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

John Dodson[1,2], Hsiao-chun Hung[3], Chenzi Li[1], Jianyong Li[4], Fengyan Lu[1] and Hong Yan[1]*

[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 Carring Capacity, College of Urban and Environmental Sciences, Northwest University, Xi'an, China

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***Correspondence:**
John Dodson
john@ieecas.cn

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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 to continue this as hunting and gathering was dependent on the success of finding food as the seasons came and went, and thus usually required a nomadic lifestyle to chase the spoils. The new methods involved herding animals and farming crops. As a result of stable food supply, the population increased substantially with the development of agriculture. Crop production required 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 and Guo, 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

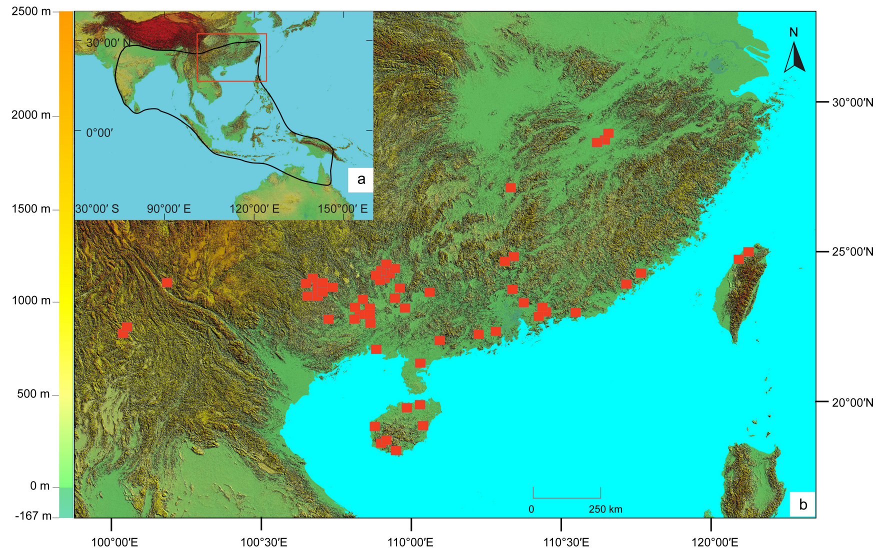

FIGURE 1 | Natural distribution of *Oryza rufipogon*. Inset shows full natural distribution. On the mainland the distribution is in Yunnan, Guangxi, Guangdong, Hunan, Jiangxi, and offshore on the islands of Hainan and Taiwan. The natural populations in Jiangxi and Taiwan are extinct due to habitat destruction. 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 Zheijiang, 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 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. rufipogon,* 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. rufipogon* 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**.

TABLE 1 | Mean temperatures (°C) averaged from 1981 to 2010 from selected sites in Guangxi, Jiangxi, Hunan and Fujian.

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
Pingle	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
Xiangzhou	91	27.4	28.7	28.4	26.5	27.8	20.8
Jiangxi							
Xiushui	147	24.9	28.1	27.3	23.6	26	16.8
Yifeng	92	25.5	28.5	27.9	24.3	26.6	17.4
Fenyi	94	25.9	29.1	28.2	24.6	27	17.9
Wanan	102	26.5	29.3	28.4	24.8	27.3	18.5
Nankang	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	68	26.7	28.9	28.5	26.6	27.6	21.2
Yongtai	86	26.1	28.7	28	25.5	27.1	19.9

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. rufipogon* 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. rufipogon* 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. rufipogon*, 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 Sihailongwan 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 (Stebich 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

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.

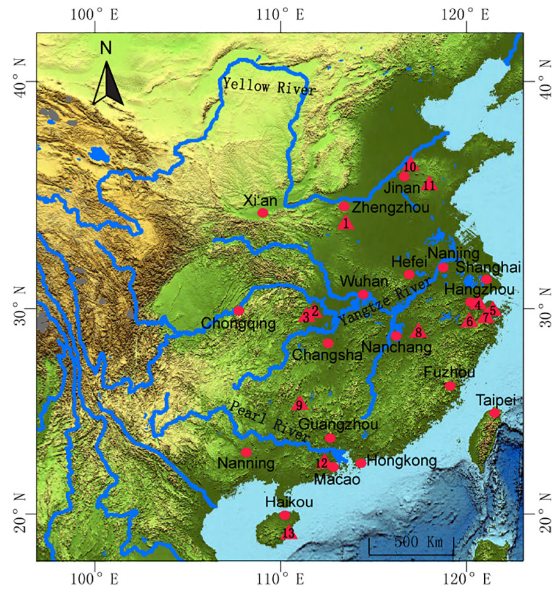

FIGURE 2 | Map showing important sites related to this study. (1) Jiahu, (2) Bashidang, (3) Pengtoushan, (4) Kuahuqiao, (5) Hemudu, (6) Shangshan, (7) Xiaohuangshan, (8) Dingnan Jiangxi, (9) Xianrendong/Daotonghuan, (10) Yuezhuang, (11) Xihe, (12) Pearl River delta.

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.

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.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

JD conceived the main idea. HH fleshed out the archeological side. FL, JL, CL, and HY helped with the analyses and writing. All authors contributed to the article and approved the submitted version.

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