Evidence for the early beginning (c. 9000 cal. BP) of rice domestication in China: a response

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Received 12 June 2007; revised manuscript accepted 29 August 2007

Abstract: This paper is a response, both to Fuller et al.’s recent criticism of Chinese research on rice domestication, as lacking evidence, and to their argument for the beginning of rice domestication around 4000 BC in the lower Yangzi River. We first survey previous publications that discuss the process from wild rice collection to rice domestication in China, and then examine early rice remains from the perspectives of rice morphology and archaeological context. We focus on three aspects: the timing of the initial rice domestication in the Yangzi River region; the earliest presence of domesticated rice in the Lower Yangzi and Huai River regions; and the implications of changes in rice grain sizes in archaeological assemblages. We also discuss problems relating to the presence of immature rice remains in the archaeological record, grain size increase and overall grain shape, which are three of the criteria used by Fuller et al. for distinguishing domesticated from wild rice. Based on published data and our research on rice, we demonstrate that by the early Holocene (9000 cal. BP), Neolithic people in both north and south China may have been harvesting wild rice and initiating rice cultivation that eventually led to domestication.

Key words: Wild rice harvesting, rice domestication, rice morphology, Neolithic, early agriculture, Shangshan, Jiahu, China, Holocene.

Introduction

Recent discoveries of early rice remains in China have stimulated debate on the origins of domesticated rice (Oryza sativa) in East Asia. Discussions about when, where and how rice domestication was initiated have contributed to the understanding of this important episode of human history. Recently Fuller and his colleagues (Qin et al., 2006; Fuller, 2007; Fuller et al., 2007) cast doubt on the preceding identification of domesticated and wild rice in a series of early sites along the Yangzi and Huai Rivers, hoping to construct new ideas regarding the use of wild rice and the timing of rice domestication. Their main arguments can be summarized as follows. (1) In the archaeological study of agricultural origins in East Asia, ‘rice domestication was taken for granted, unproven, and unquestioned’, while wild food foraging was ignored. (2) In the Lower Yangzi River environs, rice remains from the Shangshan and Kuahuqiao sites were a wild species, and the presence of abundant immature rice grains at the Kuahuqiao and Hemudu sites constitutes evidence of wild plant food production. (3) Small grains of rice recovered from the Jiahu site in the Upper Huai River region belonged to a wild species, which made no contribution to later domesticated rice. (4) Fully domesticated rice evolved around 4000 BC, as seen in changes of rice grain sizes at the Longqiuzhuang site in the Lower Huai River area.

This paper surveys these issues concerning rice domestication in China. Particularly, we focus on three aspects: the timing of the initial rice domestication in the middle/lower Yangzi River region; the possibility of the presence of early domesticated rice in Shangshan, Kuahuqiao, Hemudu and Jiahu; and the implications of changes in rice grain sizes at Longqiuzhuang. We will also discuss problems relating to grain size increase and overall grain shape (length-to-width ratios), which are two of the criteria used by Fuller et al. (2007) for determining domesticated and wild rice.

Uneven quality of data can introduce inconsistencies when comparisons are made. Most publications give only averages and
### Table 1  Sizes of rice grains from China and Korea

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- **Note:**
  - 'G' and 'S' indicate grain and spikelet.
  - Grains from Phase I at Jiahu came from T43H483, T10AH466 and T115AH478; Phase II, T40F51, T41H472, T104H229 and T113H112; and Phase III, T106H458.
ranges of grain size, whereas our own data provide measurements of individual grains. So we used two different methods to illustrate the ranges of size and shape. That is, to calculate total grain size, we merely multiplied the length by the width of individual grains from our own samples, and did not use published range values. But for grain shape, represented by varying ratios of length-divided-by-width, we used both our own individual measurements and also the ranges of published values. Table 1 provides measurements and sample sizes of rice remains discussed in the text, and Figure 1 shows the locations of the major sites.

**Research on wild rice use in the Yangzi basin in the early-middle Holocene**

Since the early 1980s, a substantial volume of publications already emphasized the importance of wild rice and other plants in the Yangzi basin (eg, Crawford, 1992, 2006; Wang and Sun, 1996; Zhao, 1998; Crawford and Shen, 1998; Lu, 1999, 2006; Yu and Xu, 2000; Yasuda, 2002; Tang et al., 2003a). Chang (1981) particularly argued that people of the Hemudu and Majiabang cultures were affluent foragers who explored the abundant wild faunal and floral resources as well as cultivated rice. Most of all, the excavation reports of Hemudu, Kuahuqiao and Bashidang clearly noted that rich faunal and floral remains from these water-logged sites indicate the importance of hunting and gathering in subsistence (Zhejiang Institute of Archaeology, 2003: 371–75; Zhejiang Institute of Archaeology and Xiaoshan Museum, 2004: 325–26; Hunan Institute of Archaeology, 2006: 512–44).

Studies on wild plants were also conducted on the middle Yangzi basin. For example, Crawford and Shen (1998: 862) suggested a broader development of aquatic plant use at the Bashidang and Hemudu sites, not just rice production. Phytolith research on the Diaotonghuan cave confirmed wild rice collection during the late Pleistocene (12 000/11 000 BP), followed by a mix of wild rice and early domesticated rice harvesting in 10 000–8000 BP, and finally the use of primarily domesticated rice about 7000 BP (Zhao, 1998). Zhang (2002) suggested the existence of an initial phase of rice cultivation in the late Pleistocene/early Holocene, based on micromorphological characteristics of early rice phytoliths.

**Were Shangshan, Kuahuqiao and Hemudu rice wild or domesticated?**

It is an overstatement to say that all rice finds in previous studies were presumed to be domesticated and equivalent to agriculture, as Fuller et al. (2007) argued. Zhang et al. (1996) emphasized that rice domestication underwent a long process from intensive collection, human selection of certain varieties, to full domestication, and this process may have been repeated many times in history. Crawford and Shen (1998: 864–65) also made a cautionary remark on the inconclusive nature of identifying rice either to wild or domesticated, without knowing the presence/absence of a brittle rachis, as shown by the example of Bashidang rice.

We need to emphasize that the process of rice domestication was apparently a continuum. Therefore the early cultivated rice may appear to be neither completely wild nor fully domesticated in morphology, and the level of domestication should be assessed by the degree of human involvement in the rice’s life cycle. Instead of only asking the question ‘were rice remains dating earlier than 4000 BCE all wild?’, we also examine how much human intervention may have been associated with Shangshan, Kuahuqiao and Hemudu rice, as reflected in the archaeological record.

**Shangshan (c. 11 000–9000 cal. BP)**

At the Shangshan site in Zhejiang charred rice husks and leaves have been found in the fibre-tempered pottery sherds and burnt clays, recorded as the earliest rice remains in the Lower Yangzi River valley (Jiang and Liu, 2006). Based on their examination of the size and morphology of spikelets and the characteristics of phytoliths of Shangshan rice remains, Zheng and Jiang pointed out that most plant matters embedded in pottery are fragmentary rice chaffs left after hulling, but some are from rice stalks (Zheng and Jiang, 2007). The presence of both husks and leaves suggest that rice was likely collected by cutting the stalks with knives, rather than beating the seeds into a boat as recorded in some ethnographic accounts, and some knife- and sickle-shaped stone implements unearthed from Shangshan may have been used as harvesting tools (Figure 2A), although use-wear analysis is still to be conducted. The harvesting method of either by uprooting or by cutting stalks with hand-held sickles could encourage selection of mature spikelets with tough rachis, while reducing the chances of slow-ripening spikelets to mature, and of spikelets with a brittle rachis to be selected. This type of harvest may have led to successful cereal domestication (Smith, 1998: 73), including rice (Higham, 1995). In an experiment of planning and harvesting wild rice, Oka and Morishima (1971) demonstrated that by employing knives in harvesting, after only five generations, the rice sample showed an increase in weight and spikelet number and a reduction in the rate of seed shedding, as a result of selection for non-shedding genes. This experiment seems to suggest that rice’s morphological change could have occurred fairly rapidly under the ‘cultivation pressure’.

A single measurable charred spikelet provided the size and shape of Shangshan rice, which is relatively large compared with remains from the later assemblages in the region, and the L/W ratio is lower than common wild rice (Figure 3, Table 1). Since rice remains are very fragmentary, only a few are preserved sufficiently for examining the patterns of rachis, to identify domesticated and wild rice. Domesticated rice spikelets shattered by humans frequently retain a fragment of panicle rachis at the bottom, which is...
Figure 2  (A) Knife- and sickle-shaped implements from Shangshan. (B) Charred rice spikelets from Shangshan pottery: 1–2, wild type rachis, arrow pointing to the smooth scar; 3–4, cultigen type rachis, arrow pointing to the rough scar
particularly evident in *japonica*, while shattered wild rice spikelets naturally show a round and smooth scar at the rachis. Microscopic observations show that the characteristics of both wild and domesticated are present (Figure 2B), and the latter appear to resemble *japonica* more than *indica*. Study of phytoliths from motor cells indicates that phytolith morphology of Shangshan rice is similar to that of tropical *japonica* (Zheng and Jiang, 2007; Zheng et al., 2007). All these lines of evidence seem to suggest that the Shangshan rice assemblage is more complex than a collection of wild rice. However, the nature of the Shangshan rice remains as found in pottery temper does not allow further quantitative analysis, so it is difficult to determine whether this assemblage represents a wild population with a very small proportion of cultigen type rachis (ie, non-brittle) that existed naturally, as the situation in wheat and barley, or it consisted of a cultivated wild-type population in which the first mutant phenotypes had appeared (cf. Hillman and Davies, 1999). In any event, the Shangshan rice provided the basis upon which people could have selected for those cultigen types and shifted the balance of the rice population.

**Kuahuqiao (c. 8200–7200 cal. BP)**

Fuller et al. (2007) used the high ratio of empty spikelets in the rice assemblage as evidence of wild rice harvesting at Kuahuqiao. In our view, this cannot be sufficient evidence for wild rice collection, with the absence of explicit proof of alternative possibilities. That is, immature grains, probably left at the site after mature grains were threshed, could have resulted from a poor year for rice growth, or represented the primitive phase of rice domestication when maturity rates were not synchronous and thus yields were low. Gene exchange between wild forms and cultivated forms grown in early rice fields could have resulted in the intermediate characteristics observed on archaeological specimens (Yen, 1982: 63).

A microscopic examination of 120 spikelets from Kuahuqiao indicates that 42% of samples show fragments of panicle rachis resembling domesticated *japonica*, while 58% of samples show a smooth scar on rachis, a characteristic of wild rice (Zheng et al., 2007). Such a high proportion of cultigen-type rachises could not represent wild rice populations as simply from immature wild spikelets, as argued by Fuller et al. (Qin et al., 2006; Fuller et al., 2007). This is because, as Willcox’s (1999) experimental study shows, green-harvested wild cereals would have disarticulated spontaneously when allowed to dry out, leaving normal wild-type scars on rachises. Therefore it is unlikely that the remains of a green harvest of a wild cereal would be confused with those of a population with non-brittle rachis under the conditions of carbonization in the archaeological record (Willcox, 1999: 109; see also Hillman and Davies, 1999: 102). The mixed wild- and domestic-types in the Kuahuqiao rice are likely to have been a result of human intervention. In addition, the middle stratum at Kuahuqiao (c. 7700–7300 cal. BP) revealed a dozen rice stalks with spikelets still attached, being empty and possibly representing immature grains (Zhejiang Institute of Archaeology and Xiaoshan Museum, 2004: 325). Absence of roots suggests that rice was collected by cutting the stalks, a harvesting method that could lead to domestication.
In view of these observations, a certain proportion of Kuahuqiao rice was probably on track toward domestication, if not having reached full domestication, during the middle phase of the site occupation, at latest.

**Hemudu (c. 7000–6500 cal. BP)**

According to Harris’ (1989) definition, ‘wild plant food production’ has a series of traits including management of plants in the wild, dispersal of propagules to new habitats and soil modification (tillage). Although Harris did not spell it out, the term seems to connote management of phytopytically wild plants that were about to undergo evolutionary processes toward domestication. Fuller et al. used two assumptions for their argument that Hemudu represents the ‘beginning of the wild plant food production’, and that Hemudu wild rice evolved to non-shattering rice for the next 1000–1500 years. These claims are problematic.

Scanning electron microscopy (SEM) examination on spikelet surfaces can distinguish domestic rice to some degree (Ahn, 1993). Among 25 spikelets from Hemudu that were examined under SEM by Sato et al. (1991), half are awnless, one of the features of domesticated rice, and half have awn traces, suggesting probable classification as wild. Among the awned spikelets, four had long dense bristles like common wild rice. Some of the 25 spikelets had a basal panicle rachis fragment, suggesting that they were removed from panicles at harvest, while three awned ones showed traces of natural shedding at maturity. Further research on 81 spikelets by Tang et al. (2003a) revealed that only four were singled out as wild, based on characteristics such as their long and thin shapes, brittle rachis and well-developed long and dense bristles on the awn surface. Based on these observations, Tang et al. (2003a) concluded that broad spectrum subsistence at Hemudu included both collecting wild rice and farming domesticated rice.

Zheng et al.’s (2007) recent study of rice remains from two waterlogged sites, Luojiagao (c. 7000 cal. BP) and Tianluoshan (c. 7500–6500 cal. BP) in the Lower Yangzi River region, also produced results consistent with the abovementioned observations on Humudu rice. Among 451 spikelets from Luojiagao and Tianluoshan, 51% show tough rachis of the cultigen type and 49% have brittle rachis like wild rice. When comparing the Kuahuqiao rice with Luojiagao-Tianluoshan assemblages, we see the proportion of cultigen type increasing from 42% to 51%, accounting for a 9% increase in 500 years from 8000 to 7500 cal. BP. If we take this figure as an average domestication rate, the initial domestication would have occurred before 10,000 cal. BP (Zheng et al., 2007). This account also suggests that hypothetically the transition from the beginning of rice cultivation (near 0% cultigen type) to full domestication (near 100% cultigen type) would have taken more than 5000 years, which is much longer than Fuller et al.’s prediction (Fuller et al., 2007) (1000–1500 years) based on no quantitative data from rice assemblages. However, Zheng et al.’s argument still needs to be tested with larger sample sizes from more sites in the future.

It is also notable that the Yuchanyan cave, preceding the Hemudu phase by more than 5000 years, yielded rice husks showing characteristics of initial human intervention. Rice husks examined by SEM show no awn on the tip of the lemma, and the length of glume hair is between that of common wild rice and indica (Yuan, 2002). Although the early dates of Yuchanyan rice await confirmation, we cannot rule out the possibility that human interference in the life cycle of wild rice was initiated during the late Pleistocene.

If rice remains from Yuchanyan, Diaotonghuan and Shangshang represent an initial stage of wild rice collection, then rice was in use for over 5000 years before the more intensive use at Hemudu (c. 7000 cal. BP). By 9000 cal. BP, rice was more habitually used in north China as evidenced in Jiahu in the Huai River region. By 8000 cal. BP rice reached north to the Lower Yellow River region, as seen in Yuezhuang in Shandong. Rice dispersed to the middle Yellow River region by 4000–3500 BCE, as exemplified by Nanjiaokou and Huizui in Henan, and then spread further to the upper Yellow River valley by 3500–3000 BCE, as seen at Qingyang in Gansu (Table 1 for measurements and references). Rice paddies and associated irrigation systems have been found at Chengtoushan in the middle Yangzi River region, dating to as early as 6500–6300 cal. BP (Hunan Institute of Archaeology, 1999) (see Figure 1 for site locations).

In summary, the view that wild plant food production began only during the Hemudu phase cannot explain the existing evidence for the dispersal of rice by 9000–8000 cal. BP in north China, and the construction of rice paddies in the middle Yangzi River valley by 6500 cal. BP.

**Abundant empty husks in archaeological deposits**

The presence of abundant empty husks in archaeological contexts can be interpreted in many ways, not necessarily related to wild rice foraging, as we reviewed for the case of immature grains earlier. Archaeological deposits in an early stage of cultivation may consist of a mix of wild, domesticated and intermediate varieties of rice. A large quantity of empty husks may also be the residue thrown away after the mature grains were threshed, or may have resulted from intentional collection of such material for specific purposes.

Hemudu is well known for its thick layers of ‘rice deposits’ at the lowest level (Stratum 4) (Zhejiang Institute of Archaeology, 2003). Rice deposits, 20–50 cm in thickness, occurred on the upper level of Stratum 4, spreading over an area of about 400 m² although not continuously. Rice remains were predominantly empty husks, mixed with stalks, leaves and carbonized grains. The grains are mainly immature ones. Underneath the rice deposits were large quantities of small wood chips. Below this layer were the remains of a timber structure, fragmentary mats made of reed, litches and pottery, suggesting pile-dwellings (Lao, 1995; Zhejiang Institute of Archaeology, 2003). A large part of the rice deposits appears to have been by-products from threshing.

Lao, an excavator of Hemudu, speculated that rice deposits most likely lay just above the dwelling floors, and were household possessions during occupation, rather than indicating garbage dumps beneath the pile-dwellings. Rice by-products may have served special purposes, perhaps used as fuel, pottery tempering and cushion for bedding (Lao, 1995). It is very likely that immature rice grains at Hemudu were stored for particular purposes, and this phenomenon deserves further study in the future.

It is also notable that most rice remains embedded in Shangshang pottery are fragmentary chaffs from hulling, rather than immature grains, as mentioned above. The newly excavated site at Tianluoshan, which was contemporary with and 7 km from Hemudu, has also revealed thick deposits of rice remains, predominantly rice chaffs from hulling (Zheng et al., 2007). These situations seem to contradict the expectation for wild rice harvesting proposed by Fuller et al. (2007). On the other hand, an example similar to the Hemudu rice deposit comes from a site dated to the late prehistoric period in southwestern Korea. The waterlogged Shinchangdong site in Gwangju, from the Late Mumun period (c. 200–100 BCE), yielded a thick layer of rice by-products, including chaffs and empty husks (Lee, 2002). In the 11 m² of excavated area, a layer of rice asssembleys as thick as 150 cm was found, as well as many wooden agricultural tools (Kwangju National Museum, 1997). Shinchingdong represents intensive rice farming long after the initial adoption of rice during the Early Mumun period (c. 1400–800 BCE) at the latest in Southern Korea (Crawford and Lee, 2003). A large quantity of empty husks in archaeological deposits does not necessarily represent either the composition of the original rice assemblages harvested from the field or wild rice foraging. Shinchingdong also produced a substantial amount of acorns.
(Quercus sp.) and other wild plants, indicating that collecting wild plants was still a part of the economy long after intensive rice farming was well established.

Considering all the above, the presence of abundant rice husks is not, in itself, sufficient evidence for wild rice collection only. Hemudu subsistence can be best explained as a mix of wild rice collection and early cultivation of domesticated rice.

Was Jiahu rice a dead-end wild rice?

Fuller et al. (2007) argued that Jiahu rice grains are ‘remarkably small, and more suggestive of a wild rice species, such as Oryza officinalis, which did not contribute to later domesticated populations’. It is inadvisable to identify rice species on the basis of grain sizes alone, despite the fact that an early study has already concluded that Jiahu rice differs morphologically from O. officinalis, based on the observation of husks (Henan Institute of Cultural Relics, 1999: 885).

The Jiahu site yielded the earliest rice in north China, dating to Jiahu Phases I to III (c. 9000–8000 cal. BP). Ten rice spikelets and some lemma fragments were found embedded in burnt clay. SEM observations on the spikelet impressions revealed resemblance to domesticated rice, as they either lack an awn or show no trace of a broken awn (Henan Institute of Cultural Relics, 1999: 883–86).

We have measured 566 complete grains that derived from seven features (pits and house floor), excavated in recent years (University of Science and Technology of China and Henan Institute of Archaeology, 2002). Compared with previously published findings on Jiahu rice (Henan Institute of Cultural Relics, 1999: 887), the new measurements suggest that Jiahu rice grains are not small, but show great variation in size. There is also a general tendency of decreasing size but less diverse in shape over 1000 years from Phase I to Phase III (Table 1, Figure 4). Previous measurements seem to have suffered from small sampling size.

In order to assess whether Jiahu rice was different from later rice in East Asia, we compared it with that recovered from several sites in northern China and Korea, dating to the Neolithic and Bronze Age cultures (6000–1500 BC) (Figure 4, Table 1). Our measurements of Jiahu grains (Figure 4: 2–4) are similar to those from later-period sites in northern China and Korea (Figure 4: 7–13). Averages and ranges of lengths, widths, as well as of L/W and L×W ratios for Jiahu rice all fall within or exceed the ranges of later rice remains. As for the overall grain shapes, represented by the L/W ratios, Jiahu rice is indistinguishable from other rice remains (Figure 4).

It is also notable that Jiahu has revealed 45 polished stone sickles, some with a denticulate cutting edge, which may have been used for harvesting rice (Henan Institute of Cultural Relics, 1999). Although this proposition still needs to be tested by use-wear analysis in the future, the existence of sickles at Jiahu contradicts to Fuller’s (2007: 18) claim that there are no clear archaeological sickles until after 3500 BC in the rice production area.
Longqiuzhuang rice: the importance of archaeological contexts

Longqiuzhuang is located on the floodplain along the lower Huai River (Longqiuzhuang Archaeology Team, 1999). A total of 5038 rice grains was uncovered by flotation from one excavation square, dating to 6600–5500 cal. BP. Rice grains from the lower strata (6 to 8) are consistently small, compared with those from Stratum 4 (Tang, 1999). Based on an increase of grain size here, Fuller et al. (2007) claimed that the process of morphological domestication took place around 4000 BC or later, as demonstrated by the rice grains from Stratum 4.

To understand this change we need to investigate the cultural background of the Longqiuzhuang site. Longqiuzhuang culture, dating between 7000 and 5000 cal. BP, is distributed in the eastern Jiang-Huai region near the coast of the Yellow Sea (Longqiuzhuang Archaeology Team, 1999: 519–20). The material deposits of the site can be divided into three phases. Phase I shows unique cultural characteristics, being different from neighbouring indigenous cultures, but resembling the Jiahu culture in burial customs, tool types and ceramic forms. This resemblance suggests that the two cultures actively interacted (Longqiuzhuang Archaeology Team, 1999: 520–23). The Jiahu culture in the upper Huai River disappeared around 7000 BP from the archaeological record, possibly because of river floods (Henan Institute of Cultural Relics, 1999: 964–65). This event coincided with the appearance of the Longqiuzhuang cultural occupation in the lower Huai River region. Longqiuzhuang culture most likely represents a culture which migrated from the Jiahu region (Longqiuzhuang Archaeology Team, 1999: 520–23). It is possible that rice was brought by migrants from the Jiahu area to their newly occupied homeland.

During the late part of Longqiuzhuang Phase II new cultural elements originating from the Lake Tai area, including tools, jades and pottery, appeared at the site. At this time Lake Tai witnessed a marked social development (Longqiuzhuang Archaeology Team, 1999: 507). The presence of the larger rice variety at Longqiuzhuang may be attributable to new immigrant groups from the Lake Tai area, who brought with them the type of rice traditionally grown in the lower Yangzi River region. Therefore, the seemingly abrupt shift of grain size in the Longqiuzhuang rice assemblage may have resulted from the diffusion of rice from the lower Yangzi area. This proposition, however, needs to be tested when rice measurements from archaeological sites in the Lake Tai region, dating to around 4000 BC, become available.

In addition, all Longqiuzhuang rice grains were uncovered from one excavation square of 16 m² in size, so it is highly questionable whether change in rice size observable from such a limited sampling area represents an evolutionary trend of rice in all China.

Problems with grain size and shape

Enlargement of grains is often used as an indicator of human intervention in plant lifecycles and certain domesticated crops. An increase in grain size is one observable change that often enables us to determine that the species has been domesticated (Smith, 1998: 18). This argument can apply to certain domesticates such as sunflower (Helianthus annuus var. macrocarpa), which are of North American origin (Yarnell, 1993), and possibly to millet, which is of East Asian origin (Crawford, 2006; Lee et al., 2007), but not to every domesticated crop. For example, rye did not change in grain size after domestication (Hillman, 2000: 380). Fuller et al. (2007) regard grain size increase as a major indication for rice domestication as occurring around 4000 BC, and the overall grain shape (L/W ratios) as evidence of immature rice, resulting from wild rice gathering, in Kuahuqiao and Hemudu. These criteria, as demonstrated below, are problematic. When samples with individual measurements (sample numbers 2 to 13 in Figure 4) are tested by the ANOVA, all are statistically different in all measures. The F ratios of length, width, L/W and L × W ratios vary from 19 to 213, which are sufficiently different to reject the null hypothesis. The result again reconfirms the presence of huge variations in grain sizes and shapes across samples that may have been from different populations, including wild, early domesticated and fully domesticated rice over 6000 years. Rice domestication processes represent a continuum with variations rather than a sharp, arbitrary division at some momentary point.

Spikelet size comparison

Previous studies classified spikelets from Hemudu into domesticated and wild rice (Sato, 2002; Zhou, 2003; Tang et al., 2003b). Therefore we pool together the Hemudu measurements from domesticated to show the full range of this rice population. As shown in Figure 3, Hemudu rice (4) has a wide variation in length, width and length-to-width ratio, whereas Kuahuqiao and Luojiajiao show much smaller ranges in the same variables, possibly as a result of their small sample sizes (Table 1). Comparing the length and width, Kuahuqiao (1) and Luojiajiao (2) rice fall into the ranges of Hemudu rice. Comparing the overall sizes (L × W), Kuahuqiao and Luojiajiao populations are smaller than Hemudu wild. Considering the huge variations of lengths and widths of Hemudu rice (Figure 3), it is likely that Kuahuqiao and Luojiajiao rice sizes fall into the range of Hemudu rice.

Through these comparisons, we can say only that earlier rice spikelets from Kuahuqiao, which Fuller et al. considered as wild, fall into the Hemudu size ranges wherein wild and domesticated are mixed together.

Grain size comparisons

In order to understand the change of grain size at Longqiuzhuang, we compared rice measurements from Strata 4 and 6 with those from other sites in northern China and Korea. As shown in Figure 4A, rice grains from Kuahuqiao (2–4) and Kuahuqiao (6), dating much earlier than 4000 BC, heavily overlap in length with the range of Longqiuzhuang Stratum 4. Rice grains from Yuezhuang (5) show a wide overlap with the average values of both strata at Longqiuzhuang. In contrast, rice grains from later sites (8–13) are mostly shorter than those from Longqiuzhuang Stratum 4 (Figure 4A). As for the width, most grains from Longqiuzhuang Stratum 6 fall into the lower half of the range shown by those from Stratum 4, and most rice grains from other sites show a wide distribution across the ranges of both Strata 4 and 6 and beyond (Figure 4B). Within a broad regional context, these comparisons suggest that Fuller et al.’s argument for an abrupt shift in size, as indicative of the evolution from wild to fully domesticated rice, does not seem to hold. The fact is, the greater the number of rice grains measured, the wider is the size range.

To examine overall grain size changes from a temporal perspective, we used ratios of grain lengths multiplied by widths to demonstrate the variability between different rice assemblages (Figure 4C). Most rice grains dating prior to 4000 BC in both north (Jiahu and Yuezhuang) and south China (Kuahuqiao) (2–6) are not necessarily smaller than those from domesticated rice dating later than 4000 BC (7–10) in North China. Given the spatial and temporal distribution of these later sites, the presence of wild rice cannot be a plausible explanation for their small sizes. Small grain sizes can result from environmental reasons, inclusion of immature specimens or a variety of smaller grains. The last scenario is exemplified by the Dazuizi rice population (c. 1300–1100 BC) (Figure 4, number 11) (Zhang, 2000a).
An example from Korea also contradicts Fuller et al.’s claim that small grain size indicates wild rice. Abundant small, immature rice grains occurred in early historical sites in Korea where intensive rice farming was well documented. For example, almost 36 kg of carbonized rice grains were found in a storage pit at Bojeongri in central Korea, dating to the Three Kingdoms period (AD 300–600) (Lee, 2006). Measurements of rice grains from this assemblage show a broad range of sizes (Figure 4, number 13), overlapping with the range shown by small rice grains from the old Jiahu measurements (Figure 4, number 1). No archaeologically recovered wild rice has ever been found in Korea, and intensive rice agriculture was well established prior to the Three Kingdoms period, as seen in both the archaeological and historical records (Ahn, 1996; Lee, 2003). Bojeongri rice is certainly a domesticated variety. This comparison suggests that, even during historical times, farmers still harvested substantial amounts of small rice grains, possibly immature. Thus, grain size, particularly if the sample size is small, is not a reliable identifier by which to distinguish domesticated from wild.

Grain shape comparison
According to Fuller et al. (2007), immature grains will have larger L/W ratios than mature ones, and thus larger L/W ratios can be used to represent immature grains as an indicator of a wild rice assemblage. Based on this premise, they proposed that Kuahuqiao has a large portion of immature grains, resulting from wild rice harvesting.

Based on our data, length-to-width ratios of grains show great variations among sites (Figure 4D). Our measurements of 556 grains from Jiahu indicate that its rice grains fall very well into the L/W ranges of domesticated rice from other sites. Some of the corresponding ratios of rice grains from Kuahuqiao exceed the ranges of other domesticated ones, but so do the ratios for domesticated rice grains from Korean historical sites at Bojeongri (Figure 4D, number 13). If we use Fuller et al.’s L/W ratio model, Jiahu rice would have to be more domesticated than that from Kuahuqiao and early historical sites in Korea. In a word, it cannot be taken for granted that a large L/W ratio represents a wild rice assemblage.

Conclusion
The concept of affluent foragers is not unfamiliar in Chinese archaeology. Substantial volumes of publications in both English and East Asian languages have discussed the significance of broad subsistence selection of wild and domesticated plants, including rice, during the Neolithic period in China. What Fuller et al. claim credit for, in their explanatory framework for the origins of rice agriculture, was in fact already discussed in previous publications.

The above discussion has demonstrated that Fuller et al.’s premise regarding late-onset rice domestication, which is based on tendentiously selective use of information and on problematic methods, does not hold up under careful examination of available data. Several flaws are particularly notable, as follows.

1. Jiahu rice cannot be simply dismissed from the process of domestication in north China, and the Shangshan and Kuahuqiao rice assemblages indeed show characteristics of initial domestication.
2. Whether or not Hemudu rice deposits contain predominantly immature husks should be a matter of investigation, not a fact, and these remains should be viewed as the end of rice processing, rather than as a criterion for determining wild rice cultivation.
3. Using Longqiuquzhuang rice as an evolutionary demarcation for fully domesticated cultigen is questionable without taking consideration of the archaeological context and small sample size. A more rigorous examination of this assemblage should be conducted in the future.
4. Domesticated rice grains from many later sites in China and Korea are as small as those from Longqiuquzhuang Strata 6, which Fuller et al. regard as wild. This situation indicates that grain sizes, particularly those of charred remains, are not a reliable indicator of rice domestication.

We prefer the phrase ‘management of phenotypically wild plants’ (in this case, rice) to the term ‘pre-domestication cultivation’ used by Fuller et al. Management indicates a range of activities from tending, harvesting, tillage and/or sowing for procurement of wild plants. As demonstrated above, this initial phase of using wild rice was already reached during the late Pleistocene/early Holocene in the Yangzi basin.

Rice went through long, non-linear domestication processes. By the early Holocene (9000 cal. BP), people in both north and south China may have been harvesting wild rice and initiating rice cultivation. Without human intervention in its life cycle, rice could not have reached the lower Yellow River region by 8000 cal. BP and the middle Yellow River region by 6000–5500 cal. BP.

There are still many unanswered questions relating to rice domestication. It is important to carefully examine the most available data in order to produce a sound, plausible explanation, as well as to take adequate consideration of methodological limitations before reaching conclusions.

Acknowledgements
We would like to thank Gary Crawford, Zheng Yunfei, Chen Xingcan, Arlene Rosen, Ma Xiaolin, Jiao Tianlong, Lan Wanli, Thomas Bartlett and an anonymous reviewer, who provided data, critical comments and expertise. The research for this project is supported by a Discovery Project Grant from the Australian Research Council (DP500982 for Liu), a research grant from the Chiang Ching-kuo Foundation (for Liu), a grant from National Natural Science Foundation of China (40772105 for Zhang) and a La Trobe University Postdoctoral Fellowship (for Lee).

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