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Modelling the chronology and dynamics of the spread of Asian rice from ca. 8000 BCE to 1000 CE

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ABSTRACT

This paper presents a quantitative chronology for the spread of rice, based on the global Rice Chronology Database that builds upon direct datings of archaeological rice remains. Bayesian and spatio-temporal modelling suggest eastern China (lower Yangzi, middle Yangzi, southern Huai River, and Shandong) and northeastern South Asia as two key origins of rice cultivation, dating to ca. 7430 and 6460 BCE, respectively. At least two episodes of spread of rice are identified. The first, dating to the 4th and 3rd millennia BCE, accounts for the appearance of rice in the middle Yellow River and Wei River regions, southeastern China, southwestern China, and Southeast Asia. An examination of population dynamics in China shows that this episode of spread might be associated with farmers whose subsistence was based largely on millets. During a second episode of spread, dating between the 1st millennium BCE and 1st millennium CE, rice spread to the Liao River region, Central Asia, and Africa.

1. Introduction

The domesticated form of Asian rice (*Oryza sativa*) has been argued to have promoted the development of civilisations in Asia and is consumed as a staple by almost half of the world's population today (Khush, 2005). It is estimated that there are more than 40,000 rice varieties, ranging from lowland types that mostly grow in paddy fields to upland types that can survive relatively dry conditions (Awan et al., 2017).

The history of this cereal crop has driven much interest. A number of regions had been proposed as the crop's domestication centre based on genetics or biogeography of the *Oryza* genus (Huang et al., 2012), such as the Yunnan-Guizhou Plateau, the Pearl River basin, and the Indian Peninsula (Fig. 1a), but archaeological evidence since the 1970s has shifted the focus to the middle and lower reaches of the Yangzi River and the Huai River (Crawford, 2012). The last two decades of interdisciplinary investigations suggest a much more prolonged and rather complex process of rice domestication than previously assumed (Fuller et al., 2010). In addition, there might have been several independent domestication centres (Fuller and Qin, 2009). The two main rice subpopulations, the subspecies *japonica* and *indica*, were separately cultivated in China and the Indian Peninsula, respectively, although key domestication genes were likely passed from *japonica* to *indica* through interbreeding following the spread of *japonica* from China to the Indian Peninsula (Civáň et al., 2015).

The spread of rice seems to have accompanied some remarkable prehistoric human population movements across Asia Pacific and into the Indian Ocean region (Deng et al., 2020), such as the expansion of the Austronesian language family (Bellwood and Dizon, 2005) and migrations which led to the emergence of the Yayoi culture across most of the Japanese Archipelago (Leipe et al., 2020). These migrations can be considered as important examples for testing the Farming/Language Dispersal Hypothesis (Diamond and Bellwood, 2003) suggesting that the dispersals of farming communities shaped the distribution of the major language families of the world today. Nonetheless, more studies are needed to reconstruct the timing of, and dynamics behind, the spread of rice.

In the current paper, we aim to build a chronology for the spread of rice using solid, spatio-temporally specific data and robust modelling techniques. First, we established a quantitative chronology for the

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spread of rice. For this we compiled a global database of rice-related radiocarbon (^{14}C) dates, the Rice Chronology Database (RCD), after critically evaluating the reliability of the gathered published age-related data and further analysed this database using Bayesian and spatio-temporal modelling approaches. Second, we tested the hypothesis that population growth resulting from rice cultivation was the main driver behind the spread of rice. This was carried out by comparing the timing of the appearance of rice in different geographical regions and that of the population development estimated from the spatio-temporal distribution of archaeological sites (Hosner et al., 2016).

2. Data and methods

2.1. Compilation of rice-related ^{14}C dates

We collated the global database of rice-related ^{14}C age estimates (RCD) based on published sources, such as the age-related records in an existing archaeological rice database (Silva et al., 2015, 2018). These information sources are available from internet-based search engines, including Web of Science, Google Scholar, and Chinese National Knowledge Infrastructure (CNKI). The quality of the published age estimates varies and was thus examined systematically. Caryopses are short-lived material that are commonly sought for Accelerator Mass Spectrometry (AMS) ^{14}C dating (Hatté and Jull, 2007). All dates based on rice caryopses were considered to be reliable and included in the database. In this study, we did not differentiate between wild and domesticated forms of rice caryopses, as this information is often not provided in the associated publications. Thereby, the current database focuses more generally on the use of rice, instead of the appearance of domesticated forms of rice. Domesticated forms of rice could have appeared long after the initial use of wild rice (Fuller and Qin, 2009). Likewise, we did not distinguish between the *japonica* and *indica* subspecies, which is problematic based on morphological traits of charred caryopses alone (Fuller et al., 2009). Dates based on carbon encapsulated in *Oryza*-type phytoliths are found to be equally reliable as caryopsis-based dates (Zuo et al., 2017) and were included in the database. Indirect datings of rice, e.g. through a correlation with typological remains (e.g. pottery and stone tools) or with ^{14}C determinations of undifferentiated organic material, bones, or wood charcoal, are often unreliable (Zuo et al., 2017) and were not included in the collated database. These indirect datings often involve additional sources of error (Long et al., 2016), such as those from the 'old wood effect' or exogenous carbon contamination (Bronk Ramsey, 2009b).

This critical evaluation of the available data ensures that only the most reliable age information on archaeological rice is included in the current study. The spatial focus excludes the Korean Peninsula and the Japanese Archipelago, which have been addressed elsewhere (Leipe et al., 2020). Some often-cited evidence for the early use of rice, which has not been supported by reliable chronologies, is not included in our database. Examples include rice remains from the Yuchanyan (e.g. *Oryza*-type phytoliths, charred caryopses, and charred chaff) and Xianrendong (e.g. *Oryza*-type phytoliths) archaeological sites in the Yangzi

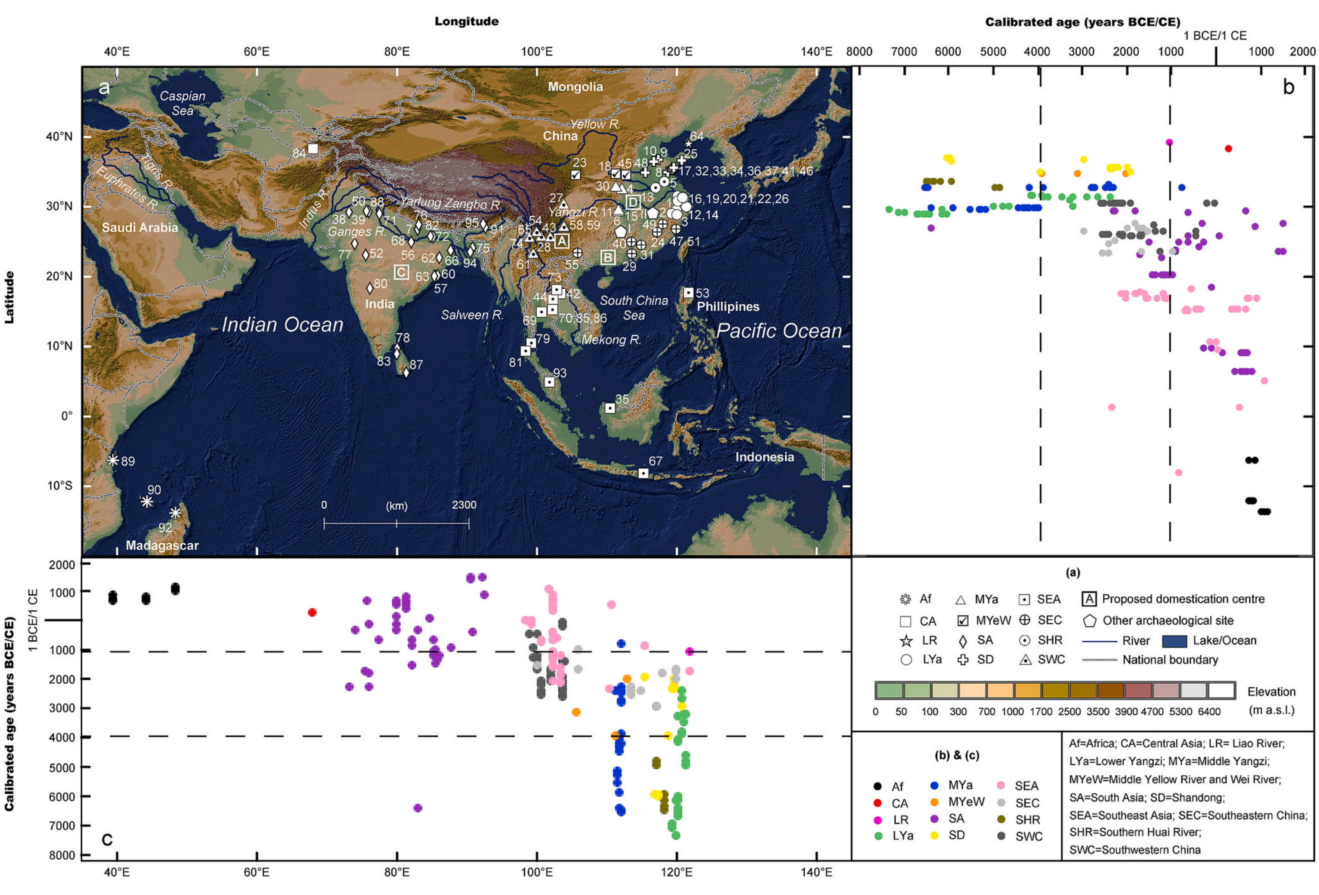

Fig. 1. Directly dated rice remains contained in the Rice Chronology Database. (a) Topographical map showing the geographical distribution of rice remains (n = 259; see Supplementary Table 2 for details) organised into 12 spatial divisions (see Methods for details). Numbers (ordered according to the median age of first appearance of rice) of archaeological sites refer to Supplementary Table 2. A (Yunnan-Guizhou Plateau), B (Pearl River basin), C (Indian Peninsula), and D (the middle and lower reaches of the Yangzi River and the Huai River) were proposed as possible domestication centres of rice. Other key archaeological sites mentioned int this study include: I. Yuchanyan and II. Xianrendong. (b) Latitudinal distribution of calibrated median ages of rice remains. (c) Longitudinal distribution of calibrated median ages of rice remains.

River basin (e.g. Wu et al., 2012; School of Archaeology and Museology at Peking University; Jiangxi Provincial Institute of Cultural Relics and Archaeology, 2014), which have been dated to, respectively, ca. 18,300 and 20,000 cal BP (Cohen, 2014). Currently available ^{14}C dates from the two sites are exclusively based on wood charcoal, bones, or charred organic matter on pot sherds (Boaretto et al., 2009; School of Archaeology and Museology at Peking University; Jiangxi Provincial Institute of Cultural Relics and Archaeology, 2014).

2.2. Correction and calibration of rice-related ^{14}C dates

The ^{14}C dates in the collated database were calibrated to calendar ages using OxCal v4.2.3 (Bronk Ramsey and Lee, 2013) and the IntCal13 calibration curve (Reimer et al., 2013). IntCal13 was adopted in the current study, in order to be consistent with our publication series on early agriculture in East Asia (e.g. Long et al., 2018; Leipe et al., 2019; Leipe et al., 2020). In addition, we corrected ^{14}C dates determined by laboratories in China before 2004 by using the internationally adopted Libby half life of 5568 ± 30 years to replace the Cambridge half life of 5730 ± 40 years, which was widely used in China before 2004 (Stevens and Fuller, 2017).

2.3. Divisions of archaeological sites with rice-related ^{14}C dates

In this study, archaeological sites with rice-related dates were grouped into 12 spatial divisions (Figs. 1 and 2), each representing a geographical region for the origins and dispersals of rice. These 12 divisions are: Africa (Af), Central Asia (CA), Liao River (LR), lower Yangzi (LYa), middle Yangzi (MYa), middle Yellow River and Wei River (MYeW), South Asia (SA), Shandong (SD), Southeast Asia (SEA), southeastern China (SEC), southern Huai River (SHR), and southwestern China (SWC). The names of these divisions do not strictly, but rather only loosely, correspond to their geographical distribution. For example, the SHR division does not include archaeological sites within today's Huai River region that are located in Henan and Shandong provinces.

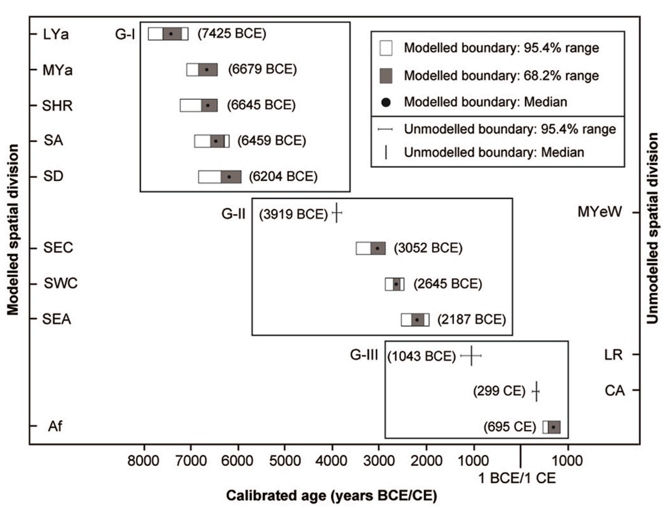

Fig. 2. The estimated age ranges and medians for the appearance of rice in the 12 rice-related spatial divisions. The results for lower Yangzi (LYa), middle Yangzi (MYa), southern Huai River (SHR), South Asia (SA), Shandong (SD), southeastern China (SEC), southwestern China (SWC), Southeast Asia (SEA), and Africa (Af) were estimated by Bayesian chronological modelling (see Methods for details). The results for middle Yellow River and Wei River (MYeW), Liao River (LR), and Central Asia (CA) were estimated from unmodelled probabilistic distribution of the oldest rice remains from each division (see Supplementary Table 2 for details). The median age for the appearance of rice in each division is given in parentheses. G-I, G-II, and G-III are chronological groups of the appearance of rice.

2.4. Bayesian chronological modelling of rice-related ^{14}C dates

We constructed a Bayesian model (Supplementary Information 1) to build a chronology for the spread of rice across the different defined regions, in order to identify its possible source region(s) and dispersal routes. We used the built-in *phase* model (Bronk Ramsey, 2009a) in OxCal v4.2.3 as a building block (i.e. a sub-model) of the Bayesian chronological model and the *overlapping multi-phase model* as the overarching structure to combine these sub-models (Supplementary Fig. 1). Each of the sub-models puts together all rice-related dates from a spatial division (Long et al., 2018). The median age of the start *boundary* in a sub-model was used as an estimate of the appearance of rice use in that particular geographical region (Long et al., 2018). However, for three of the divisions, CA, LR, and MYeW, the number of dates available in the database are less than three, which would have resulted in an unstable Bayesian model. These three divisions were therefore excluded from the modelling. Instead, for these three divisions, we tentatively adopted the unmodelled age distribution of the oldest ^{14}C date in each region to infer the appearance of rice. We excluded all ^{14}C determinations with a measurement error larger than 200 years (Long et al., 2017). To facilitate the convergence of Markov Chain Monte Carlo analysis in the model, we also excluded all ^{14}C determinations younger than 500 ^{14}C BP in the current study (Supplementary Table 2). Lastly, we introduced the built-in *difference* command in OxCal to test the relative order of all sub-models.

2.5. Mapping the spatio-temporal spread of rice across Asia

To map the spatio-temporal spread of rice across Asia, we interpolated the ^{14}C dates contained in the RCD. For this estimation we used the calibrated median age of the oldest rice-related ^{14}C date from each archaeological site as the representative time of the appearance of rice at that site. It focuses only on landmasses by masking out all ocean regions (Fig. 3). The GTOPO30 digital elevation model, freely available through the United States Geological Survey (https://earthexplorer.usgs.gov/), was used to define the boundary between landmasses and oceans. Moreover, given the fact that certain natural habitats should not have been suitable for the development of rice-related agriculture, we excluded a total of 27 terrestrial eco-regions (Supplementary Table 3), based on the classification by the Nature Conservancy (https://geospatial.tnc.org/), from the analysis. These excluded regions are largely located in western China, comprising deserts and xeric shrublands, montane grasslands and shrublands, temperate conifer forests, rock and ice, and inland water. A special exclusion is the Tarim Basin Deciduous Forests and Steppe eco-region because it is fully surrounded by deserts and xeric shrublands despite its environmental suitability for agriculture on its own. Although this exclusion of eco-regions largely ignored possible difference between past and today's vegetation in western China, it should not be too far from the reality since climate change in western China during the Holocene was not of a magnitude that could have drastically changed the aridity or coldness of a given region (Li et al., 2017), crucial factors for the growth of rice. For the interpolation we used the *Spline with barrier* tool with a smooth factor 0.01 in ArcGIS Pro v2.6.0.

2.6. Estimation of population dynamics in China

To estimate the degree to which Neolithic–Bronze Age population development is correlated with the spread of rice across China, we used archaeological site data extracted from an existing database (Hosner et al., 2016). The original dataset, which is available in the open access PANGAEA Data Publisher for Earth & Environmental Science (https://doi.org/10.1594/PANGAEA.860072) data repository, covers most parts of China, including 25 Chinese province-level administrative units, published in the series *Atlas of Chinese Cultural Relics*. Province-level administrative units in China are provinces, autonomous regions,

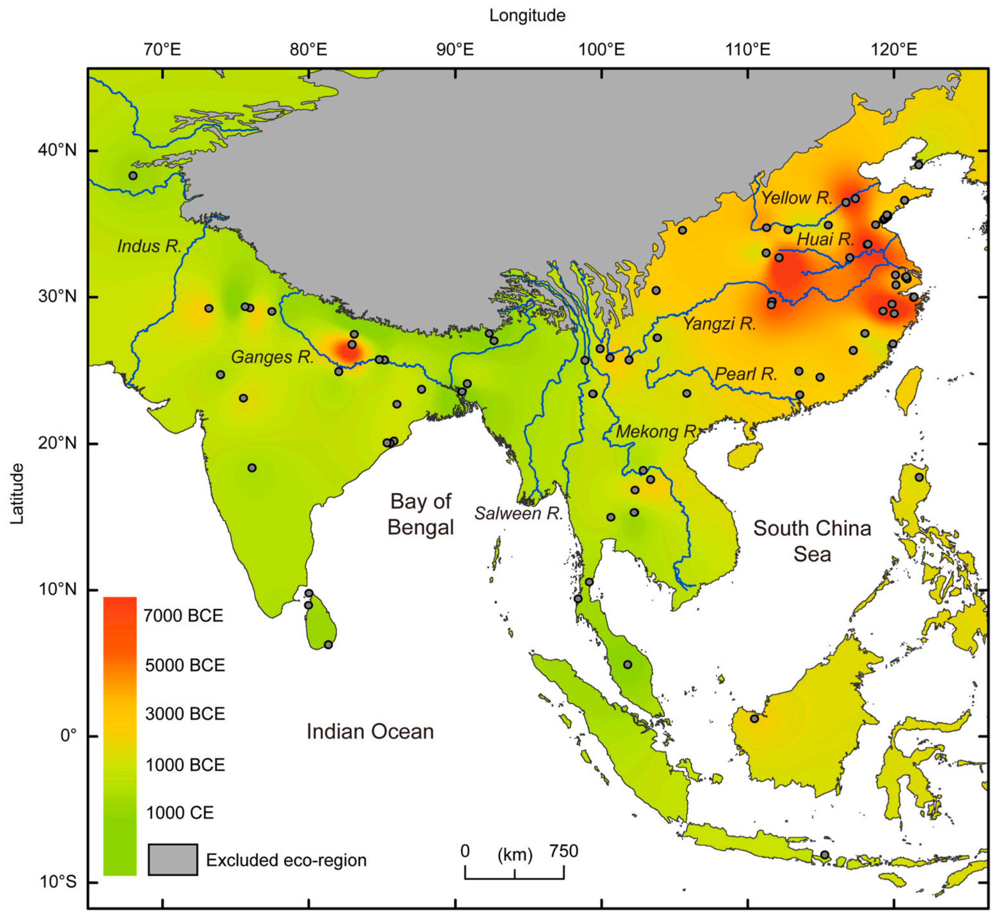

Fig. 3. Spatio-temporal distribution of the appearance of rice across Asia derived from spline interpolation of the oldest rice-related dates per archaeological site.

municipalities, or special administrative regions. In this Atlas, data are not yet available from the following administrative units: Heilongjiang, Shanghai, Jiangxi, Guizhou, Guangxi, Hainan, Taiwan, Hong Kong, and Macau. These units were therefore not included in the original dataset and in the current analysis. To acknowledge that overreliance on archaeological site numbers as a population proxy can be critical given the heterogeneous nature of the base data (Hosner et al., 2016), we used only qualitative trends instead of quantitative changes to infer population development. To estimate spatio-temporal population development, we organised the site data into eight archaeological regions that broadly correspond to the eight spatial divisions in China defined for the Bayesian chronological modelling (Fig. 4a).

The eight archaeological regions were defined based on latitudinal and longitudinal boundaries (Supplementary Table 4), including Region I: LYa (28–32°N, 118–123°E), Region II: MYa (28–33.5°N, 110–114.5°E), Region III: SHR (32–34.4°N, 114.5–123°E), Region IV: SD (34.4–38.5°N, 114.5–123°E), Region V: MYeW (33.5–36°N, 104–114.5°E), Region VI: SEC (20–28°N, 105–122°E), Region VII: SWC (21–32°N, 97.5–105°E), and Region VIII: LR (38.5–43°N, 120–124.5°E). The number of archaeological sites contained in each regional subset varies (Fig. 4b–i) between 8545 (MYeW) and 992 (SWC). Each contained archaeological site in this dataset is assigned to one or more well-dated cultural periods in Chinese archaeology. This implies that the sites represent different time ranges, which vary between 100 and 6000 years. To temporally normalise the site data, i.e. to eliminate influence of the length of the defined cultural periods, the site numbers are presented by time intervals of equal length, which was tentatively set to 100 years.

3. Results

3.1. RCD and Bayesian chronological modelling of rice-related ^{14}C dates

The RCD (Supplementary Table 2) comprises 259 rice-related ^{14}C dates from 95 archaeological sites distributed across Asia and Africa, which were classified into 12 spatial divisions (Figs. 1 and 2). Regarding the chronology, the 12 defined divisions include 9 (Af, LYa, MYa, SA, SD, SEA, SEC, SHR, and SWC) represented by a Bayesian chronological submodel and 3 (CA, LR, and MYeW) represented by unmodelled age distributions of the oldest published ^{14}C dates. Together, the modelled and unmodelled ages for the appearance of rice in the defined divisions allow us to identify three chronological groups (G-I–III; Figs. 1b and c, and 2).

The first chronological group, G-I, includes the LYa, MYa, SHR, SA, and SD divisions. The modelled 95% probability range (Supplementary Fig. 2) suggests that rice first appeared in LYa ca. 7920–7070 BCE (median: ca. 7430 BCE), which reflects the currently earliest firm evidence for the human use of rice coming from the Shangshan (phytoliths-based ^{14}C date Beta-434204: 95% probability range 7468–7185 BCE, median 7337 BCE; number 1 in Supplementary Table 2) and Huxi archaeological sites (caryopsis-based ^{14}C date Beta-130714: 95% probability range 6898–6594 BCE, median 6682 BCE; number 5 in Supplementary Table 2) in central Zhejiang province (Jiang and Liu, 2006). This is followed by MYa (ca. 7100–6440 BCE, median: ca. 6680 BCE) and SHR (ca. 7240–6440 BCE, median: ca. 6650 BCE). The appearances of rice in SA and SD are dated to, respectively, ca. 6920–6190 BCE (median: ca. 6460 BCE) and ca. 6830–5930 BCE (median: ca. 6200 BCE).

The MYeW (ca. 3990–3800 BCE, median: ca. 3920 BCE), SEC (ca. 3490–2880 BCE, median: ca. 3050 BCE), SWC (ca. 2870–2480 BCE,

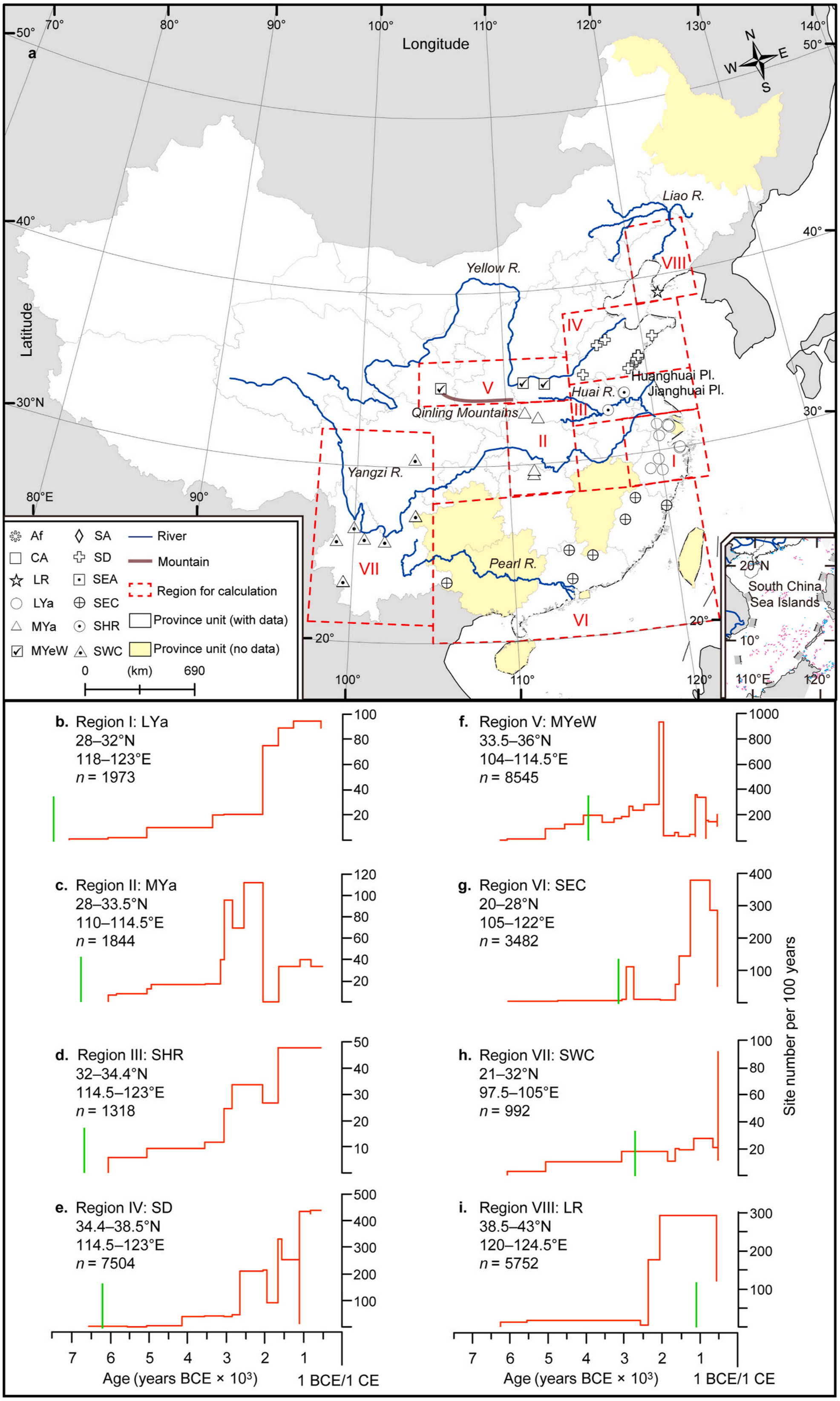

Fig. 4. Development of archaeological site numbers per 100 years for eight archaeological regions in China. (a) The locations of the eight archaeological regions (see Methods for definitions). Extents of the regions are in broad accordance with the eight defined rice-related spatial divisions in Fig. 1a. Calculations are based on a collection of archaeological sites from 25 province-level administrative units in China (Hosner et al., 2016). The line from the Qinling Mountains to Huai River marks the modern boundary of South and North China, characterised by, respectively, rice cultivation and dryland farming. Signs for archaeological sites refer to Fig. 1a. (b–i) The development of archaeological site numbers in different regions. The red curves show the number of archaeological sites per 100 years per region from 8050 to 525 BCE. The green lines show the median age for the appearance of rice in the corresponding division (Fig. 2). The numbers (*n*) indicate the number of sites contained in each subset.

median: ca. 2650 BCE), and SEA (ca. 2540–1950 BCE, median: ca. 2190 BCE) are included in chronological group G-II. Based on the median ages, the earliest appearance of rice in this group postdates that of G-I by ca. 2300 years. Of all the defined regions, rice last appeared in LR (ca. 1260–840 BCE, median: ca. 1040 BCE), CA (ca. 240–390 CE, median: ca. 300 CE), and Af (ca. 475–848 CE, median: ca. 700 CE), which form chronological group G-III.

The difference between the appearance of rice in the different spatial divisions is summarised in Supplementary Table 1. The appearance of rice in LYa predates its apparent appearance in MYa and SHR by ca. 750 and 770 years (medians), respectively, reflecting the earliest rice remains in the LYa. This appearance in LYa predated that in SA by ca. 970 years. In SEC, SWC, and SEA rice appeared, respectively, ca. 4360, 4780, and 5230 years later than in LYa. The appearance of rice in Af occurred approximately 8110 years later.

3.2. Mapping the spatio-temporal spread of rice across Asia

The map (Fig. 3) generated by spline interpolation of the oldest median calibrated ages per archaeological site shows a smoothed surface of the appearance of rice across Asia. It identifies two more or less independent source areas for rice, labelled in red, in eastern China and northeastern SA. The extent of the eastern China source area is much larger than the SA counterpart, which indicates a spatially more widespread distribution of archaeological sites with early rice remains in eastern China. The contrast between the source area in SA and its neighbouring areas is sharp.

3.3. Estimation of population dynamics in China

The analysis shows that in the LYa region, where rice was used first (Fig. 1), site numbers increased stepwise and moderately until ca. 2000 BCE when a pronounced rise in numbers occurred. The surrounding MYa, SHR, and SD regions, which are associated with chronological group G-I, saw a more or less continuous stepwise moderate increase in site numbers between ca. 6500–6000 and 3000–2600 BCE followed by a more pronounced rise. This period of relatively high numbers lasted until ca. 2000/1900 BCE when it was interrupted by a phase of site number decline, which continued until ca. 1600 BCE. While afterwards numbers in the SHR and SD regions reincreased to above pre-1900 BCE levels, the reincrease in the MYa region was below the maximum level that was reached between ca. 3100 and 2000 BCE.

In the MYeW region, site numbers started to increase from ca. 6000 BCE, around 2000 years before the appearance of rice. The overall trend is similar to that in MYa where site numbers increased until ca. 1900 BCE followed by a longer period of drastically decreased numbers and a moderate reincrease around 1100 BCE. Belonging to the same chronological group (G-II) as the MYeW region, the SEC region is characterised by a long period of low site numbers. This is superseded by a pronounced site increase around 1600 BCE. Similar to the regions contained in G-I, a continuous stepwise low-level site number increase is indicated for SWC, which started around 6000 BCE. However, this region did not experience any pronounced site number increase. The maximum values, which were reached between ca. 1100 and 600 BCE, remained on a comparatively moderate level. LR also saw a long period of low site numbers until ca. 2300 BCE, when numbers quickly rose to a substantially higher level.

4. Discussion

Both the chronological and spatio-temporal modelling results identify eastern China and northeastern SA as two possible source areas of rice use. This is largely in line with the current understanding that the Yangzi and Huai River regions were home to *japonica* and that the Indian Peninsula was home to *indica* rice (Kingwell-Banham and Fuller, 2012), but provides a quantitative timeframe for the origins of rice exploitation: ca. 7430 BCE (median) for eastern China and 6460 BCE (median) for northeastern SA.

However, the current modelling results also suggest that the region in which rice exploitation emerged stretched as far north as SD. Today, the geographical boundary between North and South China goes along the Qinling Mountains and Huai River, around ca. 32° to 34°N (Fig. 4a). This boundary corresponds to the January 0 °C isotherm and the 800 mm equipluve, marking the separation between the temperate and subtropical zones. Agriculturally, this boundary is the division between dry- and wetland farming today, mainly based on, respectively, wheat and rice cultivation. However, according to existing archaeobotanical records and the modelling results, rice was exploited in North China, such as in parts of the SHR region (those that are north of the Huai River) and the SD region, around 6200 BCE. This is probably because the mid-Holocene climate was warmer and wetter than today (Fuller et al., 2010) and the boundary between the temperate and subtropical zones was located further north. It might have been a common practice for prehistoric people across a wide range of latitudes in eastern China to exploit rice.

There are some short time lags of ca. 400–700 years (difference in medians) between the appearance of archaeological rice in LYa (ca. 7430 BCE), MYa (ca. 6680 BCE), SHR (ca. 6650 BCE), and SD (ca. 6200 BCE). These lags might originate purely from the fragmentary nature of the ^{14}C data and might not indicate any actual difference in the start of rice exploitation in these regions. An alternative possibility is that there was a gradual north-westward spread of rice habitats or rice exploitation. Accordingly, rice was first used in LYa and populations in MYa and SHR adopted this practice ca. 700 years later. After another ca. 400 years, people in SD started to exploit rice. Nonetheless, the spread of initial rice exploitation within eastern China can be considered to be a more or less continuous process.

The early appearance of rice in SA is possibly related to the origins of proto-*indica*. Archaeobotanical records in SA older than 3000 BCE are much smaller in number and less continuous than those in China, indicating that there was no intensive use of rice in SA for a long period of time. Only from around 2290 BCE, does the number of rice-related dates quickly increase for SA (Supplementary Table 2). This age postdates the appearance of rice exploitation in MYeW (ca. 3920 BCE), SEC (ca. 3050 BCE), and SWC (ca. 2650 BCE) but is similar to that in SEA (ca. 2190 BCE). The modelled appearance of rice in all these four spatial divisions of G-II, in addition to the sudden increase in the number of sites with rice dates in SA (Supplementary Table 2), might represent an important episode of the spread of rice from its region of origin in eastern China in the 4th and 3rd millennia BCE, which began at least 2300 years later than in G-I, possibly indicating a discontinuous nature of the spread of this crop. As rice turns out to have appeared in LR, CA, and Af (i.e. chronological group G-III) in the much later historic period, we focus more on this prehistoric spread of rice in the current discussion.

One approach to testing the Farming/Language Dispersal Hypothesis (Diamond and Bellwood, 2003) is to examine whether the adoption of rice has led to population growth that motivated human migrations and the spread of rice. However, comparing the chronological and population modelling results, it seems that rice did not necessarily result in major population growth in prehistory. In LYa, MYa, and SHR, the archaeological site data suggest population increased around ca. 3000 BCE, which happened significantly later than the appearance of rice in each region (Fig. 4b–d). By contrast, population increase in SD, MYeW, SEC, SWC, and LR (Fig. 4e–i) predates the appearance of rice in these regions, indicating that rice was unlikely to have been the reason behind the population growth. Moreover, LYa, MYa, and SHR, where rice appeared first in the archaeological record, are marked by a slower population growth than in other regions, such as SD and MYeW. In general, the numbers and densities of registered archaeological sites in South China are much lower compared to that in North China. This implies that there were other drivers than rice that supported the early population growth in North China.

One possible trigger for population growth is millet-based agriculture. It has been identified that the fertile crescent surrounding to the Bohai Sea is the source area for the domesticated forms of millet (Leipe et al., 2019), foxtail millet (*Setaria italica*) and broomcorn millet (*Panicum miliaceum*). After their domestication (Stevens et al., 2021), the two crops were discontinuously spread to other parts of East Asia (Leipe et al., 2019). Dryland farming based on millets seems to have triggered major population growth and expansion in North China (Li et al., 2019).

The spread of rice cultivation visible in the database could have been a side-effect of such an expansion of millet farming, at least in some regions suitable for rice cultivation. Thanks to the warmer and wetter mid-Holocene climate, rice was likely well integrated as a supplementary or luxury crop into the food production system in SD. Rice cultivation in North China might have been rain-fed—like in the case of millet cultivation—and had a higher demand for arable lands, since rain-fed rice cultivation tends to be less labour intensive but less productive than wet rice cultivation (Fuller et al., 2016). By contrast, the development of rice-related agriculture in South China likely followed a different trajectory. According to archaeological excavations, paddy field rice cultivation started to appear in LYa from ca. 5000 BCE. This form of cultivation enhanced the productivity of rice and apparently led to a moderate level of population growth. However, the growth was not of comparable magnitude to that in North China. Moreover, paddy field rice cultivation requires a constant labour input to maintain and concentrate population in established settlements, which might be the reason why rice farmers were not so expansive in nature (Qin and Fuller, 2019). Probably with the population growth and expansion from millet-based agriculture, rice was able to spread to other parts of the globe from its core domestication centres.

In contrast to a previous proposal that rice farmers in LYa were the ancestors of Austronesian-speaking people, recently available linguistic and archaeological evidence supports that the ancestors of Austronesian-speaking populations had their roots in SD (Sagart et al., 2017). They were essentially not farmers who relied solely on rice, but on mixed millet-rice farming. In Taiwan the first farmers used both millets and rice (Deng et al., 2018). One possible explanation for this scenario is that these farmers who likely originated from the eastern coast of China kept their agricultural tradition, even in southern sub-tropical and tropical environments like Taiwan where rice is relatively easy to cultivate. On the other hand, rain-fed rice cultivation is not necessarily more productive than millet-based agriculture. In mainland SWC, similarly, rice is always accompanied by millets in archaeobotanical records (Zhang et al., 2017; Dal Martello et al., 2018; Deng et al., 2018), although this might have originated at least in some regions from another wave of migration through inland routes from central China (He et al., 2017).

This wave of south-westward migration might also have merged into the initiation of Bronze Age exchange networks across Eurasia (Dong et al., 2017). The domesticated form of *japonica* was part of this first episode of food globalisation (Jones et al., 2016). The introduction of *japonica* may have led to the domestication of *indica*, which has become the main cultivated variety in SA since then (Kingwell-Banham and Fuller, 2012). Despite a tentative consistent explanation of archaeobotanical, linguistic, and population dynamics data, the possibility of millet-rice farmers spreading rice across Asia remains hypothetical and requires further tests.

Data points in the current database remain numerically limited and spatially uneven. We believe that there can be biases towards locations where archaeobotanical analysis has been routinely carried out, such as eastern China. In locations (e.g. SA, SEA) where direct dating of archaeobotanical remains is not yet common, there seems to be a lack of data. The problem needs to be addressed when data are more readily available. For the future, AMS ^{14}C analysis provides a routine tool to date even a small number of caryopses/fragments or phytoliths, and previously claimed ages of archaeological cereals need to be critically examined based on direct dating of these plant remains. An alternative approach based on genetic analysis of modern crop populations has proven to be successful and highly complementary to archaeobotanical studies (Gutaker et al., 2020). A reconstruction of the spread of rice in Southeast Asia hypothesised a mixed spread route of rice from mainland China and from Malaysia through the Philippines to Taiwan, in contrast to the traditional Out of Taiwan model in which rice largely spread southwards (Alam et al., 2021). This chronological order seems to align well with the earliest ^{14}C date in the SEA part of the current RCD, CAMS-725 (95% probability range 3013–1632 BCE, median 2326 BCE; number 99 in Supplementary Table 2), from the Gua Sireh archaeological site in Malaysia, which is ca. 600 years earlier than the currently earliest date from the Philippines, a ^{14}C date from the Andarayan archaeological site (Snow et al., 1986) originally published without a citable laboratory ID (95% probability range 2026–1431 BCE, median 1713 BCE; number 143 in Supplementary Table 2). Nonetheless, more archaeobotanical and chronological data are urgently needed to test the above hypothesis.

Moreover, differentiation of wild and domesticated rice (species level) and of the *japonica* and *indica* domesticated subspecies (subspecies level) remains a major challenge in archaeobotanical studies. A considerable amount of data in the database is without identification information to species or sub-species level, which constrains using the data in the RCD for testing the timing of the start of rice domestication or a more complete reconstruction of the spread of rice outside of China. There has been a long debate (e.g. Liu, 2008; Fuller et al., 2009; Huan et al., 2021) on the domestication process of rice during the Shangshan (ca. 10,800–8600 cal BP) and even during the Hemudu cultural complex (ca. 7100–5200 cal BP) in the LYa region (Long and Taylor, 2015). Although an increasing number of discoveries traced the start of sedentism in the region to the early Holocene or late Pleistocene (Chen and Yu, 2017), it remains questionable whether rice remains dating to such an early time are wild or represent an early stage of domestication (Ray and Chakraborty, 2018). Ascertaining the domestication status of rice is not only useful for reconstructing the history of rice per se but also critical for understanding the subsistence strategies of these early societies (Chen et al., 2019). More systematic archaeobotanical studies that investigate multiple proxies, such as macro-remains and phytoliths, in a holistic way might be of help to address identification difficulties (Sun, 2011). Recently there have been numerous successful studies using phytoliths to determine the status of domestication (Ma et al., 2016; Zheng et al., 2016; Zuo et al., 2017; Yang et al., 2018), in addition to its potential to distinguish *indica* from *japonica* (Sato et al., 1990; Zheng et al., 1999). However, more works are needed to standardise the related analytical techniques for a higher level of recognition. In addition, it is important to note from an evolutionary ecology perspective that the domestication of plants, such as rice, is not a discrete process with a narrowly defined beginning and end. It is an evolutionary process that continues even today. Thus, there is a strong need to constrain our definitions of domestication to specific traits, such as the dominance of non-shattering phenotypes.

5. Conclusions

Human use of rice appeared in eastern China and northeastern SA at, respectively, ca. 7430 and 6460 BCE. The eastern China zone mentioned here also includes an extensive area that stretched as far north as SD. However, rice seems not to have led to any intensified food production system and population growth in prehistory. The spread of rice was possibly linked to the migration of farmers whose subsistence was based largely on millets, although this hypothesis requires more rigorous testing in the future.

Author contributions

Conceptualisation, T.L.; Material and data collection, H.C., C.L., T.L.; Methodology, T.L., C.L.; Analysis, T.L., C.L., H.C.; Writing (original draft), T.L., H.C., C.L.; Writing (review and editing), T.L., C.L., M.W., P.E.T.; Visualisation, T.L., H.C., C.L., M.W., P.E.T.

Data availability

All data generated during this study are included in this article.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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