeology (eds) *Archaeological Discovery and Research at the Wangchenggang Site in Dengfeng (2002–2005)*. Zhengzhou: Great Elephant Publisher, pp. 916–958 (in Chinese).
- Fuller DQ, Denham T, Arroyo-Kalin M et al. (2014) Convergent evolution and parallelism in plant domestication revealed by an expanding archaeological record. *Proceedings of the National Academy of Sciences* 111: 6147–6152.

- Fuller DQ, Qin L, Zheng YF et al. (2009) The domestication process and domestication rate in rice: Spikelet bases from the Lower Yangtze. *Science* 323: 1607–1610.
- Fuller DQ, Sato Y-I, Castillo C et al. (2010) Consilience of genetics and archaeobotany in the entangled history of rice. *Archaeological and Anthropological Sciences* 2: 115–131.
- Fuller DQ, van Etten J, Manning K et al. (2011) The contribution of rice agriculture and livestock pastoralism to prehistoric methane levels: An archaeological assessment. *Holocene* 21: 743–759.
- Ge Q, Wang S, Wen X et al. (2007) Temperature and precipitation changes in China during the Holocene. *Advances in Atmospheric Sciences* 24: 1024–1036.
- Ge Y, Lu HY, Zhang JP et al. (2016) Phytolith analysis for the identification of barnyard millet (*Echinochloa* Sp.) and Its Implications. *Archaeological and Anthropological Sciences*. Epub ahead of print 11 May. DOI: 10.1007/s12520-016-0341-0.
- Gross BL and Zhao ZJ (2014) Archaeological and genetic insights into the origins of domesticated rice. *Proceedings of the National Academy of Sciences* 111: 6190–6197.
- Gu HB (2009) An overview of the methods distinguishing the rice phytolith between *Oryza sativa* subsp. *Hsien* and *Oryza sativa* subsp. *Keng* at archaeological sites. In: The Institute of Archaeology of Hunan Province (ed.) *Journal of Human Archaeology*. Changsha: Yuelu Publishing House, pp. 268–276 (in Chinese).
- Gu YS, Zhao ZJ and Pearsall DM (2013) Phytolith morphology research on wild and domesticated rice species in East Asia. *Quaternary International* 287: 141–148.
- Huan XJ, Li Q, Ma ZK et al. (2014) Fan-shaped phytoliths reveal the process of rice domestication at Shangshan site, Zhejiang Province. *Quaternary Science* 34: 106–113 (in Chinese).
- Huan XJ, Lu HY, Wang C et al. (2015) Bulliform phytolith research in wild and domesticated rice paddy soil in south china. *PLoS ONE* 10: e0141255.
- Huang X, Kurata N, Wei X et al. (2012) A map of rice genome variation reveals the origin of cultivated rice. *Nature* 490: 497–501.
- Jia X (2012) *Cultural evolution process and plant remains during Neolithic-bronze Age in Northeast Qinghai Province*. PhD Thesis, Lanzhou University (in Chinese).
- Jin GY, Luan FS, Cai FS et al. (2004) The phytolith research in soil samples of Liangchengzhen, Rizhao, Shandong Province. *Archaeology* 9: 81–87 (in Chinese).
- Jin GY, Wagner M, Tarasov PE et al. (2016) Archaeobotanical records of Middle and Late Neolithic agriculture from Shandong Province, East China, and a major change in regional subsistence during the Dawenkou Culture. *Holocene* 26: 1605–1615.
- Jin GY, Wu WW, Zhang KS et al. (2014) 8000-Year old rice remains from the north edge of the Shandong Highlands, East China. *Journal of Archaeological Science* 51: 34–42.
- Jin GY, Yan SD, Udatsu T et al. (2007) Neolithic rice paddy from the Zhaojiazhuang site, Shandong, China. *Chinese Science Bulletin* 52: 3376–3384.
- Jones MK and Liu XY (2009) Origins of agriculture in East Asia. *Science* 324: 730–731.
- Larson G, Piperno DR, Allaby RG et al. (2014) Current perspectives and the future of domestication studies. *Proceedings of the National Academy of Sciences* 111: 6139–6146.
- Lee G-A and Bestel S (2007) Contextual analysis of plant remains at the Erlitou-Period Huizui Site, Henan, China. *Bulletin of the Indo-Pacific Prehistory Association* 27: 49–60.
- Lee G-A, Crawford GW, Liu L et al. (2007) Plants and people from the early Neolithic to Shang periods in North China. *Proceedings of the National Academy of Sciences* 104: 1087–1092.
- Li YM (2003) *Peiligang Culture*. Beijing: Cultural Relics Press (in Chinese).
- Liu CJ, Jin GY and Kong ZC (2008) *Archaeobotany-research on Seeds and Fruits*. Beijing: Science Press (in Chinese).
- Liu CJ, Kong ZC and Lang SD (2004) Plant remains at the Dadiwan site and a discussion of human adaptation to the environment. *Zhongyuan Cultural Relics* 4: 26–30 (in Chinese).
- Liu L (2007) *The Chinese Neolithic: Trajectories to Early States*. Cambridge: Cambridge University Press.
- Liu L and Chen XC (2012) *The Archaeology of China: From the Late Paleolithic to the Early Bronze Age*. Cambridge: Cambridge University Press.
- Liu L, Chen XC and Zhao H (2013) Analysis of the function of the grinding stones excavated from the late Peiligang Cultural sites of Zhaigen and Bangou in Mengjin, Henan. *Cultural Relics of Central China* 5: 76–86 (in Chinese).
- Liu L, Chen XC, Lee YK et al. (2005) Settlement patterns and development of social complexity in the Yilou region, North China. *Journal of Field Archaeology* 29: 75–100.
- Liu L, Field J, Fullagar R et al. (2010) What did grinding stones grind? New light on Early Neolithic subsistence economy in the Middle Yellow River Valley, China. *Antiquity* 84: 816–833.
- Liu L, Lee G-A, Jiang LP et al. (2007) Evidence for the early beginning (c. 9000 cal. BP) of rice domestication in China: A response. *Holocene* 17: 1059–1068.
- Liu YF and Bao YJ (2012) Excavation and discovery of the Zhuzhai site in Zhengzhou city. *China Cultural Relics News*, 13 July, p. 8 (in Chinese).
- Lu HY, Liu ZX, Wu NQ et al. (2002) Rice domestication and climatic change: Phytolith evidence from East China. *Boreas* 31: 378–385.
- Lu HY, Wu NQ and Liu B (1997) Recognition of rice phytoliths. In: Pinilla A, Juan-Tresserras J and Machado MJ (eds) *Monografías Del Centro De Ciencias Medioambientales 4*. Madrid: CSIC, pp. 159–174.
- Lu HY, Wu NQ, Liu KB et al. (2007) Phytoliths as quantitative indicators for the reconstruction of past environmental conditions in China II: Palaeoenvironmental reconstruction in the Loess Plateau. *Quaternary Science Reviews* 26: 759–772.
- Lu HY, Wu NQ, Yang XD et al. (2006) Phytoliths as quantitative indicators for the reconstruction of past environmental conditions in China I: Phytolith-based transfer functions. *Quaternary Science Reviews* 25: 945–959.
- Lu HY, Zhang JP, Liu KB et al. (2009a) Earliest domestication of common millet (*Panicum miliaceum*) in East Asia extended to 10,000 years ago. *Proceedings of the National Academy of Sciences* 106: 7367–7372.
- Lu HY, Zhang JP, Wu NQ et al. (2009b) Phytoliths analysis for the discrimination of foxtail millet (*Setaria italica*) and common millet (*Panicum miliaceum*). *PLOS ONE* 4: e4448.
- Lu TLD (1999) The transition from foraging to farming in China. *Bulletin of the Indo-Pacific Prehistory Association* 2: 77–80.
- Lu TLD (2006) The occurrence of cereal cultivation in China. *Asian Perspective* 45(2): 129–158.
- Luo WH, Yang YZ, Yao L et al. (2016) Phytolith records of rice agriculture during the Middle Neolithic in the middle reaches of Huai River region, China. *Quaternary International* 426: 133–140.
- Ma JF and Yamaji N (2006) Silicon uptake and accumulation in higher plants. *Trends in Plant Science* 11: 392–397.
- Ma YC, Yang XY, Huan XJ et al. (2016a) Rice bulliform phytoliths reveal the process of rice domestication in the Neolithic Lower Yangtze River region. *Quaternary International* 426: 126–132.

- Ma ZK, Yang XY, Zhang C et al. (2016b) Early millet use in West Liaohe area during early-middle Holocene. *Science in China Series D: Earth Sciences* 59: 1554–1561.
- Märkle T and Rösch M (2008) Experiments on the effects of carbonization on some cultivated plant seeds. *Vegetation History and Archaeobotany* 17: S257–S263.
- Nasu H, Gu HB, Momohara A et al. (2012) Land-use change for rice and foxtail millet cultivation in the Chengtoushan site, central China, reconstructed from weed seed assemblages. *Archaeological and Anthropological Sciences* 4: 1–14.
- Pang X and Gao J (2006) An investigation of agricultural economy in the process of civilization in the Central Plain. *Agricultural Archaeology* 4: 1–13 (in Chinese).
- Piperno DR (2006) *Phytoliths: A Comprehensive Guide for Archaeologists and Paleoecologists*. New York: AltaMira Press.
- Qin L (2009) The 2007 Nanjiaokou site excavated Early to Mid Yangshao plant remains. In: Henan Provincial Institute of Cultural Relics and Archaeology (ed.) *Nanjiaokou Site in Sanmenxia*. Beijing: Science Press, pp. 427–435 (in Chinese).
- Qin L (2012) Archaeobotanical research and expectations on Chinese agriculture origin. In: School of Archaeology and Museology of Peking University, Center of the Study of Chinese Archaeology, Peking University (eds) *Archaeological Research*. Beijing: Cultural Relics Press, pp. 260–315 (in Chinese).
- Ramsey CB (2009) Bayesian analysis of radiocarbon dates. *Radiocarbon* 51: 337–360.
- Reimer PJ, Bard E, Bayliss A et al. (2013) IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* 55: 1869–1887.
- Rosen A, Macphail R, Liu L et al. (2017) Rising social complexity, agricultural intensification, and the earliest rice paddies on the Loess Plateau of northern China. *Quaternary International* 437: 50–59.
- Sato Y-I, Fujiwara H and Udatsu T (1990) Morphological differences in silica body derived from motor cell of Indica and Japonica in Rice. *Japanese Journal of Breeding* 40: 495–504.
- Sun B, Wagner M, Zhao ZJ et al. (2014) Archaeological discovery and research at Bianbiandong early Neolithic cave site, Shandong, China. *Quaternary International* 348: 169–182.
- Udatsu T, Tang LH, Wang CL et al. (1998) Exploration of the relics of paddy fields in China. *Agricultural Archaeology* 1: 138–155 (in Chinese).
- Wang C and Lu HY (2012) Research progress of fan-shaped phytolith of rice and relevant issues. *Quaternary Sciences* 32: 269–281 (in Chinese).
- Wang C, Lu HY, Zhang JP et al. (2014) Prehistoric demographic fluctuations in China inferred from radiocarbon data and their linkage with climate change over the past 50,000 years. *Quaternary Science Reviews* 98: 45–59.
- Wang C, Lu HY, Zhang JP et al. (2015) Phytolith evidence of millet agriculture in the late Neolithic archaeological site of Lajia, northwestern China. *Quaternary Sciences* 35: 200–208 (in Chinese).
- Wang C, Lu HY, Zhang JP et al. (2016) Macro-process of past plant subsistence from the upper Paleolithic to middle Neolithic in China: A quantitative analysis of multi-archaeobotanical data. *PLoS ONE* 11: e0148136.
- Wang CL, Udatsu T and Fujiwara H (1996) Relationship between motor cell silica body shape and grain morphological/physiological traits for discriminating Indica and Japonica Rice in China. *Japanese Journal of Breeding* 46: 61–66.
- Wang S and Gong D (2000) Climate in China during the four special periods in Holocene. *Progress in Natural Science* 10: 325–332.
- Wang X (2013) Lijiagou site and agricultural origin in the Central Plain. *Agricultural History of China* 6: 13–20 (in Chinese).
- Wang X and Xu X (2003) A discussion on the rice-millet blended zone in the Neolithic Age. *Agricultural History of China* 3: 3–9 (in Chinese).
- Wang Y, Zhang P, Jin G et al. (2011) Floatation results of 2007 excavation season from the Gouwan site in Xichuan County, Henan Province. *Sichuan Cultural Relics* 2: 80–92 (in Chinese).
- Wang YJ and Lu HY (1993) *The Study of Phytolith and Its Application*. Beijing: China Ocean Press (in Chinese).
- Weisskopf A (2016) A wet and dry story: Distinguishing rice and millet arable systems using phytoliths. *Vegetation History and Archaeobotany* 26: 99–109.
- Weisskopf A, Deng Z, Qin L et al. (2015a) The interplay of millets and rice in Neolithic central China: Integrating phytoliths into the archaeobotany of Baligang. *Archaeological Research in Asia* 4: 36–45.
- Weisskopf A, Harvey E, Kingwell-Banham E et al. (2014) Archaeobotanical implications of phytolith assemblages from cultivated rice systems, wild rice stands and macro-regional patterns. *Journal of Archaeological Science* 51: 43–53.
- Weisskopf A, Qin L, Ding J et al. (2015b) Phytoliths and rice: From wet to dry and back again in the Neolithic Lower Yangtze. *Antiquity* 89: 1051–1063.
- Wu WW, Wang XH, Wu XH et al. (2014a) The early Holocene archaeobotanical record from the Zhangmatun site situated at the northern edge of the Shandong Highlands, China. *Quaternary International* 348: 183–193.
- Wu Y, Jiang LP, Zheng YF et al. (2014b) Morphological trend analysis of rice phytolith during the early Neolithic in the Lower Yangtze. *Journal of Archaeological Science* 49: 326–331.
- Wu YL (1994) The rice agriculture in the Neolithic Yellow River region. *Agricultural Archaeology* 1: 78–84 (in Chinese).
- Xiao JL, Xu QH, Nakamura T et al. (2004) Holocene vegetation variation in the Daihai Lake region of north-central China: A direct indication of the Asian monsoon climatic history. *Quaternary Science Reviews* 23: 1669–1679.
- Yan WM (1987) The unity and diversity of Chinese prehistoric culture. *Cultural Relics* 3: 38–50 (in Chinese).
- Yang XY, Ma Z, Wang T et al. (2014) Starch grain evidence reveals early pottery function cooking plant foods in North China. *Chinese Science Bulletin* 59: 4352–4358.
- Yang XY, Wan ZW, Perry L et al. (2012) Early millet use in northern China. *Proceedings of the National Academy of Sciences* 109: 3726–3730.
- Yang YZ, Cheng ZJ, Li WY et al. (2016a) The emergence, development and regional differences of mixed farming of rice and millet in the upper and middle Huai River Valley, China. *Science in China Series D: Earth Sciences* 59: 1779–1790.
- Yang YZ, Li WY, Yao L et al. (2015) Plant resources utilization at the Tanghu site during the Peiligang Culture period based on starch grain analysis, Henan Province. *Quaternary Sciences* 35: 229–239 (in Chinese).
- Yang YZ, Li WY, Yao L et al. (2016b) Plant food sources and stone tools' function at the site of Shunshanji based on starch grain analysis. *Science in China Series D: Earth Sciences* 59: 1574–1582 (in Chinese).
- Yao L, Yang YZ, Sun YA et al. (2016) Early Neolithic human exploitation and processing of plant foods in the Lower Yangtze River, China. *Quaternary International* 426: 56–64.
- Zhang C (2011b) On the cultural remains of Jiahu 1 Phase. *Cultural Relics* 3: 46–53 (in Chinese).
- Zhang JP (2010) *Phytolith analysis of common millet, foxtail millet and green foxtail, and origin and spread of typical crops*

- in China. PhD Thesis, Institute of Geology and Geophysics, Chinese Academy of Sciences (in Chinese).
- Zhang YH (2011a) *Research of Starch Granules on the Surface of the Tools of Botanic Food of the Peiligang Culture*. Master's Thesis, University of Science and Technology of China (in Chinese).
- Zhang C and Hung H-C H (2013) Jiahu 1: Earliest farmers beyond the Yangtze River. *Antiquity* 87: 46–63.
- Zhang JN, Xia ZK and Zhang XH (2014) Research on charred plant remains from the Neolithic to the Bronze Age in Luoyang Basin. *Chinese Science Bulletin* 59: 3388–3397 (in Chinese).
- Zhang H, Bevan A, Fuller D et al. (2010a) Archaeobotanical and GIS-based approaches to prehistoric agriculture in the upper Ying valley, Henan, China. *Journal of Archaeological Science* 37: 1480–1489.
- Zhang JP, Lu HY, Gu WF et al. (2012) Early mixed farming of millet and rice 7800 years ago in the Middle Yellow River region, China. *PLoS ONE* 7: e52146.
- Zhang JP, Lu HY, Wu NQ et al. (2010b) Phytolith evidence of millet agriculture during about 6000–2100 aB.P. in the Guanzhong basin, China. *Quaternary Sciences* 30: 287–297 (in Chinese).
- Zhang JP, Lu HY, Wu NQ et al. (2010c) Phytolith evidence for rice cultivation and spread in Mid-Late Neolithic archaeological sites in central North China. *Boreas* 39: 592–602.
- Zhang JP, Lu HY, Wu NQ et al. (2011) Phytolith analysis for differentiating between foxtail millet (*Setaria Italica*) and Green Foxtail (*Setaria Viridis*). *PLoS ONE* 6: e19726.
- Zhao ZJ (2003) The preliminary floatation results of the Lajia site, Qinghai Province. *China Cultural Relics News*, 19 September, p. 7 (in Chinese).
- Zhao ZJ (2004) Floatation results from the Xinglonggou site and the origin of the dry-land agriculture in North China. In: Department of Cultural Relics and Museology of Nanjing Normal University (ed.) *Antiquities of East Asia*. Beijing: Cultural Relics Publishing House, pp. 188–199 (in Chinese).
- Zhao ZJ (2007) Research on the agriculture of the Central Plain during the period from 2500 BC to 1500 BC. In: The Center for Scientific Archaeology, Institute of Archaeology, Chinese Academy of Social Sciences (ed.) *Science for Archaeology* (vol. 2). Beijing: Science Press, pp. 1–11 (in Chinese).
- Zhao ZJ (2011a) New archaeobotanic data for the study of the origins of agriculture in China. *Current Anthropology* 52: S295–S306.
- Zhao ZJ (2011b) The characteristics of agriculture during the formation of Chinese civilization In: The Center for Scientific Archaeology, Institute of Archaeology, Chinese Academy of Social Sciences (eds) *Science for Archaeology* (vol. 3). Beijing: Science Press, pp. 1–35 (in Chinese).
- Zhao ZJ (2014) The process of origin of agriculture in China: Archaeological evidence from flotation results. *Quaternary Sciences* 34: 73–84 (in Chinese).
- Zhao ZJ and Jiang LP (2016) Analyses of plant remains from floatation work carried out at the Shangshan site, Pujiang County, Zhejiang Province. *Cultural Relics in Southern China* 3: 109–116 (in Chinese).
- Zhao ZJ and Zhang JZ (2009) Analyses report of floatation work carried out in 2001 at the Jiahu site. *Archaeology* 8: 84–93 (in Chinese).
- Zhao ZJ, Pearsall D, Benfer R et al. (1998) Distinguishing rice (*Oryza Sativa* Poaceae) from Wild *Oryza* Species through Phytolith Analysis, II Finalized Method. *Economic Botany* 52: 134–145.
- Zheng Y, Sun G and Chen X (2007) Characteristics of the short rachillae of rice from archaeological sites dating to 7000 years ago. *Chinese Science Bulletin* 52: 1654–1660.
- Zheng Y, Crawford GW, Jiang L et al. (2016) Rice domestication revealed by reduced shattering of archaeological rice from the lower Yangtze valley. *Scientific Reports* 6: 28136.
- Zheng Y, Dong Y, Matsui A et al. (2003) Molecular genetic basis of determining subspecies of ancient rice using the shape of phytoliths. *Journal of Archaeological Science* 30: 1215–1221.
- Zheng Y, Fujiwara H, You X et al. (1999) Morphological characteristics of plant opals from motor cells of rice in the Neolithic age of the Taihu region. *Chinese Journal of Rice Science* 13: 25–30 (in Chinese).
- Zheng Y, Yu W, Rui G et al. (2000) A comparison of morphological characters of plant opals of rice between Hemudu and Luojiajiao sites. *Journal of Zhuzhou Institute of Technology* 14: 4–6 (in Chinese).
- Zhou X, Li X, Zhao K et al. (2011) Early agricultural development and environmental effects in the Neolithic Longdong basin (East Gansu). *Chinese Science Bulletin* 56: 318–326 (in Chinese).
- Zou J, Tang L and Wang C (1998) On the origin of cultivated Keng Rice (*Oryza Sativa* L. Subsp. Japonica). *Scientia Agricultura Sinica* 31: 75–81 (in Chinese).
- Zuo XX, Lu HY, Jiang LP et al. (2017) Dating rice remains through phytolith carbon-14 study reveals domestication at the beginning of the Holocene. *Proceedings of the National Academy of Sciences* 114: 6486–6491.