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The spread of rice to Japan: Insights from Bayesian analysis of direct radiocarbon dates and population dynamics in East Asia

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ABSTRACT

The shift from foraging to agriculture as an economic way of life can be influenced by multiple ecological and cultural factors. The introduction of rice cultivation in Japan appears to have facilitated a dietary and cultural transition from the Jomon to the Yayoi cultural repertoire (10th/4th century BCE). Here we examine how rice spread across the Yayoi cultural arena (Kyushu, Shikoku, and Honshu regions) using Bayesian modelling applied to a set of radiocarbon (^{14}C) dates obtained from carbonized rice grains. The combined results of radiocarbon analysis and archaeological data suggest that rice could have appeared in the Central Highlands already in the 11th century BCE when the region was occupied by people of the Final Jomon culture group and was mainly used for ritual purposes. It then appeared in western Japan (northern Kyushu) in the 9th century BCE and continued to disperse discontinuously across eastern Japan. This dispersal pattern likely results from the fusion of Jomon hunter–fisher–gatherer groups in eastern Japan with cultural traits introduced from the Eurasian mainland. The main driving factors for the immigration of early rice farmers into Japan (starting around 1000 BCE) appears to have been sociopolitical. Transformations in China led to the dissemination of rice farmers into the Korean Peninsula about 500 years earlier. The main drivers likely comprised: (i) the eastward expansion of the Shang dynasty (ca. 1600–1400 BCE); (ii) the eastward expansion of the Zhou kingdom, accompanied by the establishment of satellite states, such as Lu (Shandong Province) and Yan (Beijing), following the defeat of the Shang in 1045 BCE; and (iii) the strengthening of local states during the early 8th century BCE after the weakening of the Zhou, due to conflicts with agropastoralists from the Asian steppes. In addition, it is likely that the gradual middle–late Holocene decrease in summer monsoon precipitation negatively affected agricultural yields in the regions located closer to the summer monsoon boundary, such as the middle Yellow River, and thus further fostered the observed population dynamics including the spread of rice farmers to the Korean Peninsula and Japan.

1. Introduction

The introduction of rice (*Oryza sativa*) cultivation in Japan marked a shift from a complex hunter-gatherer to an agricultural economy of most people during the onset of the Yayoi period (10th/4th century BCE–250 CE) (Kaner and Yano, 2015). However, rice was not the only newcomer from the mainland; foxtail (*Setaria italica*) and broomcorn (*Panicum miliaceum*) millet played an important role in this cultural transformation. In some regions the millets even constituted a substantial portion of the diet (Endo, 2019; Endo and Ito, 2013; Leipe et al., 2020a; Shitara and Takase, 2014), reflecting the spatio-temporal diversity of the agricultural landscape during the Yayoi period (Shitara, 2014). While other crops, such as beefsteak plant (*Perilla frutescens*), bottle gourd (*Lagenaria siceraria*), adzuki bean (*Vigna angularis*), soybean (*Glycine max*), and barnyard millet (*Echinochloa esculenta*) were also

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grown (Crawford, 2011), foxtail and broomcorn millet and especially rice were the main staples (Nakazawa, 2017; Nasu and Momohara, 2016; Shitara, 2019). Rice was not only pivotal in food production and population growth, but also played a substantial role in ritual practices, social stratification, concentration of political power, and the formation of the early Japanese state (Hosoya, 2009; Leipe et al., 2020b; Terasawa, 2000).

It is widely accepted that the changes in culture and economy during the Yayoi period were mainly associated with immigrants from the Asian mainland mixing with the local Jomon populations (Mizoguchi, 2013), a concept that is also inherent in Hanihara's influential dual structure model (Hanihara, 1991) introduced some 30 years ago. Evidence for this theory is found in the record of Yayoi cultural objects (e.g. Hudson, 1999), as well as human genomics. East Asian human genetic studies have notably increased in number over the last few years, showing that a significant portion of the genetics of modern Japanese is derived from continental East Asia (e.g. Kanzawa-Kiriyama et al., 2017; Shinoda et al., 2019; Watanabe et al., 2019). However, debates persist about different aspects of these demographic changes during the Jomon–Yayoi transition, such as the quantitative extent of immigration and whether it was large-scale (Lee and Hasegawa, 2011; Matsumura, 2001; Steinhaus and Kaner, 2016) or small-scale (Shitara, 2000; Tanaka, 2014).

Adding to the debates over an economic transition, archaeologists disagree over what constitutes the Yayoi culture. The concept of an early (10th–9th centuries BCE) Yayoi culture beginning is presented in opposition to that of a late (7th century BCE) onset (Kuwabara, 2015). Since its proposal by Sahara (1975), the main defining hallmark of this rather arbitrary divide has been the presence or absence of agriculture (Fujio, 2017). The Yayoi realm comprising the islands of Kyushu, Shikoku, and Honshu is characterized by spatio-cultural complexity often divided into several subregions (Fujio, 2017; Shitara, 2014). The most acknowledged subdivision separates the area into two main cultural zones. A core zone in western Japan, stretching from Kyushu Island to the Kinki region, and a peripheral zone in eastern Japan, stretching from the regions of Tokai-Hokuriku to northern Tohoku (Fig. 1b) (Barnes, 2015; Hosoya, 2009; Mizoguchi, 2013). The core zone exhibits early evidence for typical Yayoi cultural traits, such as substantial population growth, ritual practices related to bronze objects, social hierarchy, and the emergence of regional authorities and large settlement centres (Barnes, 2007; Mizoguchi, 2013; Steinhaus and Kaner, 2016), while eastern Japan reveals a general delay in Yayoi culture development including the spread of rice and millet cultivation (Tsude, 2001).

Previous studies have shown that in different parts of the world the spread of crops and agriculture is a complex process often marked by spatio-temporal discontinuity (Bocquet-Appel et al., 2012; Leipe et al., 2019; Long et al., 2018). A well-studied case in which crops and an agricultural lifestyle were introduced to an island region is that of Britain and Ireland. Like its dispersal from the Asian mainland to Japan agriculture spread to Britain and Ireland relatively late, i.e. about one millennium after it had arrived in the central European loess regions (Bocquet-Appel et al., 2012). Modelling the spread of farming shows that it was non-progressive and that it partly appeared in far northern regions, such as Northwest Scotland before it arrived in agriculturally more suitable regions such as South Scotland (Whittle et al., 2015).

Regarding Japan, the current understanding is that early rice agriculture first appeared in northern Kushu during the 9th century BCE, most probably introduced by immigrants from the Korean Peninsula (Miyamoto, 2019). From there, rice cultivation spread quickly across western Japan up to the western boundary of the Tokai-Hokuriku region (Kanaseki and Sahara, 1978; Tsude, 2001) by the 7th (Fujio, 2017) or 5th century BCE (Miyamoto, 2019). Then it continuously spread across eastern Japan (Barnes, 2015; Nasu and Momohara, 2016) and arrived in central Honshu between 850 and 350 BCE (Uchiyama, 2018) and in northern Tohoku sometime between 450 and 200 BCE (Kobayashi, 2017; Kunikita, 2012). This perception about the spatio-temporal spread of rice across Japan is based on a combination of evidence, including seed impressions on pottery, carbonized seed assemblages, rice-type phytolith data, cereal pollen records, rice paddy field remains and specific farming tools, such as reaping knifes (Nakayama, 2010). Most of these proxies are not assigned to absolute ages, but often rely on associated pottery types. In addition, reconstruction of a chronological framework for the spread of rice cultivation is hampered by a plateau in the calibration curve (Barnes, 2015) between ca. 700 and 400 BCE (Reimer et al., 2013).

Less discussed are the driving forces that motivated migration to the Japanese Archipelago. Miyamoto (2019) relates this migration to increasing population on the Korean Peninsula and a phase of cooler, unfavourable climate conditions between 850 and 700 BCE, inferred from changes in atmospheric radiocarbon (^{14}C) concentration (Imamura and Fujio, 2009). Another climate-induced scenario is discussed by Hashino (2016), who suggests that immigration was caused by cooler climate around 730 BCE and a warmer climate causing increased flooding on the southern Korean Peninsula around 670 BCE. On the side, Aikens (2018) argued that it was population pressure that, by at least 400 BCE, brought a growing number of Korean immigrants to Kyushu.

Here we examine when and why rice cultivation arrived in Japan and how it spread across the region. The study is based on a set of 179 ^{14}C dates directly derived from carbonized rice from South Korea and eastern Japan, including both new and previously published dates. The constructed Bayesian model consists of six submodels representing South Korea and five geographical regions in eastern Japan (Fig. 1). The results are correlated with available data on population estimates and discussed in the context of prehistoric developments in the continental regions of the Korean Peninsula and China. Jomon and Yayoi cultural chronologies are given according to Matsumoto et al. (2017) and Steinhaus and Kaner (2016), respectively.

2. Data and methods

2.1. Bayesian modelling

A set of 179 rice-based ^{14}C dates from cultural layers of archaeological sites in eastern Japan and South Korea was collected from available publications or obtained in the current study (Supplementary Information S1). Considering the size of the country, the number of rice-based dates from South Korea ($n = 13$) is relatively small compared to that of eastern Japan ($n = 166$). The main source of ^{14}C dates from eastern Japan is the online Rekihaku Database of Radiocarbon Dates Published in Japanese Archaeological Research Reports provided by the National Museum of Japanese History (https://www.rekihaku.ac.jp). This database represents the most comprehensive compilation of ^{14}C dates of Japanese archaeological objects, currently containing 28,560 entries. For this database, collection of ^{14}C dates from reports on archaeological sites in eastern Japan was completed in 2018, while work on site reports from western Japan will continue over the next years. To avoid potential bias by the incomplete ^{14}C dataset available for western Japan, this study concentrates exclusively on the region of eastern Japan (Fig. 1b). For discussion of the appearance of rice in western Japan, we refer to the calibrated ages of a set of rice-based ^{14}C dates (Supplementary Information S1) from cultural layers of the Ukikunden shell mound site (Karatsu City) in northern Kyushu (Fig. 1b) associated with the Initial Yayoi period, Yusu I pottery type

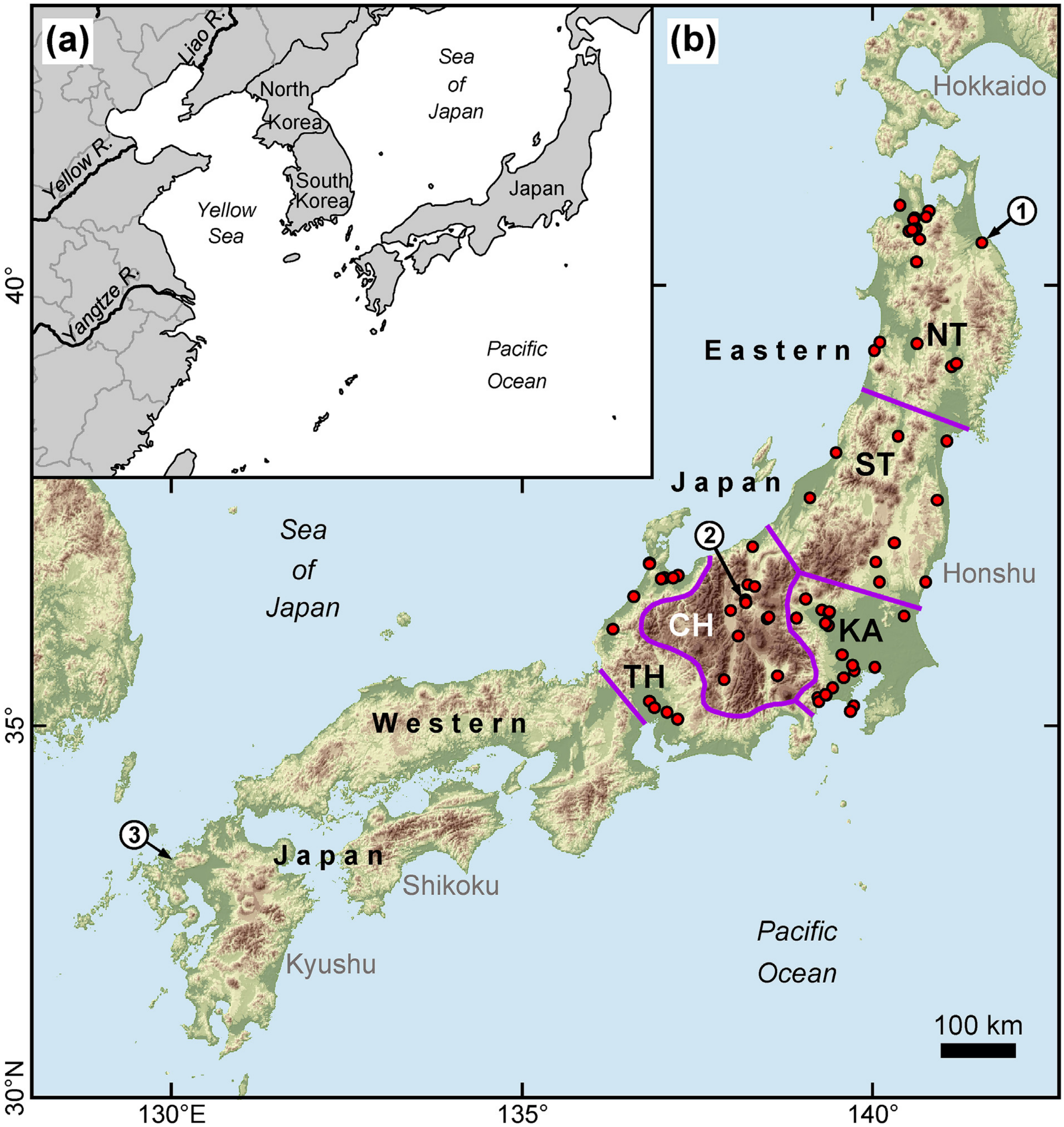

Fig. 1. Map compilation showing (a) the wider study region and (b) the regions of western Japan, comprising Kyushu, Shikoku and western Honshu, and eastern Japan. Location of the directly ^{14}C-dated rice remains from eastern Japan ($n = 166$) and South Korea ($n = 13$) contained in the compiled dataset (Supplementary Information S1) used for Bayesian modelling is indicated by red dots. Purple lines in (b) delineate the defined sub-regions of eastern Japan (excluding Hokkaido) representing the sub-models used for Bayesian modelling including northern Tohoku (NT), southern Tohoku (ST), Kanto (KA), the Central Highlands (CH) and Tokai-Hokuriku (TH). Encircled numbers show location of archaeological sites mentioned in the text including 1 – Kazahari (Hachinohe City, Aomori Prefecture), 2 – Chikaraishijori (Chikuma City, Nagano Prefecture), 3 – Ukikunden (Karatsu City, Saga Prefecture). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(Miyamoto, 2018). This pottery type is associated with the earliest immigrants from the Korean Peninsula, who arrived in Japan and settled on the Karatsu alluvial plains, and the directly dated grains from Ukikunden are so far the oldest rice remains from western Japan (Miyamoto, 2019).

Following the approach described by Long et al. (2018), the employed Bayesian model (Supplementary Information S2) uses the overlapping multiphase model for the overall structure and the phase model as a building block (i.e. submodel) implemented in OxCal v4.3.2 (Bronk Ramsey, 1995). The compiled dataset was organized into six geographical regions, including South Korea and the Tokai-Hokuriku, Central Highlands, Kanto, Southern Tohoku, and northern Tohoku, all in Japan (see Supplementary Information S3 for details on the definition of regions). Each region is defined as a submodel, which conceptually represents the archaeological phase during which rice appeared in the respective region, and the lower boundary of that modelled phase was adopted as its age estimate. Following Long et al. (2017), the critical limit for ^{14}C measurement errors was set to ±200 years. Outliers were detected on the basis of the OxCal agreement index calculation. The modelled ages are presented as both 95% and 68% probability ranges and median (point estimate). The reported ^{14}C dates of four carbonized rice grains from northern Kyushu (Miyamoto, 2018), as well as all other ^{14}C dates mentioned in the discussion section, were calibrated to calendar ages using OxCal v4.2.3 and the IntCal13 curve (Reimer et al., 2013).

2.2. Estimation of population development

To estimate population developments in Japan, South Korea, and China we used different published datasets. For Japan we reassessed population estimates by Koyama (1984) representative for the islands of Kyushu, Shikoku, and Honshu. We summed absolute population estimates given for nine regions (Kyushu, Chugoku, Shikoku, Kinki, Tokai, Chubu, Hokuriku, Kanto, and Tohoku) and calculated population numbers per century for each cultural period (Initial, Early, Middle, Late and Final Jomon, and Yayoi) for which we adopted the chronology given in Matsumoto et al. (2017). Since Koyama's (1984) publication, the accepted chronology of the Yayoi culture has changed substantially. In the early 1980s, the onset of the Yayoi period was dated to around 500 BCE, but has been shifted back based on accumulating insights from ^{14}C dating (Shoda, 2007). Although the timing of this event still remains controversial, most archaeologists date it to the 10th (Barnes, 2015; Steinhaus and Kaner, 2016), 9th (Miyamoto, 2018), or 9th/8th (Shoda, 2010) centuries BCE. As the transition between the Final Jomon and Yayoi periods, we use the midpoint (600 BCE), determined by the median calibrated age of the oldest rice grain (ca. 850 BCE) from western Japan (Miyamoto, 2018), and the end, determined by the arrival of rice in Tohoku (ca. 350 BCE) (Kobayashi, 2017; Kunikita, 2012), of the interval during which the Yayoi culture (i.e. rice cultivation) established across Kyushu, Shikoku, and Honshu. Taking into account the long-term spread of the Yayoi culture, we assume a linear population growth that started at 850 BCE (in western Japan) and reached a maximum around the BCE/CE boundary (Middle Yayoi period, 4th century BCE−1st century CE).

For China we used archaeological site data extracted from a database (Hosner et al., 2016) available from the open access data repository PANGAEA (https://pangaea.de/10.1594/PANGAEA.860072). The original database contains a total of 51,432 archaeological sites from the Early Neolithic to the early Iron Age (ca. 8000−500 BCE) published in the series Atlas of Chinese Cultural Relics and covers 25 Chinese provinces, autonomous regions, and municipalities. The virtues and shortcomings of the data, as well as quality tests, are presented and discussed in the original publications (Hosner et al., 2016; Wagner et al., 2013). To track spatiotemporal differences in archaeological site numbers, we divided the study region into three subunits, namely north-central, northeastern, and southern China. Following Leipe et al. (2019), the set of 40,696 sites representing 13 northern Chinese provinces, including Beijing, Gansu, Hebei, Henan, Inner Mongolia Autonomous Region, Jilin, Liaoning, Ningxia Hui Autonomous Region, Qinghai, Shaanxi, Shandong, Shanxi, and Tianjin (ca. 32°N to 51°N, 90°E to 131°E) was divided along 115°E forming the regions of north-central and north-eastern China, comprising 20,431 and 20,265 sites, respectively. The southern China subset consists of 10,319 sites representing 10 southern Chinese provinces including Anhui, Chongqing, Fujian, Guangdong, Hubei, Hunan, Jiangsu, Sichuan, Yunnan, and Zhejiang (ca. 20°N to 32°N, 98°E to 122°E). Each archaeological site contained in the subsets is assigned to one or more cultural periods, thus representing different time ranges (Hosner et al., 2016). To eliminate the influence of the length of the defined cultural periods (i.e. to temporally normalize the site data), the site numbers per region are presented here by time intervals of equal length, which we randomly set to 100 years.

To compare population changes and trends in different parts of the macro-region (Fig. 1) across four representative time slices (1750, 1400, 1100, and 650 BCE), we employed three different datasets. For the nine Japanese regions, population estimates were normalized by time interval (100 years) and area of the respective region (Supplementary Information S3). For the time slice 650 BCE, we took into account the spread of the Yayoi culture across western Japan, which is regarded to have been completed by the 5th century BCE (Miyamoto, 2019). Consequently, we assigned Yayoi period population estimates to the regions of western Japan and Final Jomon values to the regions of eastern Japan. The Yayoi population numbers for western Japan, for this time slice, were calculated assuming a linear growth from the Final Jomon to maximum Yayoi values between 850 BCE and the BCE/CE boundary. For South Korea we employed the stacked probability densities of ^{14}C dates (Oh et al., 2017) for each time slice. These dates were derived from objects collected from Chulmun and Mumun culture pit houses in South Korea. For China, archaeological site numbers were summarized by province or defined region and also normalized by time (100 years) and respective province/region area (Supplementary Information S3). For the time slice 1400 BCE, archaeological site data for Fujian is only available for the eastern part of the province, and for the time slice 650 BCE, data is only available for the western part. Thus, areal normalization was done using the respective surface size calculated for the two province parts (Supplementary Information S3) using ArcGIS Desktop v10.2 (Environmental Systems Research Institute, 2013).

3. Results

3.1. Bayesian modelling and AMS ^{14}C dating

Due to its anomalously large uncertainty of ±280 years, date TO8605 from South Korea was removed from the dataset prior to modelling. Thus, a total of 166 and 12 dates were used in the chronological models for eastern Japan and the Korean Peninsula, respectively. According to the modelling results (Table 1, Fig. 2), rice arrived on the Korean Peninsula between ca. 1700 and 1200 BCE (68% probability range is shown here and in the following text,

Table 1
Modelled probability distribution and probabilistic median ages for the arrival of rice in South Korea and different geographical regions of eastern Japan (Fig. 1). Results for the Central Highlands marked by an asterisk show the derived outputs when the date of the oldest rice grain (IAAA-83092; Table 2) is removed from the model (Supplementary Information S2).

Region (submodel)	Calibrated 68% range, BCE/CE	Calibrated 95% range, BCE/CE	Calibrated median, BCE/CE
Korean Peninsula	−1696− −1187	−2289− −1018	−1475
Central Highlands	−1255− −967	−1425− −848	−1119
Central Highlands*	−882− −577	−1080− −475	−747
Kanto	−764− −340	−831− −340	−594
northern Tohoku	−425− −153	−628− −1	−289
Tokai-Hokuriku	−340− −170	−475− −170	−272
southern Tohoku	−204−51	−340−170	−86

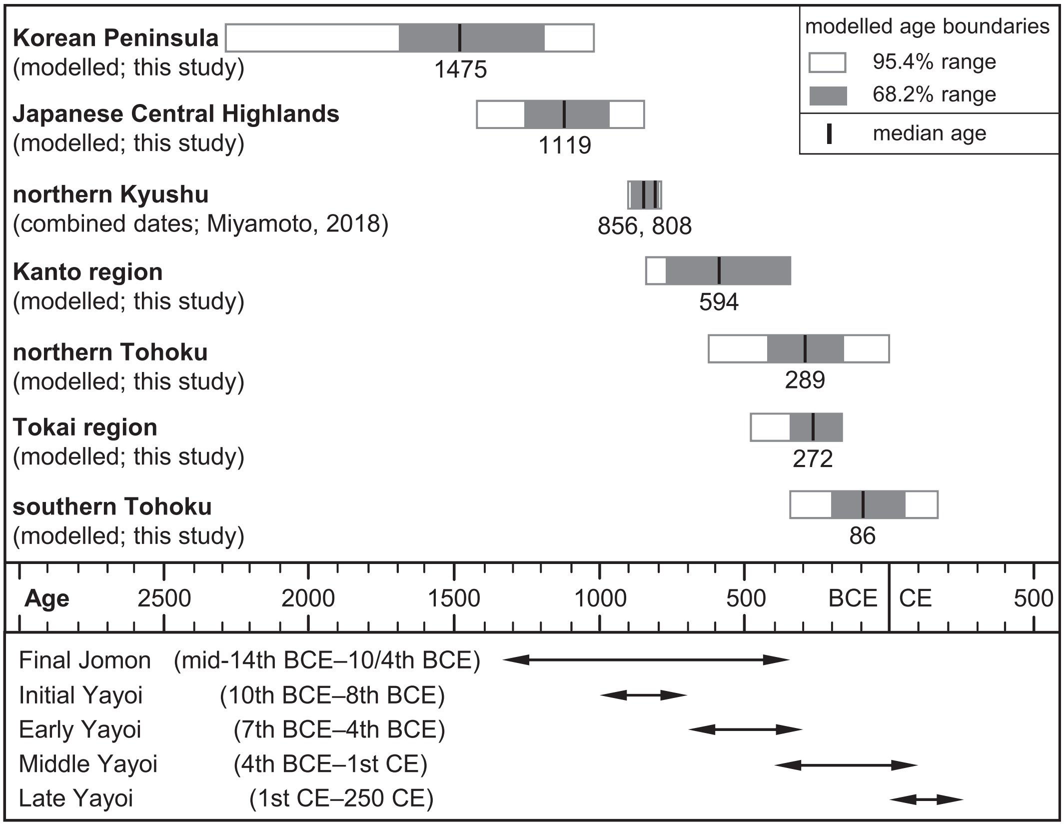

Fig. 2. The probability ranges and medians for the appearance of rice in the six modelled regions (this study) and the two oldest rice-based ^{14}C dates from the Ukikunden site in northern Kushu (Miyamoto, 2018). Numbers below the probability distributions illustrated as grey and white bars show the calibrated median ages BCE. Ranges of the Final Jomon period and Yayoi culture sub-stages in centuries are shown according to Matsumoto et al. (2017) and Steinhaus and Kaner (2016), respectively.

unless otherwise indicated), with a probabilistic median of ca. 1450 BCE. Regarding eastern Japan, the earliest appearance of rice is estimated to have occurred in the Central Highlands, between ca. 1250 and 950 BCE. With 1100 BCE, the calibrated median age of this modelled subphase is close to the one (1070 BCE) of the so far oldest directly dated rice grain from Japan (Lab ID: IAAA-83092; Table 2), which is part of a set of ^{14}C dates on rice from the Chikaraishijori site (north-eastern Nagano Prefecture, Fig. 1b). This set (Table 2) of existing (Nagano Prefecture Buried Cultural Heritage Center, 2011) and newly (this study) derived ^{14}C dates demonstrate long-term use of rice at the site. For the Kanto region the model suggests that rice appeared in the early 6th century BCE (median calibrated age 594 BCE); although, it gives a comparatively large probability range for this timing stretching between ca. 760 and 340 BCE. From around the same time rice existed in northern Tohoku (ca. 400–150 BCE) and the Tokai-Hokuriku region (ca. 350–150 BCE) with median ages (289 and 272 BCE, respectively) dating to the beginning of the 3rd century BCE. The latest appearance of rice is suggested for southern Tohoku, between ca. 200 BCE and 50 CE, with a probabilistic median of ca. 100 BCE, thus ca. 200 years after its arrival to northern Tohoku and Tokai-Hokuriku, if we use the calibrated median ages.

Table 2
AMS^{14}C dates and calibrated age ranges and median ages of 13 carbonized rice (*Oryza sativa*) seeds from infills of eight different earth pits at the Chikaraishijori site, northern Nagano Prefecture (Fig. 1b). OxCal v4.3.2 (Bronk Ramsey, 1995) and the calibration curve Intcal13 (Reimer et al., 2013) were used for conversion to calendar ages.

Lab ID	Conventional age, ^{14}C BP	Calibrated 68% range, BCE	Calibrated 95% range, BCE	Calibrated median, BCE	Earth pit ID	Reference
IAAA-83092	2889 ± 29	1113–1022	1194–980	1070	SK1405	Nagano Prefecture Buried Cultural Heritage Center (2011)
IAAA-83082	2494 ± 29	762–550	781–517	636	SK138	Nagano Prefecture Buried Cultural Heritage Center (2011)
IAAA-83090	2480 ± 27	756–542	772–490	636	SK1387	Nagano Prefecture Buried Cultural Heritage Center (2011)
IAAA-83091	2481 ± 30	757–542	775–435	634	SK1393	Nagano Prefecture Buried Cultural Heritage Center (2011)
Poz-115,541	2420 ± 30	536–411	748–402	496	SK138	this study
IAAA-83084	2385 ± 27	486–402	703–396	455	SK210	Nagano Prefecture Buried Cultural Heritage Center (2011)
Poz-115,543	2370 ± 30	482–397	540–388	444	SK1405	this study
IAAA-83085	2359 ± 28	475–392	516–383	418	SK1292	Nagano Prefecture Buried Cultural Heritage Center (2011)
IAAA-83089	2356 ± 26	453–390	510–384	408	SK1303	Nagano Prefecture Buried Cultural Heritage Center (2011)
IAAA-83086	2354 ± 29	473–388	515–380	411	SK1293	Nagano Prefecture Buried Cultural Heritage Center (2011)
MTC-10949	2320 ± 40	413–262	511–214	390	SK115	Nagano Prefecture Buried Cultural Heritage Center (2011)
MTC-10948	2300 ± 35	404–361	411–211	378	SK115	Nagano Prefecture Buried Cultural Heritage Center (2011)
Poz-115,542	2190 ± 30	356–199	361–178	287	SK1405	this study

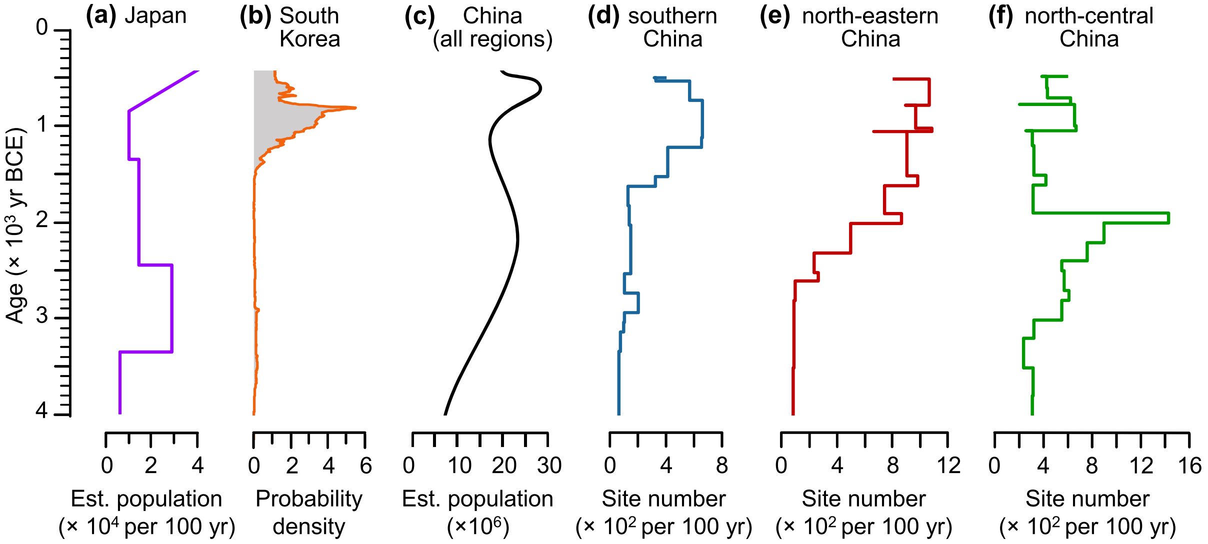

Fig. 3. Chart compilation showing (a) estimated total population per century for the Japanese regions of Kyushu, Shikoku and Honshu for the Early to Final Jomon and Yayoi cultural periods (Koyama, 1984; this study); (b) stacked probability density distribution of available ^{14}C dates from Chulmun (8000–1500 BCE) and Mumun (1500–300 BCE) culture pit houses in South Korea (Oh et al., 2017) using the Sum function in OxCal v4.3.2; (c) estimated total population for the area of China (Biraben, 2003); and archaeological site numbers (Hosner et al., 2016) per century for (d) southern, (e) north-eastern and (f) north-central China between 4000 and 500 BCE.

3.2. Population development

The datasets used to infer population changes suggest different developments in Japan and China between 4000 and 500 BCE (Fig. 3). Re-assessment of the population estimates done for the Japanese Islands of Kyushu, Shikoku, and Honshu (Supplementary Information S4) show that numbers increased from ca. 6200 individuals per century during the Early Jomon period to 29,000 individuals per century during the Middle Jomon period (Fig. 3a). During the Late and Final Jomon periods population declined to 14,600 and 10,100 individuals, respectively. A comparatively strong and unprecedented re-increase is derived for the Yayoi period, with a population number of 41,800 per century.

For southern China (Fig. 3d) the dataset demonstrates a long period of weakly increasing archaeological site numbers between 4000 and 1650 BCE. This is followed by a steep increase in site numbers that ranged on a maximum level (i.e. around 650) between 1250 and 750 BCE before they declined to 400 before 500 BCE. North-eastern China (Fig. 3e) experienced a generally continuous increase in site numbers that accelerated from 90 sites in the middle of the 3rd millennium BCE to 1060 sites before 550 BCE. In contrast to the north-central part, sites in north-eastern China did not sharply drop at about 2000 BCE, but growth was interrupted by only a weak reversal between 1950 and 1650 BCE. For north-central China (Fig. 3f) the site number curve rises up to 1430 sites per century until 2000 BCE, suggesting exponential population growth. This peak is followed by a sharp and quick drop to around 300 sites per century, a level which persisted for almost one millennium. At 1050 BCE site numbers re-increased to 650 and remained more or less stable until 700 BCE when sites decreased again to 430 by 500 BCE.

Based on the observed changes in estimated population in Japan (Fig. 3a) and South Korea (Oh et al., 2017, Fig. 3b) and in archaeological site numbers from China (Fig. 3d–f), we have selected four characteristic time slices: 1750 BCE, representing the middle of the Late Jomon period, the Late Chulmun period, and the end of the Xia dynasty; 1400 BCE, representing the end of the Late Jomon period, the beginning of the Mumun period, and the beginning of the middle Shang dynasty; 1100 BCE, representing the Final Jomon period, the Early Mumun period, and the transition from the Shang to the Western Zhou dynasty; and 650 BCE, as the Final Jomon/Yayoi periods, the Middle Mumun period and the Middle Chunqiu (Spring and Autumn) period in China. To facilitate identification and comparison of the spatio-temporal changes between the time slices, the results for each region are shown on a map (Fig. 4) and discussed in the following section.

4. Discussion

4.1. The arrival of rice in Japan

Archaeobotanical data demonstrate that rice dispersed into the islands and was the dominant crop in most regions during the Yayoi period. One reason for this preference may be the high productivity of wet field rice with two to three times higher yields than most other cereals (Fuller et al., 2016). Even rainfed rice appears to have at least slightly higher yields than millet crops (Qin and Fuller, 2019). Our model suggests that rice first dispersed into the Central Highlands. The 68% confidence interval 1250–950 BCE with a calibrated median age of 1100 BCE dating to the Final Jomon period (1350–10th/4th century BCE) are mainly determined by the oldest rice date in our dataset, which comes from Chikaraishijori in north-eastern Nagano Prefecture. Cultural remains from multiple periods (Middle Jomon–Medieval time) have been excavated, but most of them date to the late Early and Middle Yayoi periods (Nagano Prefecture Buried Cultural Heritage Center, 2011). A cluster of 56 earth pits with diameters of 1.0–1.5 m and depths of 0.5–0.7 m was documented at the southern end of the surveyed section and identified as burial sites. Flotation on sediment infills of 45 of these burial pits revealed carbonized seeds of oak (*Quercus serrata*), walnut (*Juglans*), cherry (*Prunus*), and rice. The oldest rice grain is contained in a set of 13 dated specimens (Table 2), originating from eight different pits. Three of these pits contained remains of human bones. Further documented features comprise gravel beds and artefacts, such as stone tools (e.g. obsidian blades), bone fragments and teeth of humans and animals (deer and boar), clay figurines, mortar-shaped jasper beads, red pigment, and earthenware. The time range represented by the dated rice grains with calibrated

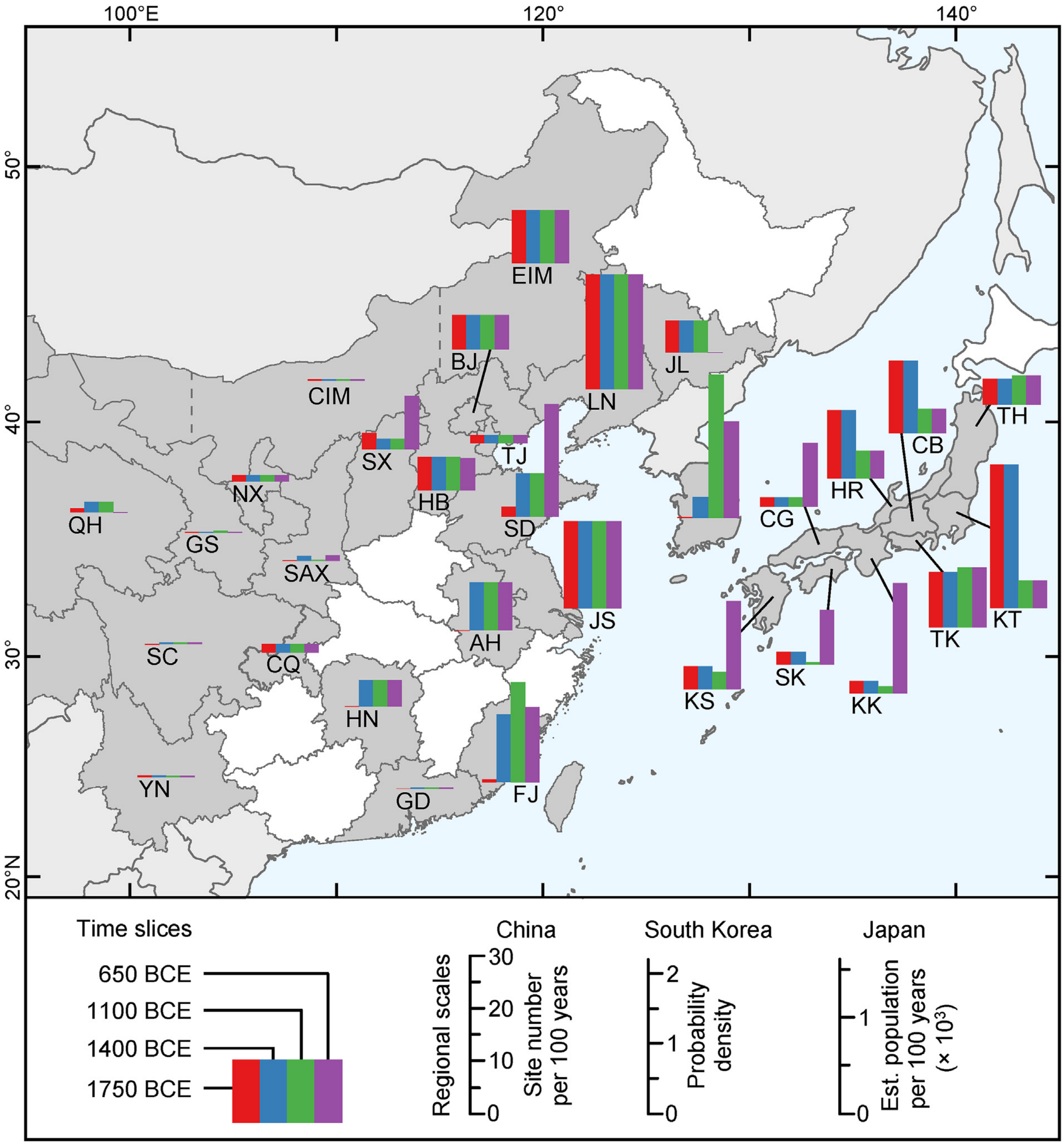

Fig. 4. Population development across four representative time slices for different regions (dark grey fill colour) inferred for 21 Chinese provinces and regions (Anhui - AH, Beijing - BJ, Central Inner Mongolia - CIM, Chongqing - CQ, Eastern Inner Mongolia - EIM, Fujian - FJ, Gansu - GS, Guangdong - GD, Hebei - HB, Hunan - HN, Jiangsu - JS, Jilin - JL, Liaoning - LN, Qinghai - QH, Ningxia - NX, Shaanxi - SAX, Shandong - SD, Shanxi - SX, Sichuan - SC, Tianjin - TJ, Yunnan - YN) from site numbers (Hosner et al., 2016) normalized by time and area, for South Korea from probability density of available ^{14}C dates (Oh et al., 2017) and for nine regions in Japan (Kyushu - KS, Chugoku - CG, Shikoku - SK, Kinki - KK, Tokai - TK, Chubu - CB, Hokuriku - HR, Kanto - KT, Tohoku - TH) from estimated total population per century (Koyama, 1984). Chinese provinces and Japanese regions for which no data is available are filled with white colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

median ages spanning between 1070 and 290 BCE (Table 2) corroborates that the site has been used for a long time, which is often the case for sacred places. The burial ground lies on the alluvial plain of the Chikuma River at the foot of a mountain that stands out against the surrounding landscape by its distinct conical shape and relatively steep slopes that rise up for ca. 400 m (see Supplementary Information S5 for details). It appears that the rice was used as an exotic prestige good, as it was recovered in a ritual mortuary context that involved cremation and placing the burned human bones and teeth in urns or directly into burial pits. Such mortuary practices first appeared in the Central Highlands during the Middle Jomon period and continued into the Yayoi period (Shitara, 2004).

Since the date (IAAA-83092) of the oldest rice grain plays a crucial role in the applied model and the discussion of the earliest rice in Japan, it deserves a more detailed description. It must be noted that the identity of this oldest rice grain cannot be verified, as photographic documentation or confirmation by the investigator of the archaeobotanical assemblages are unavailable (Nagano Prefecture Buried Cultural Heritage Center, 2011; pers. comm. with K. Nishiyama, Nagano Prefectural Museum of History, in charge of the Chikaraishijori site collections). Another concern relating to the identity of the dated rice from earth pit SK1405 is the temporal gap of its calibrated age (68% probability range) and that of the next oldest rice grain from pit SK138, which accounts for at least 260 years (Table 2). On the other hand, the calibrated ages of the reported rice grain from SK138 together with those of two other grains from SK1387 and SK1393 (Table 2) cluster around 760–540 BCE (68% probability range) and thus also substantially predate the onset of wet field rice cultivation in the Central Highlands in the 2nd century BCE (Fujio, 2017). Removing date IAAA-83092 from the model shifts the earliest likely rice appearance in the Central Highlands to younger ages, i.e. 1080–475 BCE (95% probability range), 882–577 BCE (68% probability range), and 747 BCE (median age), but does not change the reconstructed order of appearance and spread of rice in eastern Japan (Fig. 2, Table 1). Additional archaeobotanical studies combined with direct ^{14}C dating are needed to either confirm or refute the use of rice in the Central Highlands as early as suggested by the single date IAAA-83092.

One possible scenario that may explain the early appearance of rice in the Central Highlands as suggested by our model is that the local Final Jomon populations had long-distant contacts with rice farmers on the Korean Peninsula or to late Final Jomon groups in western Japan and either obtained rice by exchange or grew it locally. Impressions of millet (Endo, 2012) on Fusenmon pottery (Final Jomon) and a single rice grain (Nakazawa, 2012) on a sherd, identified as either Fusenmon or Tottaimon pottery (Initial Yayoi) from the southern Central Highlands (southern Nagano Prefecture), indicate early use of these crops in the region. This evidence also provides a link to the rice seed impressions on Tottaimon sherds associated with late Final Jomon groups from western Japan (Nakazawa and Ushino, 2009; Nasu and Momohara, 2016) and the pot sherds with features of Late Jomon pottery types recorded at Chikaraishijori (Nagano Prefecture Buried Cultural Heritage Center, 2011). However, artefacts that indicate a connection to populations on the Korean Peninsula have not been found at Chikaraishijori (Nagano Prefecture Buried Cultural Heritage Center, 2011).

The suggested early appearance of rice in the Central Highlands would partly support the hypothesis of Akazawa (1986) that the Jomon populations of inland regions were more receptive to agricultural innovations than their counterparts settling in coastal regions. This idea relies on evidence for enhanced collection of wild plants and plant cultivation (Akazawa, 1986) by Jomon population in inland regions possibly related to scarcity of other food resources, which has been substantiated by other recent studies in the region (Aida et al., 2012; Nakayama, 2015, 2019; Nasu et al., 2015). However, we suggest that, if grown locally, rice was predominantly used for ritual practices. The archaeobotanical record from the region, which documents early agricultural practices some centuries later, during the late Early Yayoi period (7th–4th century BCE), shows that they were dominated by broomcorn and foxtail millet cultivation with minor finds of rice that became more abundant only during the Middle Yayoi period (Baba and Endo, 2017; Endo, 2015; Endo and Takase, 2011). Additionally, a recent archaeobotanical study of Middle Yayoi hearth deposits at the Maenakanishi site has identified rice as an important element in empowering feasting practices probably related to ancestor worship (Leipe et al., 2020b). The site is located in north-western Kanto and believed to have been strongly influenced by immigrants from the north-eastern Central Highlands during the Middle Yayoi period.

Another interpretation is that the appearance of rice at Chikaraishijori is linked to early agriculturalists from the Korean Peninsula, who migrated to the area in search for fertile, scarcely occupied land. Although most scholars believe that the first immigrating farmers arrived in northern Kyushu (Miyamoto, 2019), it seems plausible that groups may have explored more remote regions with lower population densities away from the coasts, but still suitable for rice cultivation. The Final Jomon people at Chikaraishijori may have interacted with these newcomers from whom they may have obtained the rice used for mortuary practices in exchange with other goods. The immigrants may have not persisted over long periods and may have been eliminated or assimilated by local non-agrarian populations.

After rice first appeared in the Central Highlands of central Honshu, it dispersed to northern Kyushu, a region that is located much closer to the Korean Peninsula and believed to be the place from which rice cultivation spread across Japan. According to the oldest existing direct dates from western Japan (Miyamoto, 2018), rice appeared in northern Kyushu in the middle of the 9th century BCE (calibrated median age of oldest date 856 BCE), and is associated with Initial Yayoi type (Yusu) pottery. Seed impressions on Tottaimon sherds from Shimane Prefecture (western Honshu) assigned to the late Final Jomon period have been proposed as the earliest evidence for the use of rice on the Japanese Archipelago (Nakazawa and Ushino, 2009; Nasu and Momohara, 2016). Though, this finding has not yet been verified with an absolute age determination. Next, rice dispersed to Kanto before it arrived in Tokai-Hokuriku, which is located closer to western Japan. A further spatially discontinuous dispersal of rice is suggested for the Tohoku region. Before the crop arrived in southern Tohoku, which is located closer to central Honshu and western Japan, it appeared in northern Tohoku. It is worth noting that northern Tohoku has been long recognized as having some of the oldest evidence for rice cultivation in the Japanese Islands. This is based on two ^{14}C-dated rice grains from Late Jomon cultural context at the Kazahari site in Aomori Prefecture (D'Andrea et al., 1995). Both uncalibrated ages (TO-4086: 2810 ± 270 ^{14}C BP; TO-2202: 2540 ± 240 ^{14}C BP) have substantial uncertainties, which translated into large calibrated age ranges (68% confidence intervals 1413–673 BCE and 972–384 BCE, respectively). However, additional dating of a rice grain from the same assemblage obtained more recently revealed the much younger date 173 ± 35 ^{14}C BP (TERRA-578#10) (Takase, 2011), suggesting contamination of the two earlier dates.

In sum, our results indicate a discontinuous spread of rice throughout the Yayoi cultural area (Kyushu, Shikoku, and Honshu regions), which does not correspond to the general opinion that the spread was relatively quick (Kaner and Yano, 2015; Uchiyama, 2018) and mostly continuously (Barnes, 2015; Nasu and Momohara, 2016). One factor to which the modelled pattern may have been related is the distribution and diversity of indigenous Final Jomon populations. The postulated continuous spread of rice cultivation across western Japan after its introduction to northern Kyushu in the early 1st millennium BCE was probably favoured by relatively low Jomon population densities (Koyama, 1984). In contrast to western Japan, the temperate deciduous forest zone in eastern Japan, which is environmentally more diverse and produces more wild food resources, promoted higher Jomon population numbers and cultural diversity (Koyama, 1978). An amalgamation of this regional Jomon diversity with cultural traits introduced from the Eurasian continent formed a heterogeneous 'Yayoi cultural landscape' (Ishikawa, 2017), which probably triggered the more complicated pattern of rice dispersal. While in inland regions, such as the Central Highlands, Final Jomon communities were probably more receptive to adoption or experimentation with new crops, other communities less involved with plant management or cultivation were probably less open to and not in need of this new strategy of food procurement, as shown for the subtropical forest region of south-eastern China (Fig. 5f), located next to the rice-growing communities of the Yangtze River Delta (Ma et al., 2016; Zhao et al., 2017).

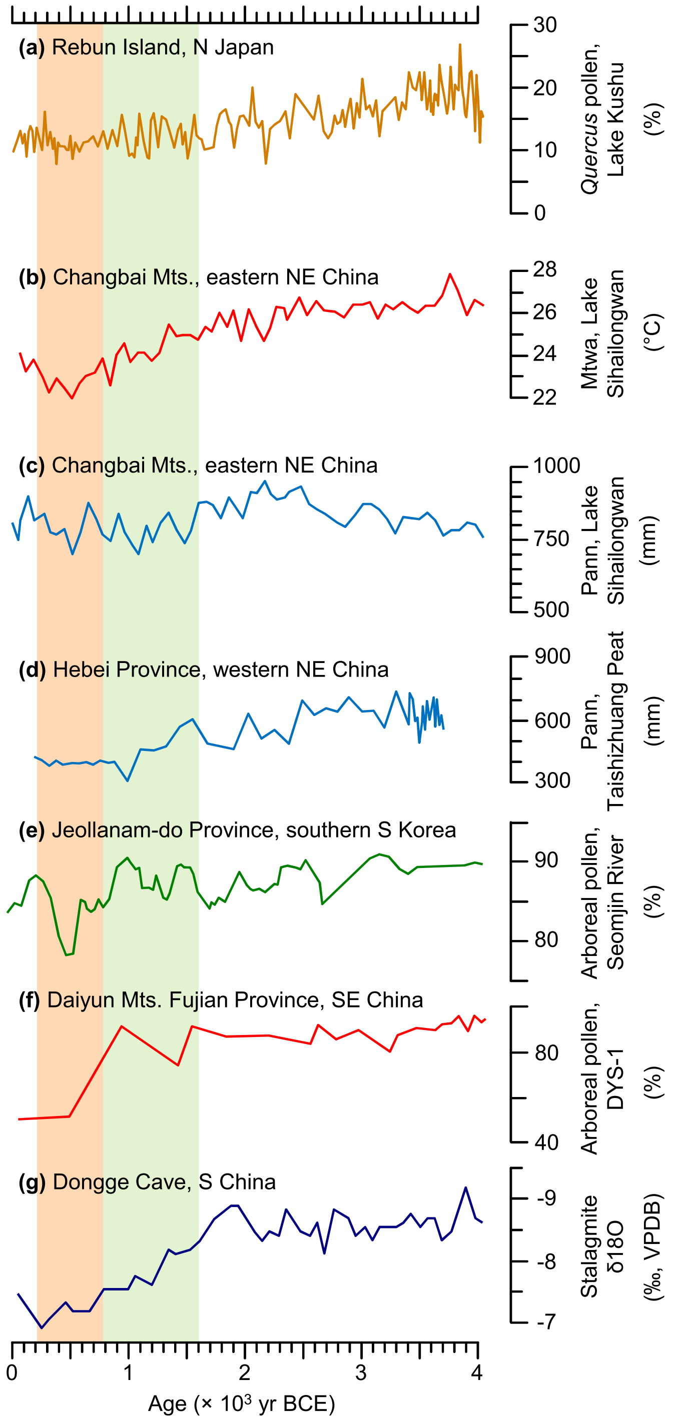

Fig. 5. Compilation of palaeoenvironmental records including (a) the *Quercus* pollen percentages of the RK12 pollen sequence from Lake Kushu (Rebun Island, northern Japan) as a proxy for changes in summer temperature (Leipe et al., 2018); (b) the pollen-based reconstructions of (b) the mean temperature of the warmest month (Mtwa) and (c) annual precipitation (Pann) from the Sihailongwan Maar Lake, Changbai Mountains, Jilin Province, north-eastern China (Stebich et al., 2015); (d) the pollen-based reconstructions of annual precipitation for the Taishizhuang Peat section in northern Hebei Province, north-eastern China (Tarasov et al., 2006); the arboreal pollen percentages of (e) a flood plain sediment sequence from the Seomjin River, southern South Korea (Park et al., 2019) and (f) the DYS-1 peat section from the Daiyun Mountains, Fujian Province, south-eastern China (Zhao et al., 2017); and (g) the stalagmite $\delta^{18}O$ record D4 from Dongge Cave, south China (Yuan et al., 2004). The two bands indicate a phase of relatively humid climate (light green) stretching from the flourishing of the Shang dynasty Erligang culture to the Western Zhou kingdom and a subsequent phase of drier climate conditions and growing anthropogenic pressure on the landscape (light orange) during the Eastern Zhou, including the Spring and Autumn and Warring State periods. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

However, the earliest rice associated with Final Jomon groups is, at least at Chikaraishijori, a rare ritual fixture, rather than a staple food, i.e. sign of a shift from a forager to an agricultural lifestyle. This might also apply to less well-dated reports of rice imprints on pottery assigned to late Jomon groups (Nasu and Momohara, 2016). The complex role of rice in the establishment of agriculture is also reflected in archaeobotanical records representing early agricultural stages. Broomcorn and foxtail millet were the first choice in different regions of eastern Japan (e.g. Tokai, Central Highlands, Kanto, and Niigata Prefecture), with rice becoming more relevant only in later periods with more developed agriculture and social organisation (Baba and Endo, 2017; Endo, 2015; Leipe et al., 2020a; Nakazawa, 2017; Takase, 2011). This 'delay' in (wet) rice cultivation was likely due to its higher demands that, compared to millets, involved higher degrees of labour organisation and input (Endo, 2016; Leipe et al., 2020a), highlighting that, within the Yayoi cultural domain, rice was not obligatory in the shift to agriculture. These findings emphasis the need to take also broomcorn and foxtail millet into account in the identification of an agricultural lifestyle, which has been the most relevant criterion in defining the 'Yayoi culture' (Fujio, 2017; Shitara, 2014).

4.2. The mechanisms behind the spread of rice farmers to Japan

A large body of archaeological evidence suggests that the immigrants, who essentially contributed to the emergence of the Yayoi culture, originated from the Korean Peninsula (Aikens, 2018; Mizoguchi, 2017). To identify and to discuss what caused and stimulated this migration, it is crucial to examine the preceding cultural developments on the Korean Peninsula and neighbouring regions. With an age range of ca. 1700–1200 BCE and a median age of ca. 1500 BCE, our model corroborates the proposed beginning of rice cultivation in South Korea. Although millet, along with azuki (*Vigna angularis*) and soybean (*Glycine max*), had been cultivated there much earlier, at least since the middle of the 4th millennium BCE (Leipe et al., 2019) as part of the mixed (foraging-farming) subsistence economy of Chulmun populations (Lee, 2017), full-scale agriculture did not develop until after the Neolithic/Bronze Age transition around 1500 BCE (Ahn and Hwang, 2015). The Early Mumun period (ca. 1500–800 BCE) is marked by the introduction and spread of other crops, especially rice along with wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*) (Lee, 2016). Although some scholars suggest that the Neolithic/Bronze Age transition was marked by cultural continuity, it is widely accepted that it was brought about by rapid immigration (Lee, 2017) that originated in the Liaodong Peninsula region of China (Ahn, 2010; Miyamoto, 2016). Indeed, the onset of Mumun, ca. 1500 BCE, coincides with the peak of the Shang dynasty (Erligang culture; ca. 1600–1400 BCE) in the middle Yellow River region, which Liu and Chen (2012) characterize as highly hierarchical, militarily organized, and aggressively procuring key resources in neighbouring areas by colonization and exchange of goods. The time slice analysis (Fig. 4) shows that between 1750 and 1400 BCE site numbers in Liaoning and neighbouring provinces were already at high levels and that only Shandong Province shows increase due to the establishment of Erligang regional centres like Daxinzhuang and Qianzhangda in modern Jinan and Tengzhou for grain and marine resources (Liu and Chen, 2012). In southern China this development started at 1600 BCE (Fig. 3d), but intensified with the keen interest of Erligang in copper and proto-porcelain (Liu and Chen, 2012). Also copper and lead mines in the Changbai Mountains were exploited for the

Erligang state (Liu and Chen, 2012). However, whether the above-mentioned immigrants on the Korean Peninsula were Erligang colonizers or the eastward expansion of Erligang kicked off a domino effect causing the inhabitants of the Liaodong Peninsula to move is a matter of future studies.

However, some archaeologists believe that intensification of crop production, including the spread of wet field rice cultivation (Kim, 2014), leading to full-scale agricultural societies and rapid population growth only occurred during the Middle Mumun period (800–400 BCE) (Ahn and Hwang, 2015; Lee, 2011). A scenario of population growth as a precondition for agricultural intensification is supported by the summed probability densities of available ^{14}C dates associated with Chulmun (8000–1500 BCE) and Mumun (1500–300 BCE) cultural layers in South Korea (Oh et al., 2017), showing a steep rise after 1500 BCE and a distinct peak at ca. 800 BCE (Fig. 3b). This suggested increase in population is mirrored by the distinct trough in arboreal pollen percentages recorded in a sedimentary succession located in the southern part of the Korean Peninsula, indicating a quick opening of forested landscapes (Park et al., 2019, Fig. 5e).

A series of political dynamics in China may have effected cultural changes, notably the eastward outreach of the Zhou kingdom from their domain in the Wei River region about 1045 BCE overthrowing the Shang state and setting up colonies in the East. For example, the state of Lu in modern Shandong Province and the state of Yan in the capital area of Beijing (Shaughnessy, 1999). When the homeland of the Zhou fell to agropastoral expansions from the west and north, the Zhou capital was relocated to Luoyang in the East at 771 BCE, and its central power weakened, but those local states grew into economically and militarily strong, administratively strictly regulated, and independent states (Shaughnessy, 1999). The intensified and extended contact of Yan with north-eastern non-Zhou neighbours is visible in many grave good assemblages at the Xiaoheishigou (Institute of Cultural Relics and Archaeology of the Autonomous Region Inner Mongolia, 2009) and Jundushan (Beijing City Institute of Cultural Relics, 2007) archaeological sites (von Falkenhausen, 2006). In the south, the states of Chu, Wu, and Yue, from the middle to the lower Yangtze River, were among the most expansive (Vogelsang, 2013) and fiercely fighting for regional hegemony (Hsu, 1999). Both closely related phenomena, an unprecedented rise of productivity in all economic spheres and centuries-old policies of territorial expansion, could have stimulated parts of the population to move from rice-growing areas colonizing overseas lands that were already known at that time. The estimated agricultural population increase in Japan (Fig. 3a) might be evidence of this process.

Although socioeconomic and political factors probably played the most important role in the propagation of agriculture to the Japanese Islands, a possible climate impact should not be left without further considerations. In his model, Miyamoto (2016) describes the migrations of rice farmers to the Korean Peninsula and Japan as a two-stage process, driven by population pressure in combination with climatic deterioration. High-resolution, well-dated palaeoenvironmental records from Hokkaido Prefecture in northern Japan (Leipe et al., 2018, Fig. 5a), the Changbai Mountains in north-eastern China (Stebich et al., 2015, Fig. 5b and c), and the South China Karst (Yuan et al., 2004, Fig. 5g) demonstrate a continuous long-term decline in temperature and atmospheric precipitation in the monsoon-dominated region of East Asia starting ca. 4000 years ago. None of the records indicate noticeable decadal- to centennial-scale climate oscillations during the 2nd and 1st millennia BCE. In the Changbai Mountains located closer to the Pacific coast, precipitation fluctuated slightly, but did not drop below modern values (Stebich et al., 2015). Although having less robust chronologies, pollen assemblages of two recently studied sediment sequences from the southern (Park et al., 2019) and eastern (Song et al., 2018) coast of the Korean Peninsula also do not reveal cooling phases, but corroborate a more or less steady long-term trend towards modern climatic conditions since the middle Holocene. In addition, the percentage curve of arboreal pollen from the sedimentary succession in the southern part of the peninsula indicates enhanced human activities after 1000 BCE (Park et al., 2019, Fig. 5e). Under the generally wet conditions at the southern end of the Korean Peninsula, which promoted forest-dominated natural vegetation throughout the Holocene, the observed decline in tree cover after 1000 BCE is most likely related to human-induced deforestation. This may reflect increased population density and expansion of agricultural land. The same causal relationship is depicted in the DYS-1 arboreal pollen percentage curve from Fujian Province in coastal southern China (Zhao et al., 2017, Fig. 5f). Under humid climatic conditions the drop in the percentages cannot be explained other than by increased human impact on the forest vegetation probably due to increasing agricultural population density.

The pollen record from the Taishizhuang site (Tarasov et al., 2006), located in the semiarid zone northwest of Beijing near the present-day limit of the summer monsoon, however, demonstrates more distinct changes in vegetation and climate during the time interval in focus. The pollen-based reconstruction indicates that the landscape around Taishizhuang became more open and more like a steppe biome than a temperate deciduous forest, except for two oscillations dated to about 2000 BCE and 1500 BCE. Arboreal pollen almost disappeared from the pollen spectra between ca. 1450 and 150 BCE, and the pollen-based reconstruction (Tarasov et al., 2006) shows a decrease in precipitation to below present-day values after ca. 1100 BCE, with the most pronounced drop (ca. 120 mm below the modern average) around 900 BCE (Fig. 5d). These results obtained from this climatically sensitive zone suggest that in dry phases, associated with a weaker-than-average summer monsoon, the water deficit may affect vegetation and agricultural population there much more severely than in the coastal regions. This example demonstrates the complexity of human interaction with the environment on a wider regional scale and suggests that even gradual (insolation-driven) changes in the regional climate can affect the existence of people triggering migration processes and demographic pressure in the coastal, climatically more stable regions.

5. Conclusions

The discontinuous spread of rice across central and eastern Honshu (i.e. the eastern Yayoi culture area), as indicated by the Bayesian model, seems to have been related to the Jomon cultural landscape, which was characterized by higher population density and cultural diversity than that in Kyushu, Shikoku, and western Honshu (i.e. the western Yayoi culture area). It was the fusion of Jomon cultural traits with those introduced from the Eurasian mainland that facilitated the formation of the complex dispersal pattern. Jomon communities settling in inland regions, such as the Central Highlands, which had been already involved in low-level food production, may have been more open to introduce new crops, while others, which had developed a higher level of social stratification, such as northern Tohoku groups, introduced rice cultivation for aggrandising purposes. By contrast, Jomon groups, which focused on exploiting coastal resources and/or the rich temperate forests of eastern Japan were probably less open to change their subsistence economy.

The model-derived oldest appearance of rice in the Central Highlands seems to be related to ritual activities rather than to a shift towards an agricultural lifestyle. This finding together with rare evidence from rice grain impressions on late Jomon pottery suggest that rice was used as a prestige good in mortuary contexts rather than as food. Moreover, the role of rice as a higher status crop is also documented for early agricultural (i.e. Yayoi) communities, which initially relied mainly on the cultivation of broomcorn and foxtail millet. The presence of rice does not necessarily prove agricultural activities. On the other hand, early (full-scale) agriculture also relied on millets and other crops.

The reconstructed population developments together with archaeological records suggest that the spread of rice to Japan is primarily the result of complex economic and political developments in continental China superimposed by millennial-scale monsoon climate transformation. Before arriving in Japan, rice was first brought by immigrants to the Korean Peninsula at a time (ca. 1500 BCE) that coincides the maximum flourishing of the Shang dynasty (Erligang culture; ca. 1600–1400 BCE) in the middle Yellow River region. This immigration likely happened in response to economic expansion of the Erligang state by colonizing peripheral regions for procuring grain and natural resources, such as copper and lead. Progressive population growth on the Korean Peninsula that continued into the early 1st millennium BCE was accompanied by the spread of agriculturalists to the Japanese Islands (around 1000 BCE) also followed by substantial population growth. We suggest that these processes were mainly triggered by the eastward expansion of the Zhou kingdom around 1045 BCE, which was accompanied by the foundation of new satellite states, such as Lu (Shandong Province) and Yan (Beijing), and continued in the 8th century BCE, forced by invading agro-pastoral societies from west and north that weakened the kingdom's central power, but led to strengthening of the local states. Ambiguous state policies of economic growth and territorial expansion may have triggered parts of the agricultural populations to migrate to neighbouring territories and/or overseas.

Our study demonstrates that gradual climate change could be another factor, which may have played a role in forcing the recorded population dynamics. Especially the progressive long-term decrease in precipitation linked to the insolation-driven decline in Asian summer monsoon intensity over the middle and late Holocene probably had a negative effect on agricultural activities in the regions located closer to the summer monsoon boundary, such as the middle Yellow River region or the region around Beijing. This prolonged drying may have been involved in the mechanisms that controlled the continued population shift, forcing farmers to move eastward, to regions that received higher amounts of summer monsoon precipitation.

Author contributions

C.L., M.W., and P.E.T. designed the research. C.L. reanalyzed the flotation samples from the Chikaraishijori site and selected carbonized rice grains for AMS ^{14}C dating. C.L. and T.L. constructed the ^{14}C datasets for Japan and South Korea. T.L. designed the Bayesian chronological model. T.G. evaluated the constructed ^{14}C datasets and dated the rice remains from Chikaraishijori. C.L. reanalyzed the archaeological site data from China and population estimates for Japan. C.L. drafted the manuscript and compiled figures and tables. M.W., P.E.T and T.L. contributed to the Results and Discussion sections.

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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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2020.106507.

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