Vegetation History and Archaeobotany (2022) 31:261–277
https://doi.org/10.1007/s00334-021-00851-0

ORIGINAL ARTICLE

Understanding crop processing and its social meaning in the Xinzhai period (1850–1750 cal BCE): a case study on the Xinzhai site, China

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Received: 9 December 2020 / Accepted: 25 March 2021 / Published online: 3 September 2021

Abstract

Although the Xinzhai period (1850–1750 cal BCE) has been widely regarded as a critical time for the development of urbanization in China, little is known about the labour and social organization of the time. In this paper, archaeobotanical assemblages have been used to explore evidence of crop processing and they have provided further insights into the organization of labour and society at the Xinzhai site on the Central Plain of China. This is the first case study linking agricultural activities and social organization in the Xinzhai period. By discussing macro-botanical and phytolith results together, we conclude that the hulled cereals *Setaria italica* (foxtail millet), *Panicum miliaceum* (common or broomcorn millet) and *Oryza sativa* (rice), and the free-threshing pulse *Glycine max* (soybean) were all partly processed before storage to reduce labour demand in the harvest period. Since these summer-sown crops are all harvested in autumn, the practice of partial processing might imply that less labour was needed before storage. Thus, the labour for crop processing appears to have been organized on the basis of small production units such as households. This pattern is different from the communal bulk processing of crops before storage by the contemporary inhabitants of Dongzhao. Different patterns of social organization in various settlements in the Xinzhai period can thus be suggested. This conclusion contributes to a comprehensive understanding of the social development of communities living on the Central Plain and indicates that a steady increase in social complexity was very likely in the period before urbanization.

Keywords Xinzhai period · Macro-botanical remains · Phytoliths · Crop processing · Labour mobilization · Social organization

Introduction

In studying past societies, one fundamental issue that needs to be addressed is how labour was organized within them (Fuller et al. 2014). As suggested and testified by many researchers, archaeobotanical assemblages can contribute to the understanding of how labour was organised and scheduled at various sites and on a broader level in past societies, by studying at what stage in the processing sequence crops were stored (for example, Hillman 1981, 1984; Jones 1984a, b, 1985; Stevens 1996, 2003; Fuller 2002; Fuller and Stevens 2009; Bates 2011, 2016; Fuller et al. 2014; Bates et al. 2017). The basic principle behind this idea is that the most important sources of seeds and chaff preserved in ancient sites were from routine daily crop processing activities for food preparation, in which crops and contaminants such as weed seeds were taken from storage and processed for consumption with household labour (Stevens 2003; Fuller et al. 2014). Crop storage methods can therefore be used to reflect

Communicated by Y. Zhao

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the size of the seasonal workforce used during the harvest period before storage versus that needed for daily food preparation in the households. Furthermore, comparative study of archaeobotanical remains from seasonal activities with those from everyday processing can provide important insights into the wider social system of an ancient culture. Whether a community organized its agricultural activities through some centralized pool of labour or with different types of human groups such as households is a fundamental part of how a society works. Thus, the labour mobilization pattern can be indicative of the social organization type (Fuller et al. 2014).

Being widely recognized as the place where the first urban centres emerged during the Erlitou culture (1750–1550 cal BCE) in China, archaeobotanical investigations on the Central Plain (Zhongyuan) are of particular interest, especially for the process of social complexity and its organization of societies (Liu and Chen 2012). Rather than an abrupt change, urbanization was a protracted process of social evolution. The emergence of the first urban centre from 1750 cal BCE can therefore be traced back to the continuous social development in the preceding Xinzhai period (1850–1750 cal BCE). Because of this, knowing the type of social organization in the Xinzhai period is vital in the understanding of early urbanization in China. However, we know surprisingly little about this. Although archaeobotanical data have shown great value in the exploration of labour and social organization, current archaeobotanical investigations on a small number of individual sites related to the Xinzhai period have been almost exclusively focused on crop finds (Yao et al. 2007; ACAC-PK and Zhengzhou 2008; Zhong et al. 2016; Yang et al. 2017; Tang et al. 2018) and questions concerning crop processing with its related social aspects were not considered. The idea of linking crop processing with social organization has only occurred recently in China, particularly aided by the ethnographic investigation of *Setaria italica* (foxtail millet) processing published in Chinese by Song et al. (2014).

Macro-botanical remains and phytoliths, with their differing preservation potentials, have successfully provided complementary insights into crop processing methods in small village-type settlements and also into urban–rural subsistence relationships in India (Bates 2016; Bates et al. 2017). However, research in China at present has either only focused on macro-botanical remains or phytoliths. Macro-botanical studies have investigated, for example, the social organization transformation in the river valleys of the upper Ying (Fuller and Zhang 2007) and Sushui (Song 2011; Song et al. 2019), with discussions on the processing of *S. italica* and *Panicum miliaceum* (broomcorn millet). Phytolith studies, on the other hand, have explored social organization at the Baligang, Shunshanji and Hanjing sites through the analysis of *Oryza sativa* (rice) processing (Weisskopf et al. 2015; Luo et al. 2021). Also, even though pulse processing methods have been recorded by ethnographical investigations in India (Fuller and Harvey 2006), *Glycine max* processing in archaeological samples in China has never been discussed so far. In the present study, processing methods of *Setaria*, *Panicum*, *Oryza* and *Glycine* were studied through a combination of two lines of botanical proxy evidence from the Xinzhai site, macro-botanical remains and phytoliths. Moreover, although there has been a sophisticated study showing the great potential of arable weeds in indicating crop processing methods (for example, Reddy 1994, 1997), they have been overlooked in current Chinese studies. Therefore, arable weeds were included in this research as well. This project is not only a pioneer study for exploring crop processing through the integration of two types of archaeobotanical remains in China but also the first systematic research into labour and social organization in the Xinzhai period.

The Xinzhai site and its setting

The Xinzhai site is located 22.5 km from the city of Xinmi in Henan province. It is situated on the floodplain east of the Song mountains and north of the Shuangji river (Fig. 1a). After its first discovery in the 1960s, it has been continuously excavated from 1979 (Second team et al. 1981) to the present. Occupation at this site includes three phases, the Neolithic late Longshan period (2050–1900 cal BCE), the Neolithic Xinzhai period (1850–1750 cal BCE) and the Bronze Age Erlitou phase 1 (later than 1750 cal BCE) (ACAC-PK and Zhengzhou 2008). Settlement at the site was fully developed during the Xinzhai period, when it was surrounded by two concentric outer ditches and an inner rammed earth wall with moats. Exquisite artefacts of jade, copper, elaborate pottery vessels and particularly a large (ca. 1,400 m^2) semi-subterranean building illustrate the advanced social and political status of the site (Zhao et al. 2009). It has been proposed as the capital of the Xia ruler *Qi* (齐) (Xu 2004; Zhao 2004) or of Houyi (后羿) and Hanzhuo (寒浞), who came from the Dongfang (东方) and took power in the Xia dynasty (Gu 2002). These interpretations assume that the Xinzhai site was the primary centre occupied by a continuous succession of leaders related to the first legendary Xia dynasty in China (Liu and Chen 2012). Currently, among all the sites that contain Xinzhai assemblages, Xinzhai in this research and Huadizui in Gongyi were two regional centres on the Central Plain, while Xinzhai was the largest (Liu 2005).

The samples analysed in this research were from the 2016 and 2018 excavation seasons, for which collaborative excavations were conducted by the Xinzhai team of the Institute of Archaeology in the Chinese Academy of Social

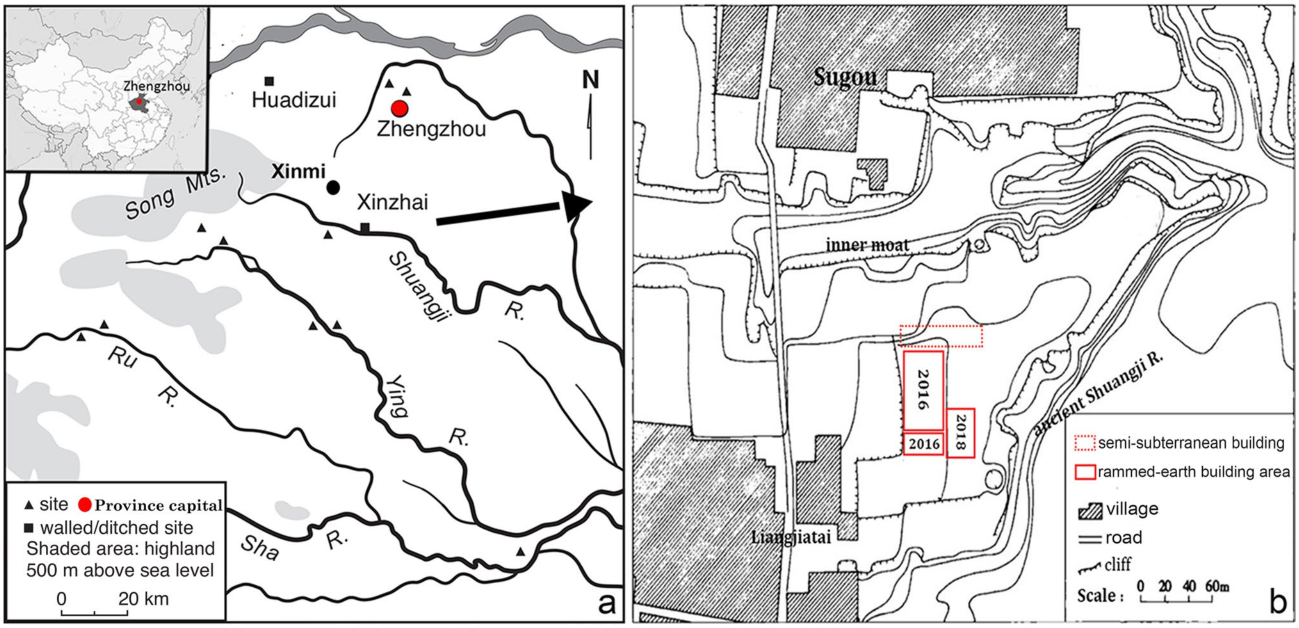

Fig. 1 **a** distribution of major Xinzhai period sites, Central Plain, China modified from Pang and Gao 2008, Fig. 1); **b** excavation areas (modified from Xinzhai, Zhengzhou 2009, Fig. 1)

Sciences, the Institute of Archaeology in Zhengzhou and the Institute of Archaeology at Anhui University (only in 2018). The excavations consisted of 53 trenches, each measuring 5 × 5 m, northeast of the modern village Liangjiatai (Fig. 1b). They were located on the highest area in the inner city at 143.8 m a.s.l. (Xinzhai, Zhengzhou 2009). During the excavation, rammed earth building foundations, pits and burials were exposed, mainly dating to the Xinzhai period, but a few to the Neolithic Longshan and Bronze Age Erlitou periods.

Materials and laboratory processing

In investigating crop processing methods from archaeological contexts, the combination of macro-botanical remains and phytoliths can provide better evidence than either alone (Bates 2016; Bates et al. 2017). In this research, 220 flotation macrofossil samples and 59 phytolith samples were collected from waste pit features (Table S1). Archaeobotanical remains of material in situ are rather rare, because most archaeological contexts do not normally contain primary botanical refuse that was burnt within the context from which the remains were recovered, but are mostly made up of tertiary refuse in which the plant remains came from many different activities and charring events, or are at least made of secondary refuse in which the plant remains from one discrete burning event were moved to another context (Hubbard and Clapham 1992; Fuller et al. 2014; Filatova 2020). However, by understanding the formation processes of deposits containing charred plant remains, it is possible to connect the resulting plant assemblages with past human activities. The analysis of charred plant remains from many different types of sites and from various periods shows that most samples are very similar in their composition (van der Veen 2007). This similarity argues for the case that the majority of plant remains can be related to a closely related set of activities. More than that, charred assemblages clearly represent a very limited range of the total floristic diversity, as almost all taxa are connected with cultivated crops, including cereals, cereal chaff and associated weeds, with only the exception of wild edible plants. According to van der Veen (2007), charred plant remains that are found in archaeological samples mainly come from five routes of entry: 1. Intentional and casual use of fuel; 2. Contact with fire during crop processing or preparation of food; 3. Accidental burning of stored food and fodder; 4. Cleaning out of grain storage pits using fire and 5. Destruction of diseased or infested crops with fire. The first two of these represent routine daily activities and the last two are rare events. Since charred plant components resulting from everyday activities are more likely to be represented in archaeobotanical material than occasional rare events (Fuller et al. 2014), most charred plant remains therefore are the waste from daily activities of burning fuel, processing crops and preparing food. So with the exclusion of firewood and gathered wild plant remains, the charred plant remains from the waste pits in Xinzhai can be used to indicate crop processing and food preparation. All the samples collected from the Xinzhai site are from the Xinzhai period between 1880 and 1745 cal BCE, according to the stratigraphy, typology of finds and also the AMS ^{14}C dating results from charred seeds and fruit remains from eight samples (Fig. S1).

Macro-botanical remains were obtained by using a bucket flotation system. An average of 10 L of sediment per sample was aimed for, although in some cases such as when the context was smaller, it was impossible. The lighter floating materials and heavier sinking materials were retained by 0.2 and 1 mm mesh sieves, respectively. After drying, the samples were sent to laboratories for analysis. The sorting work was carried out at the ancient parasite and starch analysis laboratory (APSA) in the Henan Institute of Cultural Relics and Archaeology, China. Light fraction samples were first sieved with meshes of 1, 0.5 and 0.2 mm and the fractions < 0.2 mm were excluded since no charred seeds or fruits were found in these tiny remains. The identification, counting and photographing of the charred remains were done in the laboratory of the Institute of Pre- and Protohistory at Kiel University (IPPH), Germany. Identification was done by comparison with modern reference material and followed the identification methodology of Kroll (1983), Liu et al. (2008) and Fuller (2017).

Phytolith samples were collected either by sampling sub-layers in a pit or by sampling sections every 10 cm in homogeneous units from a profile, or by the combination of two methods in the pits with thick sub-layers (Table S1). The extraction of phytoliths was carried out at APSA in Henan. Sub-samples of 2 g soil were weighed and then treated with 30% hydrogen peroxide (H_2O_2) and 10% hydrochloric acid (HCl) to remove organic matter and carbonates. Phytoliths were extracted by zinc bromide ($ZnBr_2$, density 2.37 g/cm^3) heavy liquid flotation and mounted on slides in immersion oil, using cover slips sealed with nail polish. They were observed, identified and counted with a Leica DM750 light microscope at 400× magnification at IPPH in Kiel. The main references used for identification were Twiss et al. (1969), Wang and Lu (1993), Ball et al. (1996, 1999), Lu and Liu (2003), Lu et al. (2009); Zhang et al. (2011, 2018, 2019) and Dal Corso (2018). In each sample, a sum of at least 300 items was counted. They included identifiable morphotypes, undefined morphotypes (such as indeterminate, fragmented, highly corroded silica bodies), other siliceous remains such as sponge spicules and diatoms, and pollen grains. Phytolith nomenclature followed ICPN 2.0 (ICPT 2019) and silica skeletons were named after the predominant cell types (usually elongate long cells) (Madella 2007).

Research methods

When interpreting botanical remains from archaeological contexts, ethnographic observations of crop processing methods in modern non-mechanized agricultural societies can be tentatively applied as references (Harvey and Fuller 2005; Song et al. 2019). Ethnographical investigations which are cited for the Xinzhai samples are first mentioned in the discussion of each crop (Fig. S2). Because the differentiation of crop processing steps is based on the recognition of different types of plant remains from various processing stages (Harvey and Fuller 2005), the macro-botanical finds are arranged into several groups, with only arable weeds, crops and chaff included, as they are connected with crop processing (Table S2). For *Glycine max*, which requires sieving during its processing, the beans are classified by their size. The length of modern soybean is in general > 5 mm, but in the early stage of domestication, it varied and many of the seeds were < 5 mm (Zhao and Yang 2017). Accordingly, soybean finds in Xinzhai were divided into "large soybean" (with a length > 5 mm) and "small soybean" (< 5 mm) (Fig. 2). For *Setaria italica*, *Panicum miliaceum* and *Oryza sativa*, which need to be winnowed to remove the chaff after threshing, the ratio of immature and unhulled crop grains against mature and hulled grains and the ratio of arable weeds against crop grains were used. The separation of millet and rice grains into immature and mature ones followed the identification methods of Song et al. (2013, 2014) and Fuller and Qin (2008). In both millet species, the smaller, flatter, semi-filled or unfilled grains usually with wrinkled endosperms were considered to be immature ones and the circular, fat and large ones were mature (Fig. 2). Likewise, in rice, unfilled or lightly filled, small, thin grains, sometimes with sharp papery edges were recorded as immature (Fig. 2).

However, except for the different stages in processing, the proportions of immature grains, hulled grains and arable weeds are affected by several factors. Drought years, poor soils and early harvesting time under adverse weather all have the potential to lead to a high percentage of immature crop grains (Song et al. 2019). The percentage of hulled grains might be overestimated, because cereal grains and especially small sized ones have extremely fragile lemmas and paleas that are readily removed by charring (Reddy 1994; Bates et al. 2017), so grains without attached husk remains are not necessarily fully cleaned products (Fuller and Zhang 2007). Similarly, many factors such as harvesting by gathering panicles, intensive weeding during crop growth and transplanting of seedlings in paddy fields can all effectively avoid gathering weeds and therefore affect the presence of arable weed remains in the assemblages (Weisskopf 2010). In this research, additional indicators were used to minimize these potential biases caused by single lines of evidence. First, arable weeds with different physical characteristics such as those with and without seed heads, big and small, light and heavy, vary in plant assemblages resulting from various stages of processing (Jones 1984a). Thus, they were analysed according to their weights, sizes and abilities to retain their seed heads. Second,

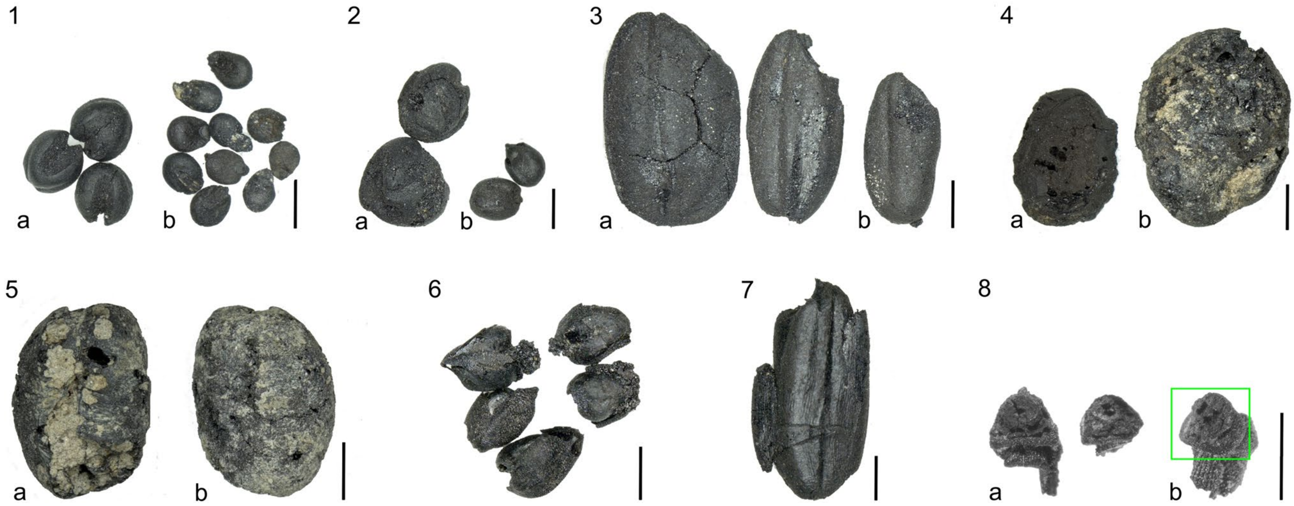

Fig. 2 Main crop macro-remains, **1** *Setaria italica* grain, **a** mature, **b** immature; **2** *Panicum miliaceum* grain, **a** mature, **b** immature; **3** *Oryza sativa* grain, **a** mature, **b** immature; **4** *Glycine max* bean, **a** small, **b** large; **5** *Triticum aestivum* grain, **a** dorsal surface (top), **b** ventral surface (bottom); **6** *Panicum* grain with husk; **7** *Oryza* grain with husk (partly) **8** *Oryza* spikelet base, **a** mature, **b** immature (protruding scar shown in the green square); scale bars = 1 mm

phytolith data were used to complement the interpretation from macro-botanical remains. The composition of phytolith morphotypes derived from different parts of plants varies in the remains from different crop processing steps (Harvey and Fuller 2005), so the morphotypes are arranged into different groups based on the plant parts where they occur (Table 1). The processing stage of each crop is indicated by the comparison of samples based on the variation of three phytolith groups, those from crop husks, from arable weed husks, and from crop and weed leaves and stems. Phytolith morphotypes included in each group are based on Weisskopf (2010), Weisskopf et al. (2015) and Bates et al. (2017). The morphotype of silica skeleton with columellate long cells (except for Ω- and η-types) is included in the processing of both rice and millet, as it was difficult to identify to species or genus level.

Results

The macro-botanical remains and phytoliths recovered from this site indicate the same cereal taxa, but *Glycine max* is not represented in the phytolith assemblage (Tables S2, S3). The *Oryza sativa* was domesticated according to the morphological features of the spikelet bases (Fuller et al. 2007, 2009; Fuller and Qin 2008). In 50 of these, except for three

Table 1 Phytolith morphotypes representing *Setaria*, *Panicum*, *Oryza* and weeds

Phytolith morphotypes	Attribution	Groups
Millet and related weeds		
SKE_COL_Ω, SKE_COL_PAP	Husk, *Setaria italica*	Millet husk
SKE_COL_η	Husk, *Panicum miliaceum*	
SKE_COL	Husk, weedy Poaceae	Weed husk
SKE_VER_BIL, SKE_ELO_PSI, SKE_ELO_SIN, SKE_ELO_CRE	Leaf/stem, weedy Poaceae	Millet and weed leaf/stem
Rice and related weeds		
DOU	Husk, *Oryza sativa*	Rice husk
CON	Husk, weedy Cyperaceae	Weed husk
SKE_COL	Husk, weedy Poaceae	
SKE_PAR_BIL	Leaf/stem, *Oryza sativa*	Rice and weed leaf/stem
BUL_FLA_FLA	Leaf, *Oryza sativa*	
LON_ROD	Leaf/stem, weedy Cyperaceae	
BUL_FLA, BLO, SKE_BLO	Leaf, weedy Poaceae	

Phytolith codes see ESM Table S3

spikelet bases which had immature features with protruding scars, all the rest showed domesticated features (Fig. 2). The solitary find of a *Triticum aestivum* (bread wheat) grain in the macro-botanical remains proved to be an intrusion from the preceding Longshan period (2050–1900 cal BCE) after AMS dating (2033–1886 cal BCE). However, wheat is still listed as a possible crop, because another charred wheat grain was recorded in a previous report from this site (Zhong et al. 2016) and more importantly, phytoliths from wheat inflorescences were found by Yao et al. (2007) and also in this study. Moreover, following Zhao and Yang (2017), cultivated soybean only included examples where the seed coats burst into pieces after burning with the explosion of the cotyledons, forming empty holes on the surface (Fig. 2). In contrast, those with intact and tightly attached seed coats were distinguished from cultivated ones and counted as wild soybeans (Fig. S3). Therefore, the crops at Xinzhai comprise four cereal species, *Setaria italica*, *Panicum miliaceum*, *Oryza sativa*, *Triticum aestivum* and one pulse, *Glycine max*. The raw data on which the following discussion is based can be found in Table S2 for macro-botanical remains and Table S3 for phytoliths. Images of the main finds are given in Figs. S3–S9.

Discussion

In this research, *S. italica* and *P. miliaceum* together with *O. sativa* are native hulled cereals which need extra processing for de-husking, but for *Glycine max*, it is essentially the same as for *T. aestivum/durum*. The remains of *Triticum* are too few to do processing analysis properly. Considering that only a small amount of phytoliths from *Triticum* inflorescences is recorded, *Triticum* might have been processed elsewhere or even brought to the site by trade. For other crops, their processing sequences were broadly divided into early and late stages to better display the results. Early processing stages refer to the initial steps before storage, which were done after harvesting and usually took place in the field or on specially prepared threshing floors. Late processing stages include those completed after storage and when the crop was about to be consumed. Such later stages were repeated regularly throughout the year, usually within settlements and were mainly done within a household (Fuller et al. 2014).

The processing of *Setaria italica* and *Panicum miliaceum*

A significant study of millet processing is the ethnographic investigation of crop processing in India and its application to archaeological samples (Reddy 1994, 1997, 2003). Many researchers have adapted this model and included phytoliths as well (Harvey and Fuller 2005; Harvey 2006; Weisskopf 2010; Bates 2011, 2016; Bates et al. 2017). In China, there are local ethnographic works on millets and their wild ancestors (for example, Lu 1998, 2002; Liu 2010; Liu et al. 2017), but the most widely cited one is the investigation of *S. italica* and *P. miliaceum* in Shandong province by Song and her colleagues (Song 2007, 2011; Song et al. 2013, 2014). Their discussion on the ratios of crop grains to weeds, immature and unhulled to mature and hulled crop grains has been widely applied to the interpretation of archaeological samples (Fuller and Zhang 2007; Zhang et al. 2010a; Deng and Gao 2012; Song et al. 2019). In this research, the exploration of millet processing is mainly based on the models from Reddy (1994) and Song et al. (2013, 2014), and the general model is in Fig. S2a.

As the first step in crop processing, the harvesting method has a critical effect on plant composition in the following stages. It is therefore important to understand harvesting before pursuing further explanation of processing methods (Reddy 2003). To study the harvesting method, the growth height of weeds can be used (Hillman 1981). If the crop was harvested by uprooting or cutting low on the straw, this might be represented in weed remains with more low growing or prostrate taxa. In contrast, if the crop was reaped high on the straw or only the panicles were harvested, more weed remains from tall plants and fewer low growing ones would be present in the processing remains (Reynolds 1985). However, the growing height of climbing plants such as *Galium tricornutum* with a twining habit that is easily tangled up with other plants is difficult to estimate. After calculating from the maximum height of the plants (Li 1998), 55.7% (2,520) of the millet field weeds belong to the low category, 23.6% (1,066) to the medium category, 20.7% (936) to the tall category and only 0.1% (3) to the uncertain category of climbing plants (Table S2). This overwhelmingly high proportion of low and medium growing weeds is indicative of cutting low on the straw. Besides, these two millets grown in China, *Setaria* and *Panicum*, fall into Reddy's type B small hulled millets (Reddy 1994). In her ethnographic observation, these ones, such as *P. miliare*, are usually harvested at the base of the plant due to its slender stalks, rather than only harvesting the panicles which is usual for the thick stemmed type A millets such as *Sorghum bicolor*. Residue analyses on harvesting tools can offer relevant evidence as well (Liu et al. 2018). As both the sites of Xinzhai and Huadizui acted as regional centres during the Xinzhai period (Liu and Chen 2012), the subsistence system at Xinzhai might be comparable to that of Huadizui. The finds of millet starch granules and Panicoideae leaf and stem phytoliths on the harvesting tools of stone sickles and knives give direct evidence for cutting millet plants at their bases at Huadizui (Tang 2018) and this was likely to have been done at Xinzhai as well.

After harvesting and before consumption, the stems and leaves as well as a wide variety of weeds have to be removed through various processing steps. The plant assemblages in the archaeobotanical remains from each step change as various elements are removed by processing, resulting in a changing ratio of crop grains to weeds to chaff (Stevens 1996, 2003). In the following discussion, the ratios of millet grains to arable weeds against the ratios of immature and unhulled millet grains to mature and hulled ones are applied to individual samples (Fuller and Zhang 2007; Song et al. 2019) and the results are plotted in Fig. 3a. During the calculation, the samples which have no arable weed finds were given the maximum value of 100 for the ratio of millet grains to arable weeds. In general, immature and unhulled millet grains decline compared to mature and hulled ones in material from later stages of the processing sequence. Thus, the lower right side of the diagram contains samples that represent de-husking remains from only the late processing stages and the upper left side includes samples that represent primitive winnowing remains from the early processing stages. In primitive winnowing remains, most samples have the ratio of immature and unhulled grains to mature and hulled grains of < 1 (Fig. 3a, blue dots on the upper left). Immature millet grains are quite common in macro-botanical remains (Fuller and Zhang 2007; Zhang et al. 2010a; Song et al. 2013), as millet seeds normally ripen unevenly (Trifonov et al. 2017) and in the past Chinese farmers started harvesting as soon as half of the grains were ripe to avoid a

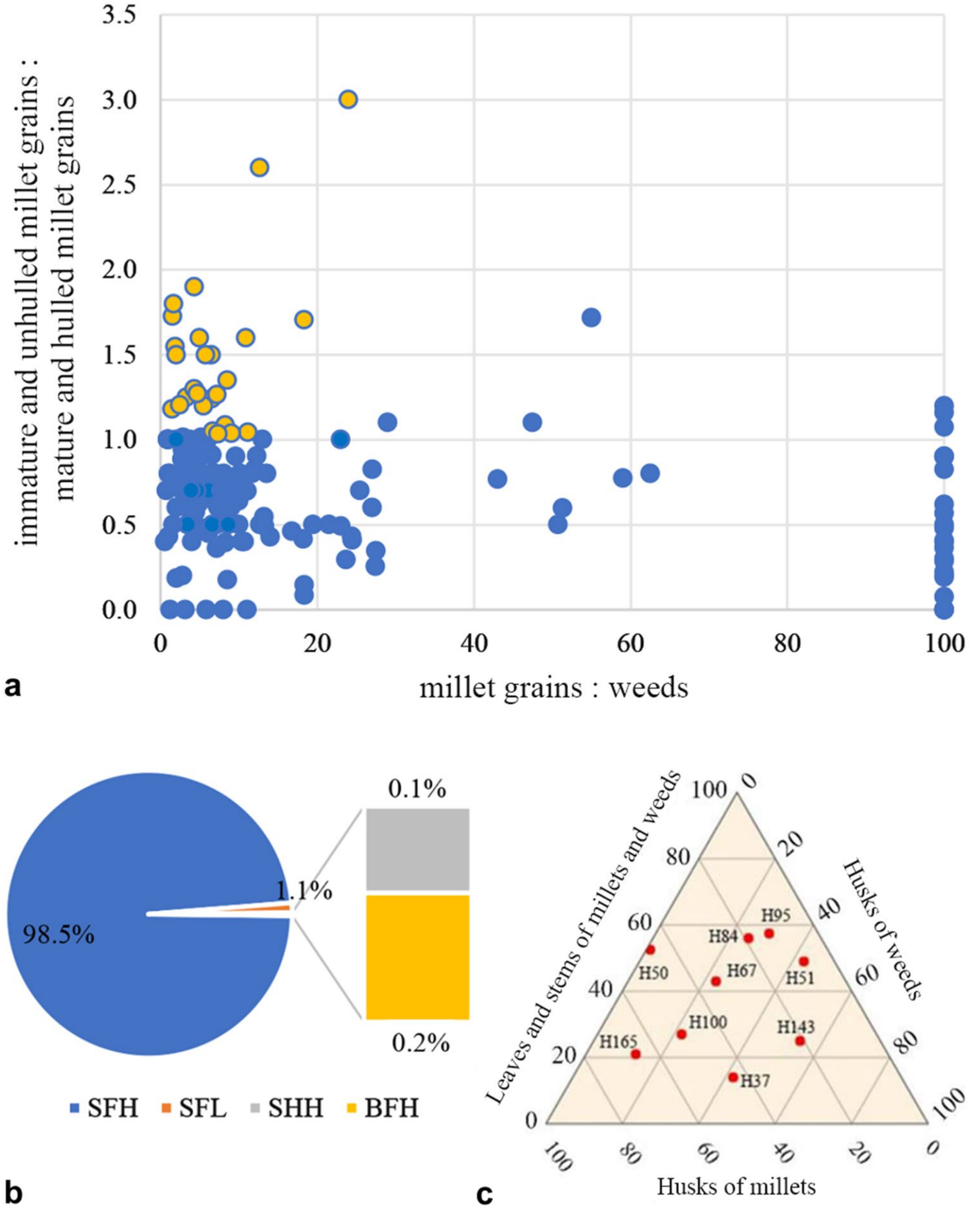

Fig. 3 **a** Scatter plot showing ratio of *Setaria* and *Panicum* grains to weeds against ratio of immature and unhulled *Setaria* and *Panicum* grains to mature hulled *Setaria* and *Panicum* grains; upper left, yellow dots are the by-products of primitive winnowing with ratio > 1, blue dots are the products of primitive winnowing with ratio < 1; **b** proportions of millet field weeds in different categories; *SFH*, small free heavy; *SFL* small free light; *SHH* small headed heavy; *BFL* big free light (Reddy 1994); **c** tri-plot of individual samples showing the relative proportions of phytolith morphotypes from to millet processing

loss of grains (Song et al. 2013). Immature grains therefore have long been a concern to Chinese farmers during millet processing and they mostly have to be removed during the primitive winnowing stage so that the mature to immature ratio in the by-product is much less than 1 but many times greater than 1 in the product (Song et al. 2013). Hence, most of the Xinzhai samples are likely to be the products of primitive winnowing as they mainly have mature grains.

Weed seeds are also a strong indicator for the identification of crop processing methods (for example, Hillman 1981, 1984; Jones 1984a; van der Veen 1990, 1992; Reddy 1994, 2003; Graham and Smith 2013). Comparison between the large amount of millet grains (39,571) and the small quantity of millet weed seeds (7,603) in the Xinzhai material suggests later processing stages. Moreover, in the processing of millet, features of weed seeds including the presence of seed heads (measured as headed or free), seed weight (measured as light or heavy) and seed size (measured as small or big) are of equal importance (Reddy 1994). Based on these factors, weed seeds have been divided into eight categories: small free light (SFL), small free heavy (SFH), small headed light (SHL), small headed heavy (SHH), big free light (BFL), big free heavy (BFH), big headed light (BHL) and big headed heavy (BHH) (Reddy 1994). The weeds from the Xinzhai millet fields fall into four of these categories: SFH (4,459), BFH (8), SFL (52) and SHH (6) (Fig. 3b). Among them, heavy weed seeds (SFH, BFH, SHH) are most common at 99.6% of the total. As they can easily remain until the late processing stages and some of them even have to be removed by hand sorting in the last step (Reddy 1994), their importance at Xinzhai indicates later stages of millet processing. A similar conclusion can be drawn by clustering the phytolith groups on the tri-plot (Fig. 3c). Most samples contain large amounts of husks from millet and related weeds, but relatively fewer from leaves and stems. The fundamental principle in crop processing is to remove the larger non-crop components such as leaves and stems in the early stages of processing, then to separate the smaller parts such as husks in the later processing stages. The abundance of husk phytoliths over ones from leaves and stems suggests late processing stages. Therefore, millet appears, according to both botanical macro-and micro-remains, most likely to have been stored in spikelet form after which only the later processing stages would have been needed.

However, some by-products from early millet processing stages seem to appear as well. Not many, but still some samples in the primitive winnowing remains have a ratio of immature and unhulled to mature and hulled crop grains > 1 (shown as yellow dots in Fig. 3a). They can be defined as primitive winnowing by-products. Also, during primitive winnowing, the closer weed seeds are in size to crop grains, the harder they are to separate, so they tend to remain together (Reddy 1994). After measuring 40 *Setaria* grains (immature and mature), 40 *Panicum* grains (immature and mature) and 50 weed seeds of millet (15 species), many weed seeds were found to be smaller than 1.5 × 1.5 mm and similar in size to immature grains of *S. italica* and *P. miliaceum* (Fig. 4, Table S4). Their presence indicates that these weed seeds accompanied immature millet grains in the primitive winnowing by-products. Due to the economic value of crop processing residues such as straw, they can enter archaeobotanical records in various ways. The most common ones are from animal fodder and organic fuels which include dried plants and animal dung (Fuller et al. 2014). Organic fuels are very difficult to distinguish from crop processing residues, although several breakthrough studies have been done recently (Lancelotti and Madella 2012; Spengler 2019). However, using animal dung and herbaceous plants as fuel can be tentatively excluded in this research, because they are more commonly used in arid and especially unwooded areas and also among herding economies (Lancelotti and Madella 2012; Spengler 2019). So far, there is little evidence that such fuels were important for the agricultural societies of east China, where there were rich wood resources and also climatic constraints on drying dung and crop chaff from seasonally intensive rains. Therefore, it is feasible to argue that the presence of millet by-products in the Xinzhai settlement might due to intentional collection for animal fodder instead of using them as fuel. As observed by Reddy (1994), if millet is intended to be used as human food alone, harvesting just the panicles is better, as only the grains are wanted. However, if millet is used as both human food and animal fodder, harvesting the entire plant by cutting it off at the base is preferred, which fits the case in Xinzhai. Besides, the analysis of animal remains suggests that domestic animals including pigs, sheep and cattle were dominant rather than wild animals in Xinzhai (Yuan et al. 2007; ACAC-PK and Zhengzhou 2008). Among these, cattle and pigs consumed substantial amounts of millet by-products throughout the

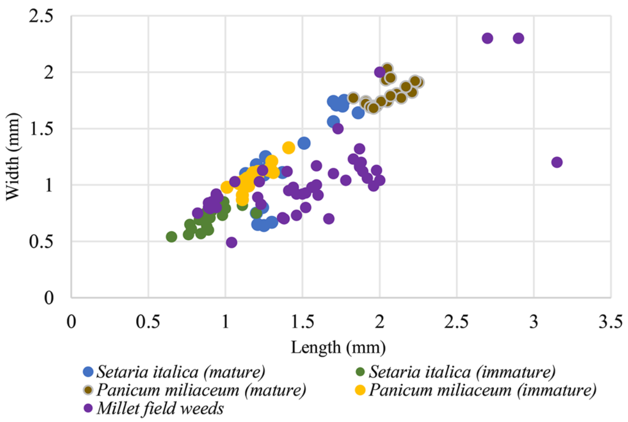

Fig. 4 Dimensions of *Panicum* and *Setaria* grains and associated weeds

whole year, as indicated by strong C_4 signals from stable isotope analysis (Wu et al. 2007; Zhang and Zhao 2015; Dai et al. 2016a, b), and sheep were grazed in the natural environment (C_3) but consumed millet by-products (C_4) in late summer when these were available (Dai et al. 2016a, b) and more than 70% of them were fed to maturity for their wool (Dai et al. 2014). Thus, millet by-products or at least part of the by-products from primitive winnowing were most probably brought back to the settlement for animal feed and were then deposited in the settlement either as fodder or as dung.

The processing of *Oryza sativa*

The ethnographic observation on rice processing carried out by Thompson (1992, 1996) in Thailand is widely cited in archaeological studies. Phytoliths have been incorporated into this model as well (Harvey and Fuller 2005; Harvey 2006; Weisskopf 2010; Bates 2011, 2016; Bates et al. 2017). As mentioned above, ancient rice processing was mainly discussed from phytolith analysis in China, such as the case study of the sites of Baligang (Weisskopf et al. 2015), Shunshanji and Hanjing (Luo et al. 2021). In the study of the Xinzhai samples, the processing models from Thompson (1992, 1996), Harvey and Fuller (2005) and Weisskopf (2010) were applied, which can be found in Fig. S2b.

The harvesting method of rice is not indicated as clearly as for millet by the growth height analysis of the weed remains. In ethnographic investigations three traditional harvesting methods, by sickles, by uprooting and by finger knives have been recorded in modern Thailand and India (Thompson 1992, 1996; Harvey and Fuller 2005). The use of finger knives is restricted to rice farmers from certain regions, mainly in China and southeast Asia (Harvey 2006). By holding a finger knife, which comprises a sharp-edged blade, usually made of mussel shell, stone, or wood, the panicles of rice are cut off from the rest of the plant (Miles 1979; Murphy 2017). Therefore, when harvesting with finger knives, only panicles and occasional tall weeds are collected, but the other two methods produce a similar weed composition with many low growing weeds incorporated. For our material with 48.5% (317) of high growing weeds, it seems that harvesting panicles with finger knives is possible. However, there is also a relatively high proportion (in total 51.4%) of low (36.5%, 238) and medium height (14.9%, 97) weeds. Thus, rice was more possibly harvested by sickles or uprooting, since these methods collect both high and low growing weeds, while by using finger knives, tall weeds are almost exclusively incorporated.

To further investigate rice processing, ratios of hulled and mature rice grains to rice chaff and immature rice grains against ratios of rice grains to weeds were calculated (Bates et al. 2017). For this, samples containing pure rice grains without chaff or immature grains, the ratio of hulled and mature rice grains to rice chaff and immature rice grains was given the maximum value of 100. Similarly, for the ratio of rice grains to arable weeds, samples with no arable weeds but only rice grains were given the ratio 100. In Xinzhai, rice chaff was found in the form of spikelet bases and also husk fragments adhering to rice grains. Most samples indicate early processing stages with high proportions of weeds, immature rice grains and chaff (Fig. 5a, lower left). Rice, like millet, was also winnowed to remove weeds, so the presence of seed heads, the weight and the size are also decisive factors in the understanding of the processing stage. Compared to millet which is dominated by heavy weed seeds, rice has a relatively broader range of weeds, of which 63.7% (415) are small free heavy (SFH) seeds and 36.2% (236) are small free light (SFL) seeds (Table S2). This fits the pattern that both early and late processing stages of rice were done as routine daily activities. Besides, the greater the difference in size between prime grains and weed seeds, the more efficient is primitive winnowing (Reddy 1994). Size comparison of 70 mature rice grains, 40 immature rice grains and 45 rice field weed seeds (5 species) shows that these weed seeds are much smaller than the rice grains, both immature and mature (Fig. 5b, Table S4). Since there is no overlap in size between them, primitive winnowing should be very efficient in removing these weed seeds that are smaller than rice grains. Consequently, the presence of small weed seeds together with rice grains in the waste pits might indicate that the material from storage contexts had not been winnowed and therefore small weed seeds can be found in the settlement as by-products of the daily practice of primitive winnowing. Moreover, compared to these samples from waste pits, samples from storage pits could offer more direct evidence of ways of crop storage. Unfortunately, botanical finds from the storage area of the Xinzhai site only provide the basic information of absolute counts and ubiquities of the main crops and weeds (Zhong et al. 2016). The only useful information about crop processing is that > 50 spikelet bases were found among 381 rice grains. This suggests that rice was not stored as hulled grains, which has no conflicts with current conclusions.

By filling in a possible taphonomic gap in the macrobotanical evidence, phytoliths provide useful additional evidence of rice processing (Fig. 5c). Phytolith morphotypes from leaves and stems of rice and associated weeds were present in large amounts in all samples. As the main material to be removed in the processing, leaves and stems occur in dominant quantities mainly or only in the material from early stages of processing. Additionally, in contrast to millet, by-products of rice processing are unlikely to have been used as animal fodder, since dietary investigations indicate that almost all domestic animals have C_4 signals. Although one sheep in the sample had consumed large amounts of C_3

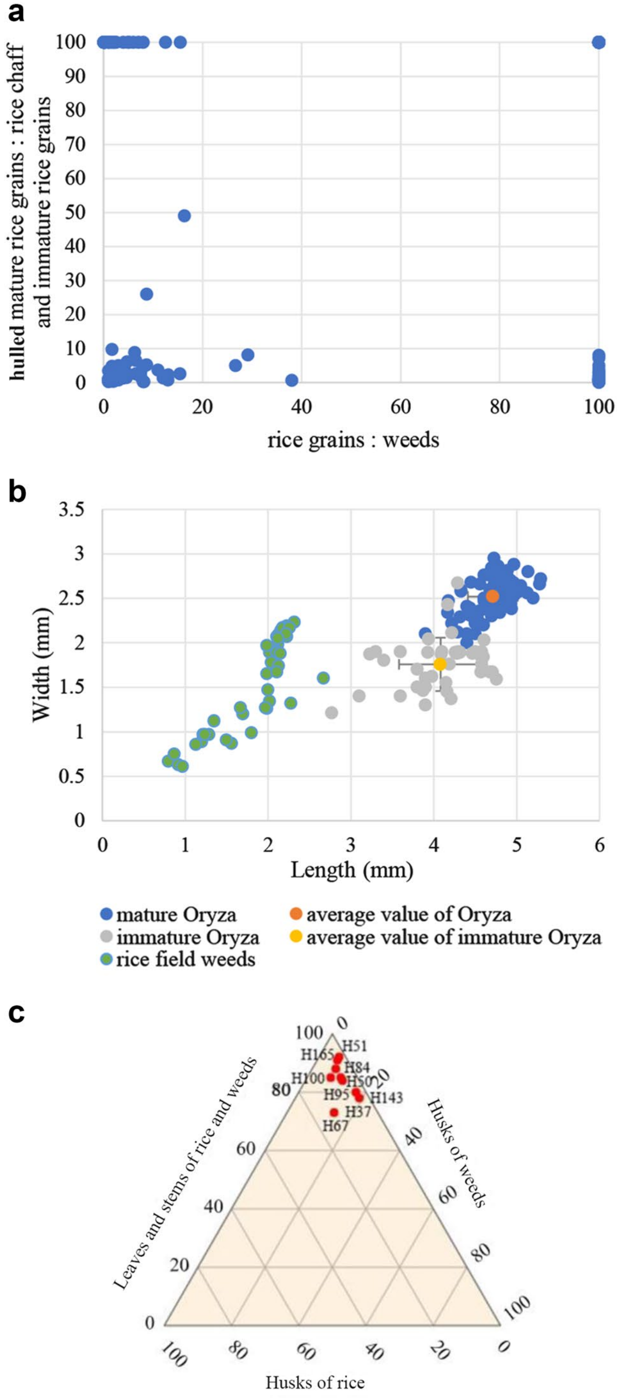

Fig. 5 **a** scatter plot showing ratios of *Oryza* grains to weeds against ratio of hulled and mature *Oryza* grains to rice chaff and immature grains; **b** dimensions of *Oryza* grains and associated weeds; **c** tri-plot of individual samples with the relative proportions of phytolith morphotypes relating to rice processing

food, this rather shows a similar diet to wild animals with the consumption of C_3 based vegetation in natural habitats (Dai et al. 2016a, b). Moreover, rice by-products have an unpleasant taste to ruminants (cattle, sheep and goats), a slow rate of digestion and low nutritional content. The amount that can be consumed is insufficient to sustain a reasonable level of meat or milk production (Malik et al. 2015). Thus, even as part of the roughage given to ruminants, rice by-products are not preferred, as in modern India (van Soest 2006). For this reason, the probability that rice leaves and stems were used as animal fodder is quite low and their deposition in the settlement is better interpreted as waste from daily processing for human food.

The processing of *Glycine max*

While most studies have concentrated on cereals, a processing model for pulses is comparatively rare. Fuller and Harvey (2006) suggested that there are two ways of processing pulses, free threshing and pod threshing. *G. max* encountered in Chinese archaeological samples requires no additional pounding and winnowing to remove the beans from the pods, so its processing follows the description of free threshing pulses (Fig. S2c; Fuller and Weber 2005; Fuller and Harvey 2006).

For harvesting free threshing pulses, uprooting and cutting off the plants near the base are common methods, while harvesting the pods is more usual for primitive cultivars with uneven ripening (Fuller and Harvey 2006). The time when *G. max* started to be selected and completed its domestication process is still poorly understood in China (Crawford et al. 2005). According to the comparison of bean size, and oil content by X-ray tomography (Lee et al. 2011; Wu et al. 2013; Zong et al. 2017), human selection of *G. max* had started during the Xinzhai period, but the morphological features of domestication were not yet established. In the early phase of domestication, the beans were much smaller and also more variable in size (Zhao and Yang 2017). We measured 100 Xinzhai beans and their average size is much smaller (4.15 ± 1.03 × 2.62 ± 0.62 mm) than that of 100 modern beans (7.42 ± 0.56 × 6.13 ± 0.37 mm) (Zhao and Yang 2017). They also have a wide size range with 58% beans within the first standard deviation (SD) and 39% within the second SD (Fig. 6, Table S5). Thus, *G. max* from Xinzhai very probably represent an early phase of domestication, and therefore all three harvesting methods were possibly practised.

The first two methods harvest all pods indiscriminately, while by gathering pods individually there is more opportunity to leave unharvested the undesirable pods that contain small beans. Moreover, beans of differing sizes could be separated by sieving, and smaller ones have more chance of being removed in this way (Fuller and Harvey 2006). In sum, 174 out of 512 beans were small, 34%. This proportion of small beans indicates a high possibility that they were harvested by uprooting or cutting near the base of the plant

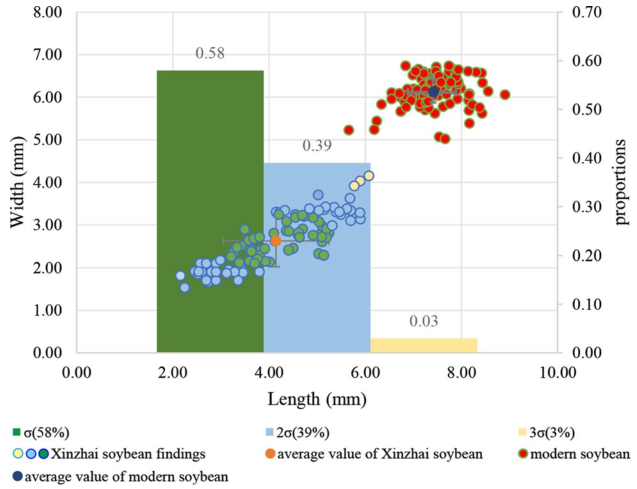

Fig. 6 Scatter plot of *Glycine max* based on the measurement data

and also that they were stored before the coarse sieving. Besides, no soybean threshing remains were found in the plant assemblage, however, instead of being used as evidence for full processing, the absence of soybean residues is better interpreted as a result of taphonomic bias. *G. max* threshing remains are rarely preserved in macro-botanical remains. The preparation and consumption of *G. max* do not necessarily involve contact with fire, so the beans are easily decomposed in the soil rather than preserved as charred remains. Even when soybeans are in contact with fire, they almost invariably burn to ash due to their high oil content. So far, only the survey report of upper Ying river valley (Neolithic Yangshao, Bronze Age Shang) and the excavation report of the Wangjinglou site (Bronze Age, Erlitou) mention *G. max* pod fragment finds in China (Fuller and Zhang 2007; Zhao and Yang 2017).

Labour mobilization and social organization

In non-mechanized ancient societies, agriculture and its related activities created a need for cooperation among human groups such as households. The need for labour was a recurrent situation for which its organisation and social relationships developed (Fuller et al. 2014). For harvesting, a substantial amount of labour is required for a short period in cases such as untimely rainfall (Fuller et al. 2014). Early processing stages of hulled crops such as threshing and primitive winnowing often need to be repeated several times to fully release and remove non-crop components, and these steps require intensive labour and time inputs (Reddy 1994). Later processing stages like de-husking and hand sorting are time-consuming, but these can be done during the slack times for farming (Fuller et al. 2014). Therefore, labour availability is the main factor in determining how many processing steps are carried out in bulk shortly after the harvest and how many are done nearer the consumption time (Bates et al. 2017). In other words, it determines if an intensive labour investment is needed before or after storage. With less labour available to complete the large amount of work at harvest time, fewer processing steps can be done before storage.

For the Xinzhai site, the analysis of archaeobotanical remains reveals that none of the crops were fully processed before storage. *S. italica* and *P. miliaceum* were stored as spikelets, *O. sativa* as entire plants and *G. max* was stored before coarse sieving. Compared with storing crops in the form of hulled grains, these partial types of processing at the Xinzhai settlement indicate that there might have been too little labour to carry out more processing steps shortly after harvest, and so more of them were done later, after storage (Fig. 7). For this, we tentatively argue that the farming season could be one of the causes. According to Stevens (2003) and Fuller et al. (2014), the seasonality of farming leads to a corresponding requirement for labour, and its availability at harvest time determines the way in which crops were stored. In China, historical documents record rich information about ancient farming seasons (Table 2; Han 2012; Zhang 2016). Different lunar (Yinli阴历) and lunisolar calendar systems (Nongli农历) and different starting months of the new year (Suishou岁首) of Yin (寅) month and Wu (午) month according to the Zodiac system (Tiangandizhi 天干地支) were used during the Xia (1750–1550 cal BCE) and Shang (1550–1046 cal BCE) periods (Wang 1994; Chang 1998; Han 2012; Zhang 2016). Therefore, for reconstructing the farming season based on ancient documents, we need to match the different calendar systems with the Gregorian one used today. Taking the harvest of *Triticum* as an example, oracle inscriptions and historical literature indicate that newly harvested *Triticum* became available for the inhabitants (*Shimai*食麦) (Wan 1980; Guo 1983; Miu and Miu 2008) and ancestors (*Changmai*尝麦) (Chen 2002; Huang et al. 2007) in May in the Xia calendar, equivalent to January in the Shang calendar and June in the Gregorian calendar (Zhang 2016). After studying all the available historical information, we know that *S. italica* and *P. miliaceum*, *O. sativa* and *G. max* were all native summer-sown summer crops, while *Triticum* was the only autumn-sown winter crop (Table 2).

Based on the sowing and harvesting times of the various crops, autumn, from September to November, was the busiest period for the Xinzhai farmers with the harvest season for summer crops (Table 3). As wheat was sown and harvested at different times compared with summer crops, its growing and harvesting had very little or no labour conflicts with other crops. On the contrary, rather than being an extra burden, wheat growing was probably beneficial as it would have spread the need for labour to

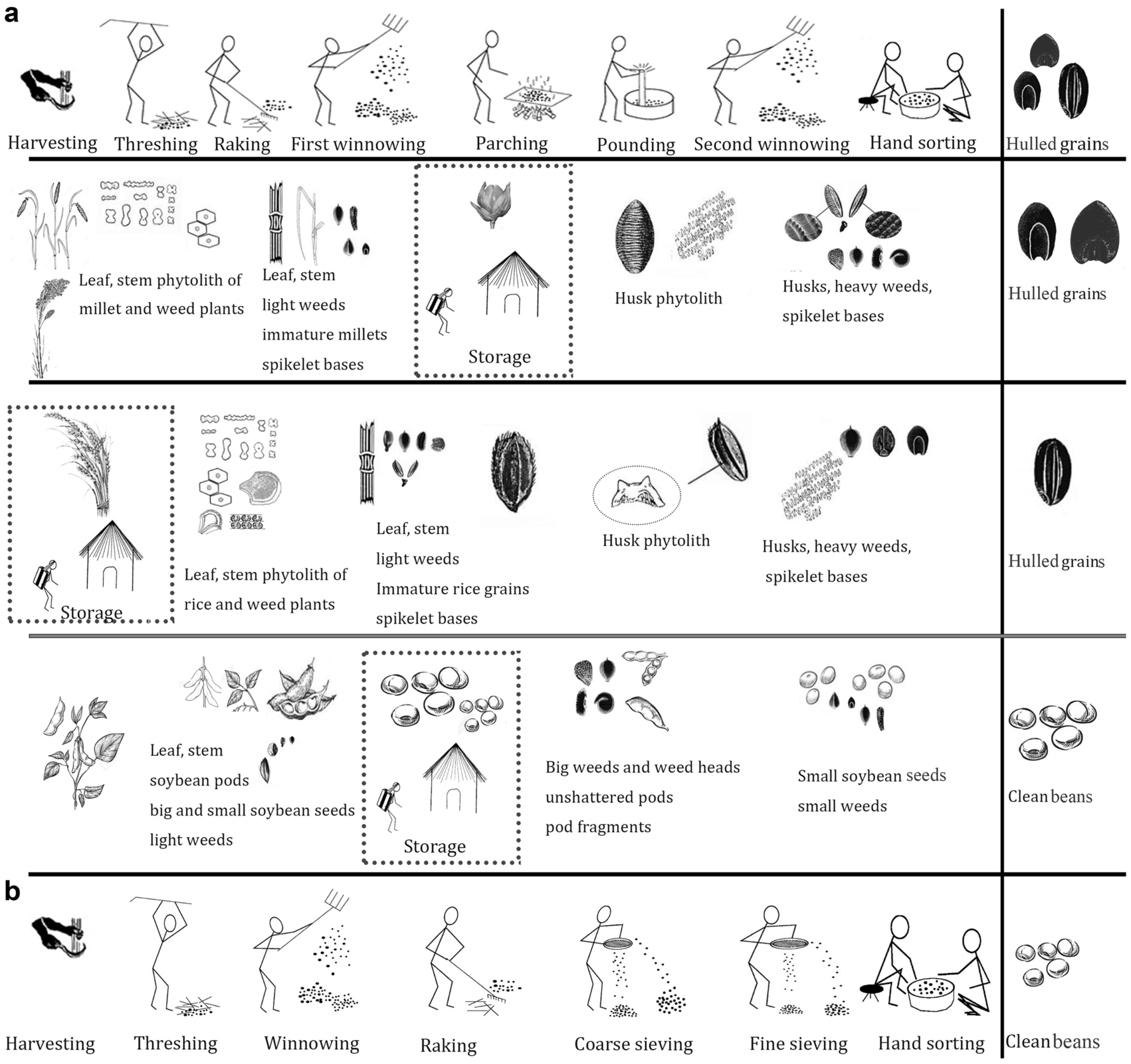

Fig. 7 Different types of storage and requirements for the late stages of processing the main crops at the Xinzhai site; **a** processing stages of the hulled crops, *Setaria italica*, *Panicum miliaceum* and *Oryza sativa*; **b** processing stages of free threshing *Glycine max*; after Hastorf (2016, Fig. 4.3), Harvey and Fuller (2005, Figs. 3, 5)

a previously slack farming time. More importantly, wheat was only a minor component in the Xinzhai farming system. Therefore, the processing of wheat is not further considered here in the discussion of labour distribution. Nevertheless, the relatively concentrated harvest time of summer crops very probably led to a labour shortage for some processing stages before storage. What is also worth considering is the construction or frequent maintenance of public building works such as the rammed earth city walls, the semi-subterranean architecture and also the irrigation system for rice farming, all of which inevitably occupied much labour. Hence, partial crop processing might have been necessary because of a labour shortage at harvest time.

Further light can be shed on the wider social systems of the past by considering crop processing in terms of routine everyday activities as compared with seasonal ones (Fuller et al. 2014). Indeed, one might expect the whole community to have mobilized its labour in cooperation to do seasonal work, as part of its social organization. Archaeobotanical studies from the upper Ying valley (Fuller and Zhang 2007),

Table 2 Sowing and harvesting times of different crops based on historical records, shown as months in modern calendar

Crop	Sowing season	Harvesting season	Historical documents	References
Setaria italica (foxtail millet)	May (Xia calendar); January (Yan calendar)	August and September (Xia calendar); April and May (Yan calendar)	*Oracle inscription* 甲骨文	Guo and Hu (1978–1982)
Panicum miliaceum (common millet)	May (Xia); January, occasionally February (Yan)	August (Xia); April (Yan)	*Xiaxiaozheng* 夏小正; *Shuowenjiezi* 说文解字; *Oracle inscription* 甲骨文	Xia (1981), Duan (1988), Guo and Hu (1978–1982)
Triticum sp. (wheat)	August and September (Xia); April and May (Yan)	May (Xia); January (Yan)	*Xiaxiaozheng* 夏小正; *Fanshengzhishu* 汜胜之书; *Dongluwangshi Nongshu* 东鲁王氏农书; *Liji* 礼记月令; *Guanzi-Qingzhongyi* 管子轻重乙; *Oracle inscription* 甲骨文	Wan (1980), Xia (1981), Miu and Miu (2008), Guo and Hu (1978–1982), Han (2012)
Glycine max (soybean)	June (Xia); February (Yan)	September (Xia); May (Yan)	*Fanshengzhishu* 汜胜之书; *Qiminyaoshu* 齐民要术	Wan (1980), Miu and Miu (2009)
Oryza sativa (rice)	January (Yan)	May (Xia); September or October (Yan)	*Shijing* 诗经豳风七月; *Oracle inscription* 甲骨文	Liu and Li (2011), Guo and Hu (1978–1982)

Table 3 Farming seasons at the Xinzhai site, according to the ancient Xia and Shang calendars and the modern one (S—*Setaria italica,* foxtail millet; P—*Panicum miliaceum*, broomcorn millet; O—*Oryza sativa*, rice; T—*Triticum aestivum*, wheat; G—*Glycine max*, soybean)

Calendar system	Periods	Spring			Summer			Autumn			Winter		
Lunar calendar (*Yinli*)	Xia dynasty	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lunisolar calendar (*Nongli*)	Shang dynasty	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Gregorian calendar (*Gongli*)	Modern	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
Sowing of crops						S,P,O	G		T				
Harvesting of crops						T			P,S	S,O,G	O		

Sushui river (Song 2011; Song et al. 2019) and Baligang sites (Weisskopf et al. 2015) have suggested that during the Yangshao period (5000–2500 cal BCE), crop processing was carried out in bulk on a communal basis, while a change to processing by individual households was noted on many, but not all, sites in the Late Neolithic Longshan culture (2300–1900 cal BCE), and this trend was also observed in the Bronze Age Erlitou-Shang period (1750–1046 cal BCE). These results show that there was variation in social organization in which some settlements kept the communal organization, but others changed to working as small nucleated household units since the Longshan period.

The results of this research into the Xinzhai period by analysing the phytolith datasets from Xinzhai (this research) and Dongzhao (Luo et al. 2018) show remarkable consistency over time with previous studies. According to Zhang et al. (2010b) and Luo et al. (2021), rice grain (DOU-type; 357,953 ± 35,968/g) produces almost the same amount of phytoliths as rice leaves and stems (BUL_FLA_FLA-type; 372,646 ± 249,387/g). In Dongzhao, 170 DOU-type phytoliths and 54 BUL_FLA_FLA-type and SKE_PRA_BIO-type were recorded. Therefore, the morphotype from husks (76%) is dominant in Dongzhao, while in Xinzhai there are more from leaves (61%). Following Fuller and Stevens (2009), we argue that this difference reflects different crop processing methods and also different social organizations at each site. Rice was stored together with its leaves and stems and further processed on an individual basis probably by small households as routine activities in Xinzhai. In contrast to this, at Dongzhao *Oryza* was stored as hulled grains after most of the processing steps had been completed, probably on a communal basis. This conclusion fills the time gap between the Late Neolithic and Early Bronze Age in previous studies. It shows a similar situation to the Longshan period and implies that the differentiation of social organization among settlements might have been continued in the Xinzhai period. This assumption also fits the conclusion from the archaeological settlement pattern analysis, which shows that the social arrangement of the Xinzhai period may have been rather similar to that of the Longshan period (Liu and Chen 2012). Furthermore, a complex and hierarchical society developed together with increasing status and wealth differentials in the Central Plain during the Longshan period (Underhill 1991; Liu 1996, 2005; Liu and Chen 2012). A similar wealth differential can be expected in the Xinzhai period since the agricultural resources were more or less controlled by individual households rather than by the whole communal society, at least at the Xinzhai site. Therefore, the first urban centre that appeared in the subsequent Erlitou period was derived from a complex and hierarchical society, and the development of social complexity in the Central Plain was continuous and without interruption. This kind of gradual social change might be one of the reasons for the outstanding progress of societies in the Central Plain in the early Bronze Age, compared with elsewhere in China.

Conclusions

This research by the analysis of macro-botanical remains and phytoliths from the Xinzhai site, as a pioneer study of its kind, shows the potential of combining two botanical lines of proxy evidence in the study of ancient crop processing methods and also explores the patterns of labour mobilization and social organization in the Xinzhai period for the first time.

The results reveal that the Xinzhai inhabitants harvested rice using sickles or by uprooting it, stored the entire plants and processed the crop in the settlement as daily activities. Millets were harvested by cutting the plants at the base, threshed in open areas and stored as spikelets. The understanding of *G. max* processing is restricted by the absence of processing residues, but as there is a wide range of bean sizes with many small soybeans, they are thought to have been harvested by uprooting the plants or cutting them off near their bases and then stored before coarse sieving. In conclusion, not only hulled crops such as rice and millets, which require a great amount of processing to extract the grains, were stored in a semi-processed form, but also the free threshing soybean. However, in the contemporary Dongzhao site, *Oryza* was stored as unhulled grains which then only needed de-husking before consumption. Therefore, the organization of labour and society varied between settlements in the Xinzhai period. So that less labour was needed during the harvest period but more after storage for the routine daily processing, agricultural activities were mostly done by nucleated household units at Xinzhai. In contrast, large amounts of labour were required for processing crops before storage and so agricultural labour was communally organised at Dongzhao. This kind of diversification in labour and social organizations between different settlements has been observed in sites of the Longshan period, and as indicated by this research, very possibly continued into the subsequent Xinzhai period. The development of social complexity towards urbanization in the Central Plain of China from the Neolithic to the Early Bronze Age has therefore been a continuous process.

Last but not least, to complete the current conclusions, more sampling of archaeobotanical remains from primary deposition contexts is required in the future to get more information on the parts of sites where particular crop processing steps were done and therefore to recover the spatial pattern of processing activities. Likewise, comparative samples from outside the inner city of the Xinzhai site, at least outside the core area of elites, are also needed to distinguish the possible differences in labour distribution between the elite living area and that of ordinary inhabitants, to eliminate potential bias caused by social hierarchies.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00334-021-00851-0.

Acknowledgements The authors want to thank all the 2016 undergraduate students from the Institute of Archaeology at Anhui University for the collection of samples, Weihong Wu, Huadong Zhu (Anhui University), Honghong Wei (Archaeological Institute of Zhengzhou) and Guangxiang Geng (Xinyang Museum) for detailed archaeological information during and after the fieldwork, Wanli Lan and Yaping Li (Henan Institute of Cultural Relics and Archaeology) for laboratory facilities and preliminary laboratory work assistance in China, the Young Academy of the Cluster of Excellence ROOTS (EXC 2150) at Kiel University for facility support of the subsequent laboratory work, Ingo Feeser (Kiel University) for technical support with the phytolith counting program Countpol 3.2, and Marta Dal Corso (Kiel University) for introducing J. An to phytolith identification and interpretation. We also gratefully acknowledge the financial support from the China National Natural Science Foundation (41771230) granted to G. Jin and the China Scholarship Council for doctoral research (Fund No. 201706220058) granted to J. An. Finally, the editors and reviewers are sincerely appreciated for their precious advice and suggestions to improve this manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL.

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