The Probable Critical Role of Early Holocene Monsoon Activity in Siting the Origins of Rice Agriculture in China

John Dodson1,2*, Hsiao-chun Hung3, Chenzi Li1, Jianyong Li4, Fengyan Lu1 and Hong Yan1

1 State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi’an, China, 2 School of Earth, Atmospheric and Life Sciences, University of Wollongong, Wollongong, NSW, Australia, 3 Department of Archaeology and Natural History, Australian National University, Canberra, ACT, Australia, 4 Shaanxi Key Laboratory of Earth Surface and Environmental Carrying Capacity, College of Urban and Environmental Sciences, Northwest University, Xi’an, China

The long process of rice domestication likely started 10,000–8,000 years ago in China, and the pre-existing hunter-gatherer communities gradually adopted more sedentary lifestyles with the dependence of rice agricultural economies. The archeological evidence builds a strong case for the first domestication of rice to *Oryza sativa* centered in the Middle-Lower Yangtze Valley during the early Holocene. The genetic evidence identifies the main ancestor of *O. sativa* was *O. rufipogon*, however, this now occurs naturally south of the Yangtze where its distribution is limited by summer temperatures and mean annual temperature. The mismatch between occurrence of ancestors and presumed sites of early cultivation leads to a number of hypotheses. These include that first domestication actually took place further south, such as in the Pearl River valley but archeological evidence is currently lacking for this. Or domestication took place, when *O. rufipogon* had a more extensive natural range in the past. Early to mid-Holocene palaeoclimate reconstructions show that the East Asian Summer Monsoon was more active in the early Holocene and estimates show that the temperature requirements for *O. rufipogon* were met for a substantial area of northeast China at the time. This would mean that earliest known domestication sites and presumed ancestor distribution coincided for several millennia. Thus early records of rice farming in Henan and Shandong were easily accommodated by early to mid Holocene climates.

Keywords: early rice agriculture, role of Holocene monsoon activity, wild rice climate controls, Yangtze and NE China Holocene climates, role of summer and annual temperatures

INTRODUCTION

Cereal crops became an important part of human activity in the early Holocene, in several places. These were millets and rice in China, and wheat and barley in the Fertile Crescent of western Eurasia. Several hypotheses have been developed around the timing of this, and a common theme that the Holocene was a time of more reliable and stable climate than that of the late Pleistocene and human populations had begun to increase. New methods of providing food were essential...
consider whether the main ancestor of domesticated rice had a archeological record of growing rice in the Neolithic period, and natural range of its supposed ancestors. Here we review the domestication is best documented for the Hemudu cultural sites supplemented with some cropping. The turning point of clear or fish which suggest a hunting and gathering life-style was often the evidence for early pre-domestication cultivation is clear evidence of sedentary societies associated with the tools of cultivation or clear evidence of improved land management and some form of land ownership. People then developed a more sedentary lifestyle, and once food production became more reliable and surpluses were established, settlements, division of labor, time for innovation and cultural differentiation followed.

Rice is one of the world’s most important crops. It is widely believed that rice agriculture first developed in the Middle to Lower Yangtze valley region of China since archaeobotanical data for a wider consideration of areas is scarce. The success of growing rice comes from its high grain yields, in the right environmental setting, and today two or sometimes three crops per year can be grown, and that the grain keeps well in storage. Several species of the rice genus Oryza occur naturally in China. The supposed trajectory of rice agriculture developed from a period where the grains were gathered from wild species, at some point plants were deliberately planted beyond their normal range, which of course worked where conditions were within their ecological tolerance. Then followed a gradual domestication process, which Gross and Zhao (2014) and Stevens and Fuller (2017) postulated took 1–2,000 years or more. Domestication was accompanied by improved tools for cultivation, and resulted in plants which could grow in additional ecological settings, some of which were created by humans. Overall grain productivity was gradually enhanced. In the course of this the domesticated form had become an annual species. The latter trait helped because ripening narrowed the time period required for harvesting the grain, and storage was also convenient. Crop enhancement processes for rice continue to the present day.

The early sites where rice was apparently cultivated seem to be focused on the Middle to Lower Yangtze valley and sites nearby. These include sites in Hunan (e.g., Anping, 1998; Hunan Provincial Institution of Archaeology and Cultural Relics [HPIACR], 2006; Gross and Zhao, 2014; Guo et al., 2014), Zhejiang (e.g., Fuller et al., 2007, 2009, 2011; Zuo et al., 2017; Qiu et al., 2019), southwest Henan (e.g., Zhang and Hung, 2013; Deng et al., 2015), Jiangsu (e.g., Zhang et al., 2014; Qiu et al., 2018), and near the Jiangsu-Shanghai border (Atahan et al., 2008). The problem with interpretation of the early dates is that sites are often not always associated with the tools of cultivation or clear evidence of sedentary societies associated with the crops. Often the evidence for early pre-domestication cultivation is associated with considerable amounts of wild foods and animals or fish which suggest a hunting and gathering life-style was supplemented with some cropping. The turning point of clear domestication is best documented for the Hemudu cultural sites around 4000 BC (Fuller et al., 2009).

The apparent site of origin of rice agriculture is outside the natural range of its supposed ancestors. Here we review the archeological record of growing rice in the Neolithic period, and consider whether the main ancestor of domesticated rice had a wider distribution in the past. For this we estimate the parameters which define the natural occurrence of Oryza rufipogon and consider early Holocene climates of eastern China as a possible reason for a much wider distribution in the past. The latter could account for several other early sites known for rice farming.

THE GENUS ORYZA

Oryza is a genus of about 24 species, with four occurring naturally or naturalized in China. O. latifolia was probably brought to China from Central or South America (Wu et al., 2006). The widely cultivated form is O. sativa, and the subspecies indica and japonica varieties of it; it is an annual aquatic plant. This is the main domesticated species (and subspecies). Oryza glaberrima is the other cultivated species, it is also an annual, it is grown in Hainan and Yunnan, and is much less widely grown than O. sativa. Several species of Oryza occur in Bangladesh, Cambodia, India, Indonesia, Malaysia, Myanmar, New Guinea, Sri Lanka, Philippines, Thailand, Vietnam and northern Australia. According to the Flora of China the three main native species of Oryza are perennials and grow in flooded environments in lowland settings. Many are weeds in cultivated rice fields. The natural occurrence of the native species are generally in Guangdong, Guanxi, Hunan, Jiangxi, Yunnan and the islands of Hainan and Taiwan. O. rufipogon is the most common wild form in China, and intermediates with O. sativa occur. O. meyeriana is regarded as the genetically most primitive form of the genus. O. glaberrima occurs in Hainan and Yunnan. Figure 1 shows the natural distribution of Oryza rufipogon in China and elsewhere.

O. rufipogon is regarded as the immediate ancestor of O. sativa and its most widely spread cultivars (O. sativa var japonica and O. sativa var indica). Huang et al. (2012) analyzed 446 genome sequences of a diverse array of domesticated varieties and O. rufipogon from within a cross-section of its natural range. They concluded that first development of cultivated rice likely occurred in the middle reaches of the Pearl River valley in Guangxi. Wei et al. (2012) also suggested that domestication may have been centered on southern China, perhaps 10,000 years ago, with O. sativa ssp. indica, arising from lower latitude forms, and O. sativa ssp. japonica from higher latitude forms of Oryza rufipogon in line with their different tolerance ranges and attributes. Kovach et al. (2007) and Gross and Zhao (2014) observe there is a case that can be built on genetics for multiple sites and times of domestication. There is currently insufficient archeological evidence to test these hypotheses and consider a southern origin for domestication of rice. Perhaps abundant food resources in southern China made cropping an unnecessary activity in the early Holocene.

Huang and Schaal (2012) used a climate envelope approach to investigate the possible past distribution of O. rufipogon in an attempt to account for the richness of the genetic groups within the species. A predicted Last Glacial Maximum range was raised as a possible explanation for the derivation of the range of traits observed amongst the richness of the present genetic diversity seen for the species. Using the present range of the species they found that annual precipitation, mean temperature of diurnal
FIGURE 1 | Natural distribution of *Oryza rufipogon*. Inset shows full natural distribution. On the mainland the distribution is in Yunnan, Guangxi, Guangdong, Hunan, Jiangxi, and offshore on the islands of Hainan and Taiwan. The natural populations in Jiangxi and Taiwan are extinct due to habitat destruction. Based on Flora of China, *Oryza*, in volume 22, Huang and Schaal (2012) and Zhou et al. (2010).

range in the warmest quarter and minimum temperatures of the coldest months gave the main explanations for the observed modern range. There is no definitive fossil evidence for Last Glacial Maximum range of *O. rufipogon* outside the current known range, but it probably does not preserve well as fossils.

Early domestication beyond the natural limit of *O. rufipogon* has been used to suggest that the native species was possibly transported northward for possible cultivation purposes or that a Holocene climatic optimum may have been essential for the establishment of a more northerly distribution of rice farming, including the Yangtze Valley (Fan et al., 1999; Fuller, 2011). But the latter has not been tested against the tolerance limits of *O. rufipogon*.

Zhou et al. (2013) examined the geographic variation of a number of traits across the climatic range of *O. rufipogon* in China. The traits differed in northern and southern populations. The main climate controls were mean annual temperature, mean temperature of the warmest quarter and mean temperature of the wettest quarter. They also carried out some transplantation experiments in Hubei and Hainan to test the viability of several groups. The northern populations were better able to survive the Winter in Hubei. We examine this in more detail below.

THE ARCHEOLOGICAL RECORD

The number of sites with early rice in the Chinese archeological record is vast. Only a general summary can be presented here. A summary of many of the main arguments are given in Fuller (2011) and Gross and Zhao (2014). The archeological records center mainly on the middle to lower Yangtze River in Zhejiang, Hunan, Jiangsu and southwest Henan, dated to as early as 8700-8000 BP. Most of these are based on distinctive phytoliths (e.g., Wu et al., 2014; Ma et al., 2016; Qiu et al., 2018), individually dated seeds or seeds in a stratigraphic context (e.g., see Deng et al., 2015; Yang et al., 2018), and cereal pollen of presumed rice origin (e.g., Dodson et al., 2006).

Beyond the core areas of the Middle to Lower Yangtze, a similar date (about 8,700–8,300 cal BP) has been reported for a primitive form of rice from Jiahu, located in the east on the Huai River in Henan province, south of Zhengzhou (Zhang and Tang, 1996; Zhang and Wang, 1998; Zhang and Hung, 2013). Crawford et al. (2016) report what is probably domesticated rice from Yuezhuang in Shandong at about 8,000–7,700 cal BP, and d’Alpoim Guedes et al. (2015) regard these as within the tolerance range of *O. sativa*. Rice dated to similar age, ca. 8000 BP, was reported from another site (Xihe) in Shandong, although its identification was uncertain as possible wild, cultivated, or domesticated (Jin et al., 2014). It is unclear how far along the pathway to domestication these samples were. There is evidence that rice was grown in the Guangzhong basin of Shaanxi, on the Loess Plateau, and in Henan in the mid-Holocene (e.g., Li et al., 2009; Rosen et al., 2017). In fact, mid to late Holocene dates are widespread, including from Shandong (Jin et al., 2016) to Hainan provinces (Wu et al., 2016; see below). Zhang and Hung (2010) and Yang et al. (2018) summarized the published evidence and they present a case for routes taking rice agriculture southward from the Yangtze area. This included a route to the southeast through Fujian and to Taiwan, and a route to the southwest that led to Mainland southeast Asia.

The earliest record of rice farming in Guangdong is particularly interesting. As it stands rice was introduced into the Pearl River Delta, Guangdong, around 4,000 BP (Yang et al., 2018) or 4,500–3,700 BP (Xia et al., 2019), and diffused elsewhere from there. Thus, there is no hard evidence to suggest domestication took place there and in any case the dates are
significantly later than the Yangtze records. The early date for domesticated rice in Hainan, 5,600 cal BP (Wu et al., 2016), does not fit with the larger picture. So far the earliest known domesticated rice in coastal southern China is no earlier than 5,000 cal BP. This may need further clarification. Apparently rice agriculture contracted southward after the mid-Holocene Optimum, and retreated from more marginal areas in the north and west. The pathways to Fujian and Guangdong were likely along river valleys and radiocarbon dates based on phytoliths in sediment sequences and archeological sites show an orderly transfer of rice farming to these areas between 5 and 4 kyr BP. Even though rice appears to be present, often the number of recovered grains is small and it can be difficult to prove that rice was actually intensively grown in them as sometimes no accompanying sedentary living sites or agricultural tools are reported in association.

The low numbers of rice grains in the early sites and the note that they are usually accompanied by many wild species of plants and animals, suggests a mix of hunting and gathering was accompanied by some cropping. In other words, there appears to be no hard boundary between hunting and gathering and agriculture.

What is clear from the available records is that the earliest known sites are outside the natural range of native Oryza species.

### CLIMATE CONTROLS ON THE NATURAL DISTRIBUTION OF ORYZA RUFIPOGON

Zhou et al. (2013) found that mean annual temperature and mean temperature of the warmest quarter were important controls on the natural distribution of O. rufoipogon, and that more northerly natural populations were able to better withstand winters, for example, when transplanted to Hubei. To examine this in more detail we collected the mean monthly temperature data for 20 sites across Guangxi, Jiangxi, Hunan and Fujian where O. rufoipogon occurs. These were averages across a 30 years period from 1981 to 2010 (China Meteorological Data Service Centre [CMDSC], 2020), which is presumed to be a fitting period for a perennial species. We selected sites around 100 m asl as modern distributions are rarely much below this. The data for the sites is shown in Table 1.

In general, a comparison of the means from the climate data across the 20 sites show that monthly temperatures are in decline after summer and by September at all stations, and while mean temperatures for the warmest quarter are generally around 26–27°C the mean annual temperatures show differences between provinces, with Guangxi (the most southerly and warmest) to more inland provinces (Hunan, the coolest). But none of the differences appear to be pronounced. Mean annual temperatures around 17–21°C predominate, with the lower values due to lower temperatures in winter months, which are likely important for a perennial species. To examine the likelihood of expanded O. rufoipogon distribution further north than today would require mean summer temperatures above about 26°C and mean annual temperatures above 17°C. The modern climate of Changsha (Hunan), Zhengzhou (Henan) and Shanghai shows they have mean summer temperatures of 29, 27, and 27°C, respectively, and they all have mean annual temperatures well below 17°C. While favorable specialized niches for O. rufoipogon may exist around the Yangtze and beyond, generally speaking, the modern distribution as published in the Flora of China does not identify these.

The early to mid Holocene climates of northeastern China.

A case for a more northerly distribution of O. rufoipogon, and overlapping early rice farming sites would require a warmer and possibly wetter climate north of the Yangtze compared to today. This would imply a more active East Asian Summer Monsoon.

There are now many data sets that have been used to reconstruct early to mid-Holocene temperatures in northern China. Zhou et al. (2010) and Li et al. (2011) examined lipids in peat in Jilin and pollen from Jingbo lake in Heilongjiang and identified warmer climates than today from about 10.5 kyr to about 6 kyr BP. They invoked a stronger East Asian Summer Monsoon to account for this. The Shihailingwan Maar in NE China (Jilin) has annually laminated sediments and high-resolution pollen analysis has been used to reconstruct temperatures for the past 15,000 years (Steibich et al., 2015), Zheng et al. (2018) measured organic compounds in peats from northeast China and estimated that temperatures were ~5–7°C warmer than today, and that soil moisture increased from the early to late Holocene. Zhang et al. (2018) used two stalagmite records to infer that monsoon intensity was greater in the early

| Site       | Elevation (m asl) | June       | July       | August      | September   | Mean for warmest quarter | Mean annual |
|------------|------------------|------------|------------|-------------|-------------|--------------------------|-------------|
| Guangxi    |                  |            |            |             |             |                          |             |
| Liucheng   | 108              | 27.1       | 28.4       | 28.5        | 26.4        | 27.6                     | 20.3        |
| Pingxi     | 106              | 27.2       | 28.8       | 28.6        | 26.4        | 27.8                     | 20.3        |
| Tiandong   | 111              | 27.8       | 28.4       | 28.3        | 26.4        | 27.7                     | 22.2        |
| Shanglin   | 115              | 27.1       | 27.9       | 28          | 26.2        | 27.3                     | 21          |
| Zhangzhou  | 91               | 27.4       | 28.7       | 28.4        | 26.5        | 27.8                     | 20.8        |
| Jiangxi    |                  |            |            |             |             |                          |             |
| Xushui     | 147              | 24.9       | 28.1       | 27.3        | 23.6        | 26                       | 16.8        |
| Yingli     | 92               | 25.6       | 28.5       | 27.9        | 24.3        | 26.6                     | 17.4        |
| Fenli      | 94               | 25.9       | 29.1       | 28.2        | 24.6        | 27                       | 17.9        |
| Wanan      | 102              | 28.5       | 29.3       | 28.4        | 24.8        | 27.3                     | 18.5        |
| Nankiang   | 127              | 26.8       | 29.2       | 28.5        | 25.4        | 27.5                     | 19.3        |
| Hunan      |                  |            |            |             |             |                          |             |
| Ningxiang  | 75               | 25.5       | 28.9       | 28          | 23.5        | 26.5                     | 17.1        |
| Pingjiang  | 106              | 25.2       | 28.4       | 27.6        | 23.6        | 26.2                     | 17          |
| Anren      | 102              | 26.4       | 29.6       | 28.4        | 24.5        | 27.2                     | 18          |
| Yongxing   | 124              | 26.2       | 28.9       | 27.8        | 24.2        | 26.8                     | 17.9        |
| Shuangfeng | 100              | 25.6       | 28.9       | 28          | 23.8        | 26.6                     | 17.2        |
| Fujian     |                  |            |            |             |             |                          |             |
| Shaxian    | 121              | 26.1       | 28.6       | 28.1        | 25.6        | 27.1                     | 19.6        |
| Youxi      | 137              | 25.7       | 28         | 27.4        | 24.9        | 26.5                     | 19.2        |
| Fuzhou     | 84               | 26.1       | 29.2       | 28.8        | 26.1        | 27.6                     | 20.1        |
| Anxi       | 88               | 26.7       | 28.9       | 28.5        | 26.6        | 27.6                     | 21.2        |
| Yongtai    | 88               | 26.1       | 28.7       | 28          | 25.5        | 27.1                     | 19.9        |
Holocene in north China. The current mean July temperatures are about 20–21°C, however, these are estimated to be above 26°C between 8,500 and 4,200 cal yr BP. Branched membrane lipids from soil bacteria in the Mangshan loess, near Zhengzhou in central China, have been used to model July temperatures. These were, with tolerable errors, over 26°C between 8,700 and 4,200 cal yr BP (Peterse et al., 2011). Zhang Z.Q. et al. (2020) argued that an expansion of trees in Heilongjiang suggested it was warmer there from about 8–4.6 kyr BP. Overall, the start and end dates of the warmest and wettest periods do not match precisely, but it is clear that the early to mid-Holocene of northeastern China was warmer than today, while the various records show some disagreement about whether the climate was necessarily wetter than today. Moisture definitely increased in the later Holocene but this may have been due to reduced evapotranspiration when temperatures were lower. Goldsmith et al. (2017), Zhang Z.Q. et al. (2020), and Zhang R. et al. (2020), suggest that a stronger East Asian Summer Monsoon in northeast China was due to orbital configurations and a reduction in northern ice sheet cover.

The climate around the earliest archeological sites in the Yangtze valley during the Holocene may have been critical for the domestication of rice. Yi et al. (2003a,b) found that there was a wet and warm climate in the Lower Yangtze Valley from about 10,300–9,000 cal yr BP, it cooled a little after that until about 7,600 cal yr BP then warmed again. Li et al. (2018) estimated that climates were warmer and wetter between 10,000 and 7,000 cal yr BP also in the lower Yangtze region, and there were strong oscillations after 7,000 cal yr BP. Fu et al. (2018) also found that summer rainfall was about 30% higher than modern between about 10,000 and 6,000 cal yr BP. While the modeled temperature estimates are for July, the warmest month, they can probably be extrapolated across summers. Reconstructions for the Lower Yangtze also easily exceed the requirements based on modern day O. rufipogon distribution (Li et al., 2018), and indeed precipitation was perhaps 30% higher than present.

In summary, early Holocene climates show warmer and wetter conditions compared to today, and these brought a much wider area within the tolerance limits and therefore distribution of O. rufipogon. The driving force behind this was a more active East Asian Summer Monsoon, which was controlled by orbital forcing and a reducing northern ice sheet.

**DISCUSSION**

The importance of rice as a crop is widely recognized due to its characteristics, productivity and storage capabilities. Once domestication was well-advanced it was spread widely in China and elsewhere.

As the record stands the most compelling evidence that agricultural systems with rice as their center were first established in the Middle to Lower Yangtze valley region (Figure 2). The main domesticated form of rice in China is Oryza sativa, an annual, and its subspecies. It is well-established that the key ancestor was O. rufipogon, a perennial species.

The path to domestication probably took place over many centuries. The genetic diversity of native species of Oryza is probably centered on the Pearl River Valley in southern China, and the modern natural occurrence of native species is south of the sites where early cultivated rice appears in archeological records.

The mismatch in distribution of O. sativa in the early archeological record and modern natural distribution of O. rufipogon requires some explanation, and this may shed light on how, where and when domestication took place. The most parsimonious explanations are that domestication took place further south where O. rufipogon occurs, but an archeological record for this is missing, or that O. rufipogon had a wider distribution in the past into the area where we do see early domesticated rice. It seems unlikely that wild O. rufipogon plants were transplanted to the north where we currently see that domesticated forms developed.

Many plant and animal species were first domesticated in the Pearl River Valley (Dodson and Dong, 2016) but rice is missing from that list. If O. rufipogon had a more northerly occurrence in the past it may have overlapped with the first farming sites for rice. O. rufipogon can occur outside its natural range and occurs as a weed in O. sativa paddy fields. This is likely due to habitats and microclimates created by humans to grow rice crops. Climate tolerance limits for O. rufipogon, based on its natural occurrence are warm summers with temperatures above about 26°C, and mean annual temperatures above 17°C. Today these conditions are generally south on the Yangtze, and in the provinces including Fujian, Hunan and Guangdong.

![Figure 2](image-url)
Some have argued that domestication of rice took place just very close to the natural limit of *Oryza rufipogon* in the Yangtze valley (e.g., Fuller, 2011). If this was the case the species may have been under stress and therefore malleable to change to the domesticated form. However, as a perennial grass it probably had wide dispersible capacity, and may have been able to colonize areas within its environmental envelope quite quickly.

Warmer and perhaps wetter climate occurred much further north that today in the early Holocene. And where temperatures can be quantified they easily exceed the minimal requirements for *O. rufipogon*. These conditions were driven by a more intense East Asian Summer Monsoon, and this is recorded in a wide variety of records. The most likely cause of this was the orbital forcing which enabled monsoon activity to expand into the region as far as northeast China. It appears that once the northern ice sheets decayed sufficiently the Westerlies became more intense and the northeast cooled and became drier, and warmth loving species retreated southward. While there is no clear evidence of *O. rufipogon* in northeast China during the early Holocene it is clear that conditions were suitable for its occurrence and with sufficient overlap in time in sites where rice was fully domesticated and probably beyond.

A wider occurrence of *O. rufipogon* into northeast China provides support for the early evidence of domesticated rice in Shandong and elsewhere in the northeast.

**CONCLUSION**

There is a mismatch between the current distribution of native *Oryza* species and the earliest known sites of domestication into *Oryza sativa*. This may indicate that *Oryza rufipogon*, in particular, had a much wider distribution in the past, and overlapped with the earliest sites of domestication, or that the latter first occurred in the Pearl River basin. There is no compelling evidence to support a Pearl River basin origin. The bulk of evidence for first rice farming is centered around the Yangtze valley or nearby. However there are a small number of intriguing cases that point to early domesticated rice north of the Yangtze. Additional research to identify early *O. rufipogon* occurring much further north, and overlapping the early archeological sites is needed to test this.

As things stand the simplest explanation for the development of rice agriculture in the Lower Yangtze Valley possibly took place from native *O. rufipogon* growing nearby when the climate of the early to mid-Holocene had extended that species range much further north compared to today. This would require a more active East Asian Summer Monsoon compared to today and there is abundant evidence to support this from northeast China, perhaps as far north as Shandong or even further north into Jilin as the climate envelopes are suitable according to quantitative climate estimates. This makes the apparent outliers of early rice in Shandong and elsewhere well within the bounds of possibility.

**REFERENCES**

Anping, P. (1998). Notes on new advancements and revelations in the agricultural archaeology of early rice domestication in the Dongting Lake region. *Antiquity* 72, 878–885. doi: 10.1017/s0003598x00087512

Atahan, P., Itzstein-Davey, F., Taylor, D., Dodson, J., Qin, J., Zheng, H., et al. (2008). Holocene-aged sedimentary records of environmental changes and early agriculture in the lower Yangtze, China. *Quat. Sci. Rev.* 27, 556–570. doi: 10.1016/j.quascirev.2007.11.003

China Meteorological Data Service Centre [CMDSC]. (2020). *China Meteorological Data Service Centre*. Available online at: https://data.cma.cn/ (accessed July, 2020).

Crawford, G. W., Chen, X. X., Luan, F., and Wang, J. (2016). People and plant interaction at the Houli Culture Yuezhuang site in Shandong province, China. *Holocene* 26, 1594–1604. doi: 10.1177/0959683616650269

d’Alpoim Guedes, J., Guiyun, J., and Bocinsky, R. K. (2015). The impact of climate on the spread of rice to north-east China: a new look at the data from Shandong Province. *PLoS One* 10:e0130430. doi: 10.1371/journal.pone.0130430

Deng, Z., Qing, L., Gao, Y., Weisskopf Alison, R., Zhang, C., and Fuller, Q. D. (2015). From early domesticated rice rice in the Middle Yangtze basin to millet, rice and wheat agriculture: archaeobotanical macro-remains from Balang, Nanyang basin, Central China, 6700 -500 BC. *PLoS One* 10:e0239865. doi: 10.1371/journal.pone.0139885

Dodson, J. R., and Dong, G. H. (2016). What do we know about domestication in eastern Asia? *Quat. Int.* 426, 2–9. doi: 10.1016/j.quaint.2016.04.005

Dodson, J. R., Hickson, S., Khoo, R., Li, X.-Q., Toia, J., and Zhou, W. J. (2006). Vegetation and environmental history for the past 14 000 yr BP from Dingnan, Jiangxi Province, South China. *J. Integr. Plant Biol.* 48, 1018–1027. doi: 10.1111/j.1744-7909.2006.00274.x

Fan, S. G., Zhang, Z. J., Liu, L., Liu, H. X., and Liang, C. Y. (1999). “Species and geographical distribution of wild rice and their biological characteristic in China,” in *Proceedings of the Third National Symposium on the Conservation and Sustainable Use of Biological Diversity*, (Beijing: China Forestry Publishing House).

Fu, F., Ma, C., Zhu, C., Lu, H. Y., Zhang, X. J., Huang, K. Y., et al. (2018). Variability of East Asian summer monsoon precipitation during the Holocene and possible forcing mechanisms. *Clim. Dyn.* 52, 969–989. doi: 10.1007/s00382-018-4175-6

Fuller, D. Q. (2011). Pathways to Asian civilizations: tracing the origins and spread of rice and rice cultures. *Rice* 4, 78–92.

Fuller, D. Q., Qin, L., and Harvey, E. (2007). “Evidence for a late onset of agriculture in the Lower Yangtze region and challenges for an archaeobotany of rice,” in
Human Migrations in Continental East Asia and Taiwan: genetic, Linguistic and Archaeological Evidence, ed A. Sanchez-Mazas, R. Blench, M. D. Ross, M. Lin, and I. Pejros (London: Taylor and Francis).

Fuller, D. Q., Qin, L., Zhao, Z. J., Zheng, Y. F., Hosoya, L. A., Chen, X. G., et al. (2011). “Study on the botanic remains from the Tianluoshan site, in Center for the Study of Chinese Archaeology,” in Integrated Studies on the Cultural Remains from Tianluoshan, ed. Peking University and Zhejiang province Institute of Archaeology and Cultural Heritage (Beijing: Wenwu Press), 470–496.

Fuller, D. Q., Qin, L., Zheng, Y. F., Zhao, Z. J., Chen, X. G., Hosoya, L. A., et al. (2009). The domestication process and domestication rate in rice, spikelet bases from the Lower Yangtze. Science 323, 1607–1610. doi: 10.1126/science.1166605

Goldsmith, Y., Broecker, W. S., Xu, H., Pratigya, J., de Menocal, P. B., and Porat, I. (2011). “Decoupled warming and monsoon precipitation in East Asia over the last deglaciation.” Earth Planet. Sci. Lett. 301, 256–264. doi: 10.1016/j.epsl.2010.11.010

Rosen, A., Macphail, R., Li, L., Chen, X. C., and Weisskopf, A. (2017). Rising social complexity, agricultural intensification and the earliest rice paddies in the Loess Plateau of northern China. Quat. Int. 437, 50–59. doi: 10.1016/j.quaint.2015.10.013

Stebich, M., Rehfeld, K., Schütz, F., Tarasov, P. E., Liu, J., and Mingram, J. (2015). Holocene vegetation and climate dynamics of NE China based on the pollen record from Sihailongwan Maar Lake. Quat. Sci. Rev. 124, 275–289. doi: 10.1016/j.quascirev.2015.07.021

Stevens, C. I., and Fuller, D. Q. (2017). “The spread of agriculture in eastern Asia,” in Language Dynamics and Change, ed. J. Good (Brill Publications).

Wei, X., Wang, R. S., Cao, L., Yuan, N., Huang, J., Qiao, W., et al. (2012). Origin of Oryza sativa in China inferred by nucleotide polymorphisms of organelle DNA. PLoS One 7:e49546. doi: 10.1371/journal.pone.0049546

Wu, Y., Jiang, L., Zheng, Y., Wang, C., and Zhao, Z. (2014). Morphological trend analysis of rice phytoliths during the early Neolithic in the Lower Yangtze. J. Archaeol. Sci. 49, 326–331. doi: 10.1016/j.jas.2014.06.001

Wu, Y., Mao, L., Wang, C., Zhang, J., and Zhao, Z. (2016). Phytolith evidence suggests early domesticated rice since 5600 cal BP on Hainan Island of South China. Quat. Int. 426, 120–125. doi: 10.1016/j.quaint.2016.01.008

Wu, Z. Y., Raven, P. H., and Hong, D. Y. (2006). Flora of China, Volume 22: Poaceae. Beijing: Science Press. Available online at: http://flora.huh.harvard.edu/china (accessed July, 2020).

Xia, X. M., Zhang, P., and Wu, Y. (2019). The analysis of rice remains from the Chaling Site in the Pearl River Delta, Guangdong Province. Quat. Sci. 39, 24–36.

Yang, X., Chen, Q., Ma, Y., Li, Z., Hung, H.-C., Zhang, Q., et al. (2018). New radiocarbon and archaeobotanical evidence reveal the timing and route of southward dispersal of rice farming in South China. Sci. Bull. 63, 1495–1501. doi: 10.1016/j.scib.2018.10.011

Yi, S., Saito, Y., Oshima, H., Zhou, Y., and Wei, H. (2003a). Holocene environmental history inferred from pollen assemblages in the Huanghe (Yellow River) delta, China: climatic change and human impact. Quat. Sci. Rev. 22, 609–628. doi: 10.1016/j.quascirev.2002.07.017

Yi, S., Saito, Y., Zhao, Q., and Wang, P. (2003b). Vegetation and climatic changes in the Changjiang (Yangtze River) Delta, China, during the past 13,000 years inferred from pollen records. Quat. Sci. Rev. 22, 1501–1519. doi: 10.1016/j.quascirev.2003.10.004

Zhang, C., and Hung, H. C. (2010). The emergence of agriculture in southern China. Antiquity 84, 11–25. doi: 10.1017/S0003598X00097373

Zhang, C., and Hung, H. C. (2013). Jiahu 1: earliest farmers beyond the Yangtze River. Antiquity 87, 46–63. doi: 10.1017/S0003598X00048614

Zhang, J. H., and Wang, W. K. (1998). Notes on the recent discovery of ancient cultivated rice at Jiahu, Henan Province: a new theory concerning the origin of Oryza japonica in China. Antiquity 72, 897–901. doi: 10.1017/ s0003598X00078536

Zhang, J., Weiya, L., Chenglong, Y., Zhijie, C., Yuzhang, Y., Luo, W., et al. (2014). The Holocene vegetation and climate dynamics of NE China based on the pollen record from Sihailongwan Maar Lake. Quat. Sci. Rev. 101, 363–373. doi: 10.1016/j.quascirev.2014.09.019

Zhang, M., and Tang, L. (1996). The primitive rice farming in the east of the Yangtze River and Huai River. Agricult. Archaeol. 1996, 106–121.

Zhang, N., Yang, Y., Cheng, H., Zhao, J. Y., Yang, X. L., Liang, S., et al. (2018). Timing and duration of the East Asian summer monsoon maximum during the Holocene based on stalagmite data from North China. Holocene 28, 1631–1641. doi: 10.1177/0959683618782606

Zhang, R., Jiang, D. B., and Cheng, Z. G. (2020). Holocene precipitation changes in NE China from CCSM3 transient climate simulations. Holocene 30:095968362096148. doi: 10.1017/s0959683620961485

Zheng, Z. Q., Bianchette, T. A., Meng, C., Xu, Q., and Jiang, M. (2020). Holocene vegetation-hydrology-climate interactions of wetlands on the Heiixai Island, China. Sci. Total Environ. 743:140777. doi: 10.1016/j.scitotenv.2020.140777

Zheng, Y. H., Pancost, R. D., Naafs, B. D. A., Li, Q. Y., Liu, Z., and Yang, H. (2018). Transition from a warm and dry to a cold and wet climate in NE China across the Holocene. Earth Planet. Sci. Lett. 493, 36–46. doi: 10.1016/j.epsl.2018.04.041
range in China. *J. Ecol.* 101, 1498–1508. doi: 10.1111/1365-2745.12143

Zhou, W. J., Zheng, Y. H., Meyers, P. A., Jull, A. J., and Xie, S. C. (2010). Postglacial climate-change record in biomarker lipid compositions of the hani peat sequence, Northeastern China. *Earth Planet. Sci. Lett.* 294, 37–46. doi: 10.1016/j.epsl.2010.02.035

Zuo, X., Lu, H., Jiang, L., Zhang, J., Yang, X., Huan, X., et al. (2017). Dating rice remains through phytolith radiocarbon reveals domestication at the beginning of the Holocene. *Proc. Nat. Acad. Sci.* 114, 6486–6491. doi: 10.1073/pnas.1704304114

**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Copyright © 2021 Dodson, Hung, Li, Lu and Yan. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.