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SHORT COMMUNICATION

Experiments on the effects of charring on *Setaria italica* (foxtail millet)

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Abstract This study aims to better understand taphonomical effects relevant to *Setaria italica* (foxtail millet), particularly the deformation caused by charring in fully-formed grains, and the potential preservation of underdeveloped seeds. Foxtail millet is a staple grain commonly found in Neolithic and later sites across Eurasia after initial domestication in northern China. Precise control of atmospheric conditions enabled determination of ideal parameters for charring without seed destruction. These experiments were able to produce charred seeds that strongly resemble archaeological specimens, making three key findings: (1) lateral expansion found in many ancient foxtail millet seeds indicates that charring occurred with the seeds in the husks. (2) Oxidizing conditions produced far better results in terms of seed preservation and retention of identifiable characteristics. (3) Smaller and less developed or 'filled' seeds survived in the same conditions as larger, plump seeds. These results allow for better interpretation of depositional context of millet seeds, and point to heat treatment during the de-husking process as a common way for seeds to enter the archaeological record.

Keywords *Setaria italica* · Neolithic · Agriculture · Experimental archaeology

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Introduction

Comparison between archaeological seeds and their modern equivalents is essential to archaeobotanical identification, but the effect of taphonomic processes on ancient seeds can be highly variable among different taxa. This study aims to reproduce the distinctly distorted morphologies of archaeological seeds of a single species, *Setaria italica* ssp. *italica* (foxtail millet) (Fig. 1). In so doing, crucial information is discovered regarding ideal conditions for seed preservation during archaeological site formation.

Setaria italica was domesticated, along with *Panicum miliaceum* (broomcorn millet), by nomadic groups in northern China during the early Holocene (Crawford 2009; Lu et al. 2009; Yang et al. 2012). Seeds with a fully domesticated morphology, indicated by an increase in grain size and plumpness, occur by 8,000 cal BP and spread across Eurasia during the Neolithic and later (Hunt et al. 2008; Bettinger et al. 2010; Lightfoot et al. 2013). The archaeological specimens that serve as morphological examples for the experiments in this paper were recovered from seven sites in the Yiluo region of central northern China, ranging in date from the mid-Neolithic Yangshao culture (7,000–5,000 cal BP) to the early state period Erligang culture (3,600–3,300 cal BP) (Liu et al. 2002; Lee and Bestel 2007; Lee et al. 2007; Walsh et al. 2016). Seeds from the site of Huizui, a large settlement with evidence of specialized stone implement production, were sampled from a storage pit feature dating to the Yangshao period. Seeds from the other six sites were sampled from ash pit features recovered during regional surveying. Such ash pits are common in the Yiluo region, and likely represent the deposition of hearth sweepings and other household and economic activities. The dominant taxa in the majority of the Yiluo samples are *Setaria* seeds, and specific morphological

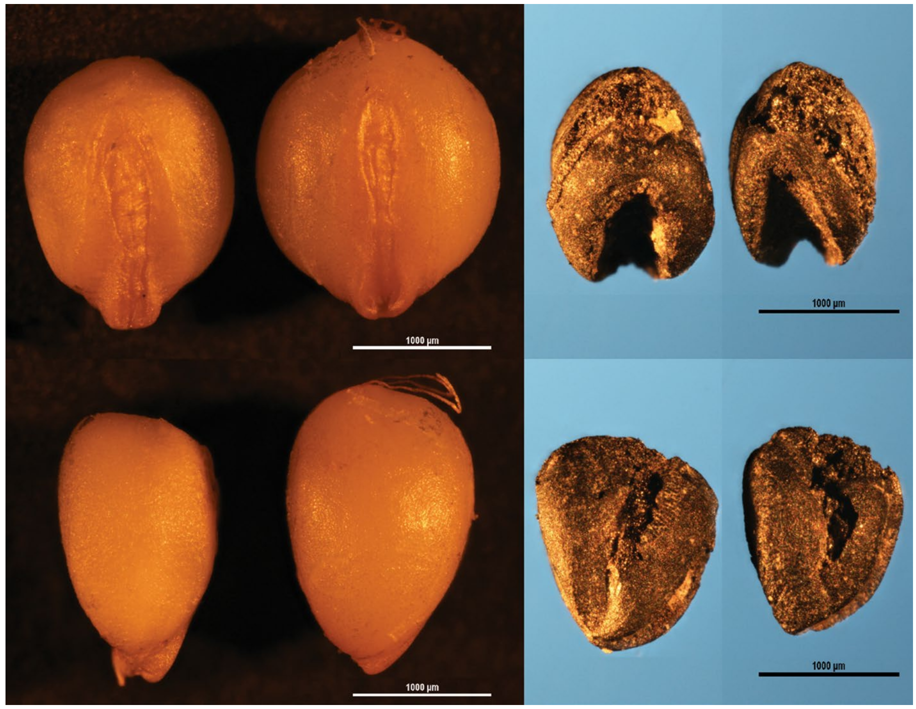


Fig. 1 Ventral (*top*) and lateral (*bottom*) views of modern (*left*) and archaeological (*right*) *Setaria italica* seeds. Expansion in archaeological seeds tends to push the dorsal and ventral faces away from each other, resulting in a puffed-up appearance like popcorn

trends were observed and recorded with detailed measurements (Walsh et al. 2016). Of particular interest here, the characteristic plumpness of modern domesticated millet was exaggerated in much of the archaeological sample by a specific type of seed expansion. The ventral and dorsal faces of the seed are pushed apart toward the distal end, while remaining joined proximally, near the rachis attachment, in an expanded pattern (Fig. 1). This gives the seeds a 'popped' appearance, recognizable as the result of exposure to the heat that charred them, as in popcorn. Archaeological seeds therefore show greater lateral dimensions than modern counterparts, even approaching the thickness of modern seeds that outsize them otherwise (Fig. 2). Similar distortion has been found in foxtail millet from Neolithic contexts in neighbouring Korea (Crawford and Lee 2003; Lee 2011). This complicates direct comparisons between modern and archaeological seed populations, and prompted this study to determine the process by which seeds became expanded in this way.

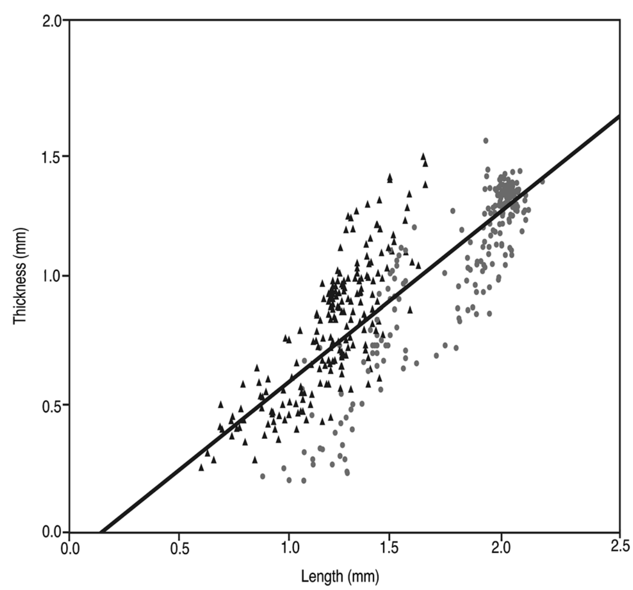


Fig. 2 Scatterplot showing linear fit of modern *S. italica* seeds (*grey circles*, n = 218) and *Setaria* seeds from seven archaeological sites in the Yiluo region, China (*black triangles*, n = 206), expressed in length (full length of seed from proximal to distal end) against thickness (lateral length from the seed's dorsal to ventral faces). Archaeological seeds are consistently shorter in length than modern seeds, but proportionally greater in thickness due to popping effects

Plants can enter the archaeological record in a variety of ways, but carbonization or charring is the most common in East Asia and many other regions (Hillman 1981; Gustafsson 2000; Wright 2003; van der Veen 2007; Gallagher 2014). Carbonization, the physical and chemical process of converting a plant's molecules to carbon, occurs upon exposure to heat, and allows preservation while greatly biasing the archaeobotanical record (Wright 2014). Plants come into contact with heat most commonly as fuel for fire (Hillman 1981), but certain parts of any given plant are more likely than others to survive the process without being reduced to ash (Boardman and Jones 1990). Seeds, as relatively small and dense structures, have a high likelihood of survival, as opposed to chaff, straw, and other parts that might provide information on the human-plant interactions at play in an archaeological site. In addition to fuel, seeds can become charred via accidents in parching, cooking, storage, and cleaning (van der Veen 2007).

As seeds are likely to form the bulk of archaeobotanical remains, stages of plant processing such as harvesting, winnowing, and threshing must generally be understood from seeds, rather than stalks, spikes, leaves, and chaff. Studies on broomcorn and foxtail millets by Motuzaite-Matuzeviciute et al. (2012) and Song et al. (2013) have demonstrated the usefulness of immature seeds in making inferences on crop processing, but these small seeds may survive at different rates during carbonization.

The specifics of carbonization, its morphological effects, and implications for preservation bias have been investigated by researchers working across the globe and with a variety of taxa (Braadbaart 2008; Sievers and Wadley 2008; Antolín and Buxó 2011; Aldeias et al. 2013; Braadbaart et al. 2016). A general trend of this research has been the acceptance that reducing conditions are more favourable to seed preservation (Wright 2003, p 582; Braadbaart 2008, p 155; Sievers and Wadley 2008, p 2912), though few studies have dealt specifically with East Asian millets. One of the few experimental studies to do so found that a reducing atmosphere resulted in the total destruction of *Panicum* seeds, while increasing the chances of survival in other seeds (Märkle and Rösch 2008). Taking a cue from this research, Motuzaite-Matuzeviciute et al. (2012) produced useful results by charring *Panicum* in fully oxidizing conditions. Märkle and Rösch's findings on *Setaria* are somewhat more ambiguous. While reducing conditions expanded the range of temperatures under which *Setaria* seeds were preserved, the authors state that "foxtail seeds have better chances of being preserved at sites where enough oxygen is available during the charring process" (2008, p S259). In charring millets and other crops from Asia in both oxidizing and reducing conditions, both with and without husks, Märkle and Rösch noted the popping phenomenon as being specific to *S. italica*. Their paper, however, does not explain the morphology of the seed expansion, or the particular conditions under which it was most frequent.

Materials and methods

Two main experimental stages were used to find the clearest and most consistent methods for obtaining useful results. These were based on the experiments carried out by the authors cited above, with modifications to suit the available resources and the specific questions being investigated.

Oxidization level

The first priority was to track the precise effects of oxidization on seeds. For this, sealed vacuum tubes of the type used in AMS dating were employed to provide known quantities of oxygen for individual seeds. Each seed was placed in one glass tube with a measured amount of CuO wire and sealed in a vacuum. Ten seeds were sealed in tubes with no wire, representing pure reducing conditions. Ten seeds were given an amount of wire to provide approximately 10% atmospheric oxygen, simulating a midpoint between oxidization and reduction. Ten seeds received enough wire for 20% or more oxygen, fully oxidizing. Seeds were then placed in a cold muffle furnace and heated to a temperature of 250 °C, which was held for one hour. This temperature was chosen due to its success at charring seeds in Märkle and Rösch's (2008) experiments. All seeds in this portion of the experiment had their husks removed before heating.

Muffle furnace

In the second stage of experiments, *S. italica* seeds were heated in open crucibles in a muffle furnace, each crucible containing 30 seeds. Temperatures ranged from 200 to 350 °C at 50° intervals. At each temperature, two groups of seeds were heated with their husks and two without husks. One pair with and without husks was heated for 1 h and the other for 2 h.

Results

In the oxidization experiments, seeds provided with no oxygen were largely destroyed by the charring process, leaving them more or less unidentifiable (Fig. 3). Some seeds at 10% oxygen were preserved, but many, including all the larger seeds, were not. Seeds heated in normal atmospheric conditions, however, retained their shape and did not char as thoroughly. This implies that the presence of oxygen slows the carbonization process in *S. italica*, and is beneficial to the retention of recognizable traits. Based on comparison with archaeological seeds, the seeds charred in the presence of oxygen appeared most like the Yiluo archaeological material.

Using open crucibles in the muffle furnace to provide oxidizing conditions, several temperatures used by Märkle and Rösch were tested using seeds both in husks and with husks removed. Immature seeds were present in all subsamples. In agreement with earlier studies, 200 °C was insufficient to char seeds (Fig. 4). However, my results found that temperatures over 300 °C resulted in destroyed, unidentifiable seeds, often fused into charred masses. 300 °C provided

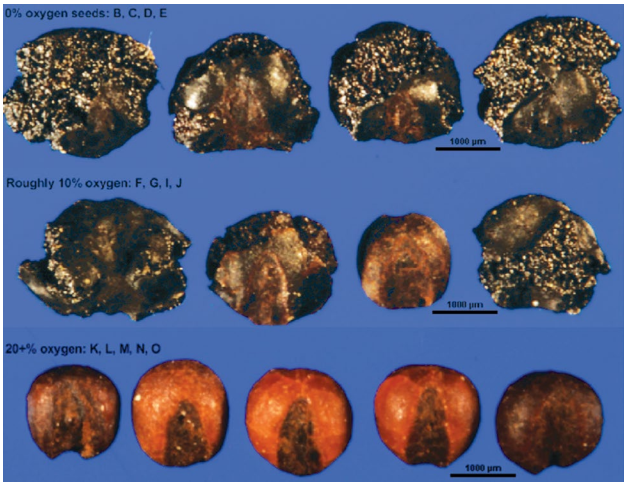


Fig. 3 Modern seeds heated at 250 °C for 1 h with 0% oxygen (*top*), roughly 10% oxygen (*middle*), and more than 20% oxygen (*bottom*). Seeds deprived of oxygen were generally destroyed beyond recognition, while 10% oxygen resulted in some destruction of larger seeds, and seeds heated with atmospheric levels of oxygen remained fully intact

some identifiable seeds, especially smaller seeds, which did not expand explosively like the larger seeds (Fig. 5). Out of all samples, seeds heated at 250 °C returned results most consistent with those seen in the Yiluo samples (Fig. 6).

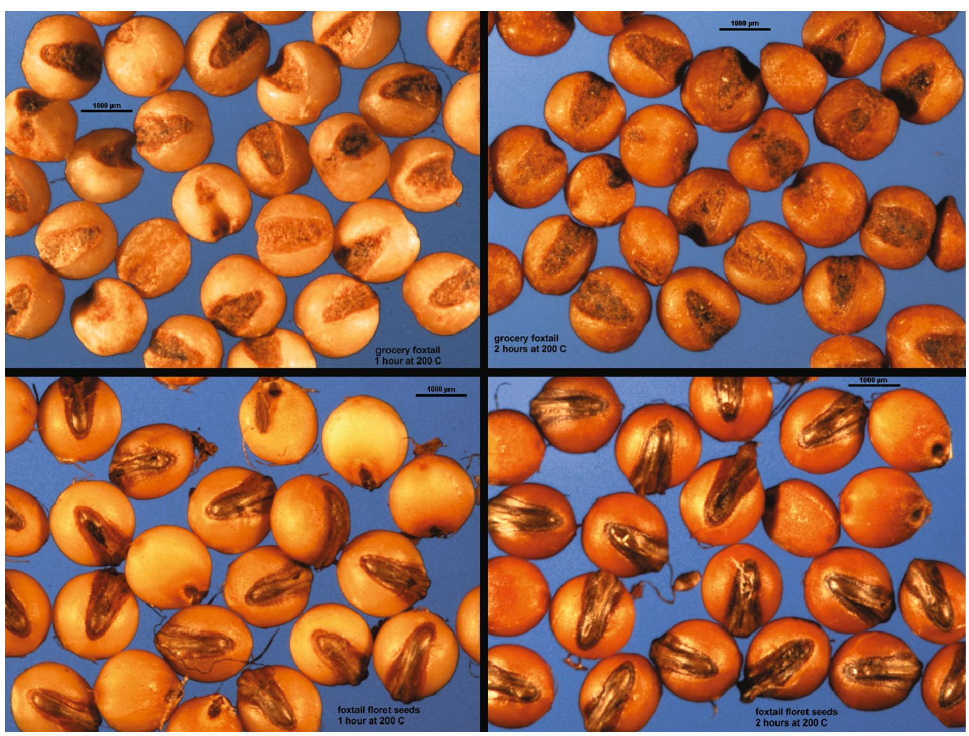
At 250 °C, seeds with their paleas and lemmas intact and of the fully developed, plump type expanded in the distinctive pattern like popcorn. Seeds charred out of their husks expanded randomly at various points on their surface. Smaller seeds either with or without their husks tended not to expand, but were preserved in their normal shape. When present, the paleas and lemmas became friable after charring, and were easily removed with forceps, often breaking apart with the application of slight pressure.

Discussion

These experiments successfully replicated the particular pattern of seed expansion observed in the Yiluo archaeobotanical remains. While initially expected to result from specific temperatures and oxygen levels, it was found that the essential component in producing this morphology is charring seeds with their husks intact. Other factors were not irrelevant, however, and the best results for charring seeds were consistently obtained at 250 °C with full oxidization.

These experiments suggest that small, underdeveloped seeds preserve equally as well as their developed counterparts, at least in the initial charring process. In fact, especially plump seeds appear to be the most vulnerable at higher temperatures, often burning beyond recognition. This would suggest a preservation bias toward small seeds, though it would still be possible for these small seeds to disappear from the record if they were less resilient to other site formation processes, or proved more fragile overall.

Fig. 4 Seeds heated at 200 °C for 1 h (*top*) and 2 h (*bottom*) with husks removed (*left*) and husks intact (*right*). This temperature was insufficient to char seeds



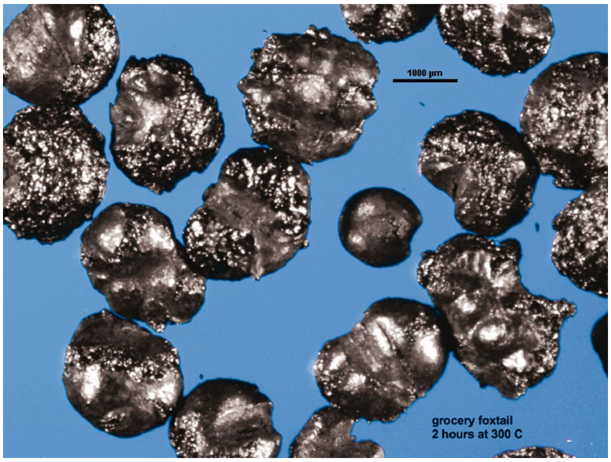


Fig. 5 Seeds heated at 300 °C for 2 h with husks removed. Most seeds were destroyed but one smaller seed was well preserved

Implications for archaeological interpretation

These results allow archaeologists to infer the processing stage of an assemblage of millet based on seed appearance, even in the absence of husks and rachises. As stated above, one sub-sample of the archaeological seeds in this study was recovered from a large storage pit of charred *Setaria* and *Panicum* seeds at the site of Huizui, a settlement where stone implements were made from the mid-Neolithic into the state period (Lee and Bestel 2007). These seeds exhibit the distinctive popping pattern indicating charring with intact husks, demonstrating that the husks were not removed before the storage of seeds in this granary. Whatever their involvement in the farming, harvesting, and threshing of these crops, the inhabitants were apparently responsible for at least this final hulling. *Setaria* seeds showing the distinct expanded distortion like popcorn are also frequent in middens recovered from smaller villages (Walsh et al. 2016), raising questions about the behaviours that led to these seeds entering the archaeological record.

The ethnographic literature on millet cultivation and its processing describes specific stages when seeds come into contact with heat around the time when their husks are removed. Reddy (1997) investigated the practices of South Asian millet producers, noting that seeds were removed from their husks only as the step immediately before grinding them into flour. The removal of husks was often accomplished by pounding, but particularly ripe seeds were roasted before pounding. This strategy takes advantage of the friability of husks once exposed to heat. The use of an open flame at this stage provides an excellent opportunity for archaeological preservation, as seeds that fall from the roasting pot or pan are likely to fall into the hot ash surrounding the fire, rather than into the fire itself.

Heat treatment of seeds in their husks is frequently observed in ethnographic accounts of millet processing. In a study on modern *Eleusine coracana* (finger millet) processing in East Africa, Young (1999) found that husks were removed from seeds first by grinding and winnowing, with the seeds then roasted to remove the last pieces of chaff.

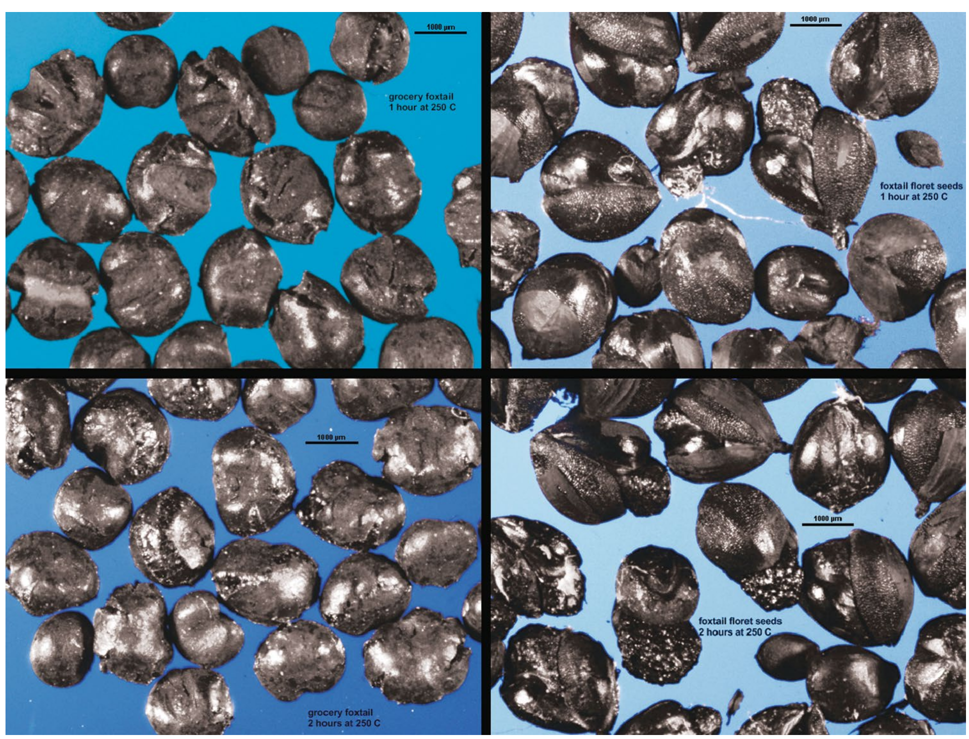


Fig. 6 Seeds heated at 250 °C for 1 h (*top*) and 2 h (*bottom*) with husks removed (*left*) and husks intact (*right*). The seeds were charred but most remained recognizable, with seeds in their husks puffed up like popcorn

Moreno-Larrazabal et al. (2015) note that in the Iberian Peninsula, *P. miliaceum* is heated gently to help remove husks, either by exposure to sunlight or baking in an oven at 40–50 °C. Similar observations could not be made on *S. italica*, as in this region *Setaria* is harvested while immature and used as fodder.

Scholars have often discussed the usefulness of small seeds, chaff, and other crop remains to distinguish threshing and winnowing processes in the archaeological record (Shahack-Gross et al. 2009; Motuzaite-Matuzeviciute et al. 2012; Song et al. 2013). This curiosity has rarely been extended to later stages of crop processing, though ethnographic observation identifies husk removal as perhaps the likeliest stage at which seeds enter the archaeological record (Reddy 1997). For *S. italica* and other crops that behave in similar ways when exposed to heat, this study finds that seed expansion is a simple and reliable way to detect the stage of processing. *Setaria* seeds expanded like popcorn demonstrate that they were charred with their husks intact, even in the absence of husks from the archaeological material, providing valuable information towards interpreting depositional context.

Conclusions

Several key insights were gained through these experiments in archaeobotanical taphonomy. First, and perhaps most surprisingly, higher oxygen levels proved beneficial to the retention of identifiable seed features, while vacuum and low oxygen conditions were far likelier to result in the destruction of seeds. Second, the full range of modern *Setaria* seed sizes survived intact in ideal conditions, with oxidization, indicating that immature and intermediate seeds should enter the archaeological record with the same or even better rate of success as their fully developed counterparts. Third, the lateral expansion of many archaeological seeds is demonstrated to result from seeds that were charred with their husks (paleas and lemmas) intact. This pattern results from the firm hold of the palea and lemma at the proximal end of a seed, causing steam to escape from the distal end, splitting the ventral and dorsal faces of the seed from each other. These data combined with ethnographic information on millet processing in various regions of the Old World lead to the conclusion that dehusking foxtail, and potentially other species of millet, is a primary mechanism for seeds to enter the archaeological record. Removal of millet husks frequently involves heat treatment to roast grains and/or weaken the paleas and lemmas, which can then be removed by pounding or grinding. The results of these experiments therefore allow for more detailed interpretation of the social behaviours surrounding plant use in Neolithic China and beyond.

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