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Lipid residue analysis reveals divergent culinary practices in Japan and Korea at the dawn of intensive agriculture

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The dispersal of millet and rice agriculture from Korea to Japan from around 3,000 y ago has been well documented through radiocarbon analysis of botanical remains and surveying seed impressions on pottery. Much less is known about the extent to which these novel crops were consumed and incorporated into everyday culinary practices. In Japan, agriculturalists moving from Korea would have encountered large, sedentary Final Jomon populations who had well-established hunting, foraging, and cultivation strategies for exploiting indigenous fauna and flora. The degree to which these encounters hindered or enhanced the emergence of agriculture is a key question. To investigate potential changes in food exploitation, we analyzed the contents of pottery through lipid residue analysis of 260 vessels from Bronze Age (Mumun) Korea and contemporary Jomon and Yayoi pottery from Northern Kyushu. A lipid biomarker for broomcorn millet was only found in samples from Korea, suggesting that this crop was not routinely prepared in early agricultural pottery from Japan, despite some botanical evidence for its cultivation. Instead, aquatic products continued to be used in early agricultural pottery, pointing to continuity from the Jomon period despite the arrival of new "continental" ceramic forms. Rice remains difficult to identify conclusively, but by modeling carbon isotope values, we were able to determine the maximum extent that rice may have contributed. Overall, we show that there was a change in culinary practices as agriculture dispersed from Korea to Japan, most likely influenced by different long-standing traditions of preparing and cooking foods in each locality.

organic residue analysis | lipids | agriculture | pottery | East Asia

Significance

Rice and millet dispersed from the Korean peninsula to the Japanese archipelago, arriving first on the island of Kyushu around three millennia ago, beyond that little is known about their culinary use. Pottery was used extensively in East Asian prehistory and retains evidence of use through lipids that penetrate the surface. By extracting and characterizing lipids, we identified clear differences in the use of ceramic cooking vessels from Bronze Age Korea and pre- and postagricultural sites in Kyushu. While Korean pottery was extensively used for processing common millet, this product was absent in contemporary Japanese vessels despite extensive testing. We attribute this discrepancy to different "culinary traditions" that prevailed beyond the arrival of intensive agriculture.

The dispersal of agriculture and the degree to which food production transformed society are enduring themes in archaeological research. Of particular interest are cases where the spread of farming, people, and their material cultures was halted, slowed, or altered due to cultural or geographical barriers. These potentially important spatiotemporal nodes of cultural, demographic, and economic divergence often create lasting legacies for subsequent developments and drive cultural evolution. An example is the transmission of rice and millet agriculture from the Korean peninsula to Japan, specifically to its most westerly island, Kyushu, which lies less than 200 km across the straits with islands spaced tens of kilometers apart in between. At the point that rice and millet were introduced during the early 1st millennium BCE, Japan was occupied by Jomon hunter-gatherers who exploited a broad spectrum of terrestrial and aquatic species and actively managed plants such as soy (*Glycine max*) and adzuki bean (*Vigna angularis*) (1), chestnut (*Castanea crenata*), lacquer (*Toxicodendron vernicifluum*), hemp (*Cannabis sativa*), perilla (*Perilla frutescens*), and barnyard millet (*Echinochloa esculenta*) (2). Understanding how intensive agriculture became established in this context and its impact on well-developed and seemingly successful Jomon lifeways is an important question with broader implications for agricultural dispersals.

What we know of the transition to farming in Japan is often driven by an agenda focused on dating and documenting the earliest botanical evidence and associated material culture, such as pottery, stone tools, and dolmens (3, 4). For example, it is widely accepted that the appearance of paddy fields marks the beginning of the Yayoi period (5), which in Northern Kyushu is tentatively dated to the early 1st millennium BCE. However, direct dating of paddy fields is notoriously difficult and may not be a prerequisite for other forms of wetland rice or millet cultivation (6). Seed impressions left on the surface of potsherds during the manufacturing of pottery vessels and AMS dating of rice and millet grains directly offer a potentially useful line of inquiry for precisely dating the arrival of

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agriculture. Indeed, millet impressions have been identified on early phase "Final Jomon" Tottaimon pottery from Kyushu that predates evidence of paddy fields (4), although these rely on typological dating. A recent synthesis of radiocarbon dates made directly on carbonized rice grains from archaeological sites across the Japanese archipelago (7), provides a credible arrival for the arrival of rice in Northern Kyushu as early as the late 2nd millennium BCE (90% HPDI: 1,251–872 cal BC). The introduction of farming also marks a cultural shift. During the first few centuries of the 1st millennium BCE, we see elements of a continental cultural package, which includes new polished stone tools and burial practices (8).

While these studies are important for tracking the appearance of agriculture, they say relatively little about the extent to which agriculture was practiced and its effect on diets and foodways or the degree to which the indigenous (Jomon) economy and lifeways were influenced or transformed. The botanical evidence is also insufficient in this respect, due to differential preservation and recovery biases. Here, other sources of evidence can be more revealing. For example, during the 1st millennium BCE in Korea (Mumun period), stable isotope analysis of human remains has shown that millet, a C_4 crop with a distinctive isotopic signal, was a major dietary stable in Bronze Age Korea, contributing to up to 40% of their dietary protein (9, 10). Yet due to poor preservation of osseous remains, the application of this technique has, so far, been limited to a small number of samples from just three sites (Hwangsok-ri, Jungdo, and Maedun cave) from a relatively narrow geographical area in the central inland region of the Korean peninsula (Fig. 1*A*).

Similarly, there are only human remains from two sites in Kyushu over this period that have been analyzed isotopically. Stable isotope analysis of remains from the Ohtomo site in NW Kyushu buried in Final Jomon and Yayoi traditions show only slight differences in values with both groups obtaining the majority of their protein from marine resources (11). Conversely, the isotope analysis of predominantly Middle Yayoi "jar burials" from Yoshinogari mound (Fig. 1*B*) points to a diet richer in terrestrial and potentially freshwater resources (12). Importantly, there is no evidence of a C_4 plant contribution to any of the individuals analyzed so far in Kyushu, although the bulk isotope approach deployed in this case is insensitive to sustained low or infrequent consumption. However, even more broadly in Japan, there are no individuals in the Yayoi period as enriched in C_4 plants as those from the Korean Bronze Age (13, 14).

Other sources of evidence are also beginning to emerge. Ancient DNA analysis, albeit of a limited number of Jomon and Yayoi skeletal remains, points to substantial population migration from mainland Asia during the Yayoi period (15–17). Key to this evidence is the analysis of two individuals from Shimomotoyama Rock Shelter in Northern Kyushu dating toward the end of the Yayoi period (3rd century CE) (18) who derive ancestry broadly equally from Jomon and mainland Asian populations (15). In addition, a single mid-Yayoi individual from the Doigahama site in Yamaguchi prefecture (4th century BCE) suggests a greater proportion of mainland Asian ancestry despite an early date (16). However, exactly when admixture between incoming farmers from the Korean peninsula and indigenous hunter-gatherers occurred is harder to discern from these data, largely due to the lack of human remains associated with the earliest evidence of farming in Japan. Broadly, the genetic data are consistent with archaeological evidence for the persistence of hunting, fishing, and gathering beyond the arrival of agriculture, either as separate forager enclaves (19) or as a mixed foraging-farming economy (20).

Here, we add another important line of evidence to complement the existing data by undertaking a comparative analysis of the use of ceramic containers from contemporary sites in Southern Korea and Northern Kyushu during the 1st millennium BCE using lipid residue analysis. In Japan, ceramic vessels were widely used both before and after the arrival of millet agriculture, and their widespread occurrence provides the potential for comparing changes through time over multiple sites. Patterns of pottery use have been widely used as a proxy to investigate economic and dietary change with the arrival of agriculture (21, 22), although strictly they pertain to aspects of behavior involving the manipulation of food (foodways) (23). A reasonable hypothesis is that subsistence practices and cultural foodways already established in Korea should be reflected in Japan during the Initial Yayoi period.

Unlike the other forms of analysis, lipids preserved in pottery reveal aspects of culinary practice. In East Asian contexts, this includes the direct identification of food products such as aquatic animals and broomcorn millet through the presence of biomarkers (24, 25) or the use of compound-specific isotope measurements to crudely determine the main sources of lipids, such as ruminant animals, freshwater/marine fish, or C_4 plants (26, 27). So far, the approach has not proved successful for the unambiguous identification of rice from other potential starchy C_3 plants (27, 28) which remains an obvious limitation. In both Korea and Japan, pottery predates agriculture, but the degree to which agricultural products were incorporated into everyday culinary practice offers insight into both cultural and economic spheres and is a potentially valuable additional source of evidence, given that ceramics are one of the most ubiquitous artifact classes.

In total, lipids were extracted from 260 individual vessels analyzed from 12 sites across the region Fig. 1, Table 1, and Datasets S1 and S7) (29) using acidified methanol and analyzed by gas chromatography-mass spectrometry (30). These included 138 vessels from Northern Kyushu, of which 77 were from Initial to Early Yayoi sites dating to the early 1st millennium BC, thought to be associated with millet and rice agriculture. A further 61 vessels were analyzed from Late and Final Jomon sites in the same region (Table 1). For comparison 122 Early and Late Bronze Age vessels were analyzed from seven sites from the western Korean Peninsula (Fig. 2 and Table 1) dating to the 1st and 2nd millennia BCE. Based on use-wear alteration and their forms, vessels from across the entire study area were interpreted to be cooking pots. Lipids were extracted predominantly from ceramic samples (n = 245) drilled from the ceramic interior walls (*Materials and Methods*). In addition, 15 interior carbonized surface deposits ("foodcrusts") were analyzed from the Initial Yayoi sites of Nabatake (n = 13) and Sasai (n = 2) in Northern Kyushu. Overall, the proportion of sherds with interpretable absorbed lipid profiles (31), varied by region (56% from Kyushu; 95% in Korea; Table 1). This discrepancy may be attributable to the different preservational environments, the amount of lipid transferred through differential uses, or the capacity of ceramics to retain lipid residues. For example, plant products (particularly grains and legumes) generally yield much lower lipid concentrations than animal carcass fats. Lipid quantities were particularly low at the Final Jomon site of Ryumatsu Mizota with the majority of potsherds yielding only traces of fatty acids. Interpretable amounts of lipid were obtained from all the foodcrusts.

Using the approach described by Heron et al. (24), we deployed highly sensitive mass spectrometry methods for the detection of miliacin, a pentacyclic triterpene methyl ether that is highly concentrated in the grains of common/broomcorn millet (*Panicum miliaceum*) but absent in other wild and domesticated species across this region. Miliacin was identified in a total of 28 of the

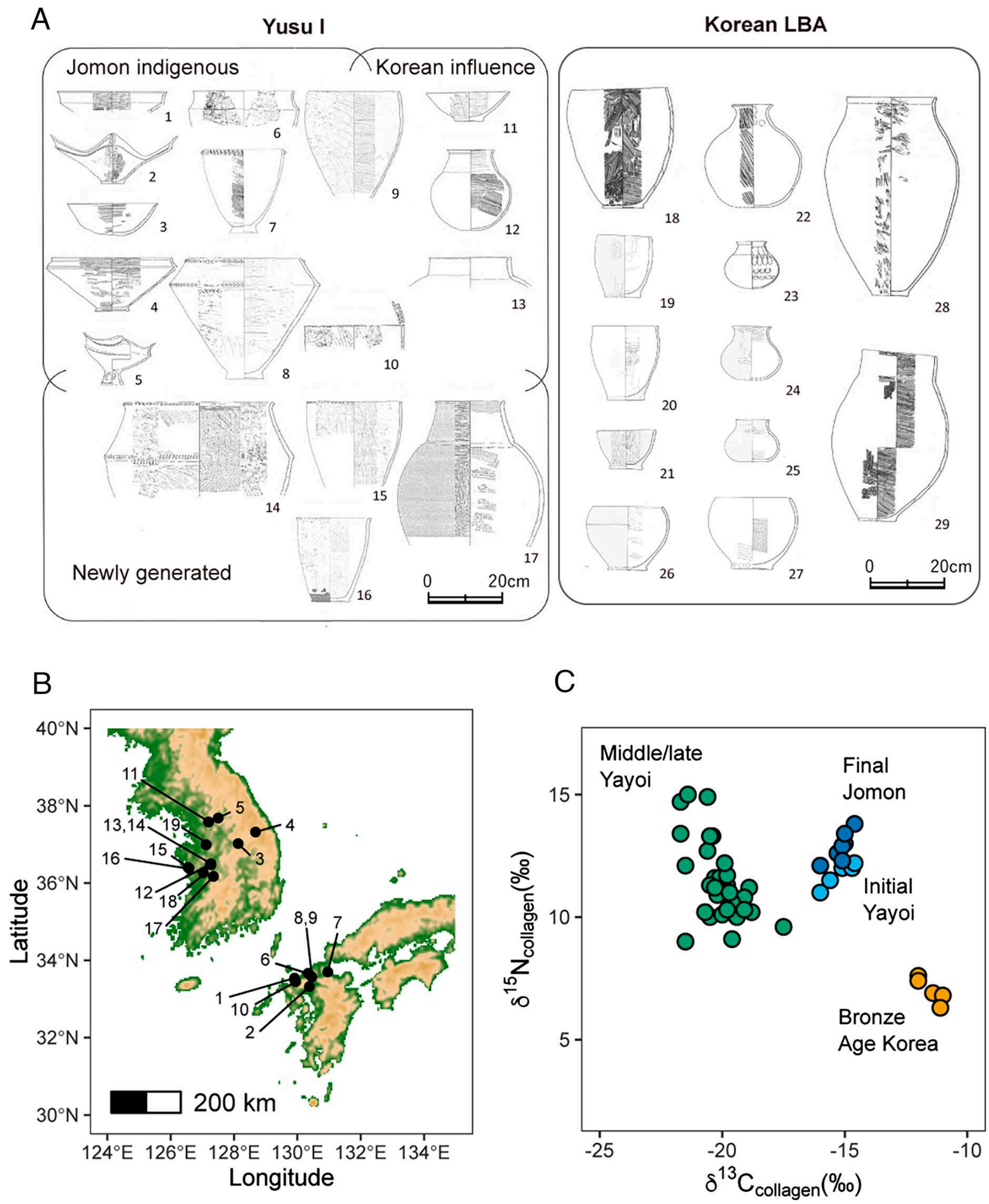

Fig. 1. Overview and contextual information. (*A*) Similarities and differences in Initial Yayoi pottery (Yusu-I style) with pottery from the same period on the Korean peninsula (after Misaka 2022, Shoda 2004, Fukasawa & Shoda 2009). 1-4, 6, 10, 12: Nabatake, 5: Ukikunden, 7: Itadsuke, 8, 9, 11, 13-17: Magarita, 18-22, 24-29: Daepyoeng-ri, 23; Shincheon-ri. (*B*) Location of Sites with human remains - 1. Ohtomo, 2 Yoshinogari, 3. Hwangsok-ri, 4. Maedun Cave, 5 Jungdo; Location of sites with pottery - 6. Obaru D, 7. Ryumatsu Mizota, 8. Shimotsukiguma C., 9. Sasai 10. Nabatake, 11. Misa-ri, 12. Daepyong-ri, 13. Songdam-ri, 14. Songwon-ri, 15. Jukyo-ri, 16.Kwanchang-ri, 17. Majeon-ri, 18. Songguk-ri, 19 Sosa-dong. (*C*) Bone collagen isotope values from Bronze Age Korea (Orange), Ohtomo (Final Jomon - Light blue, Initial Yayoi - Dark blue) and Yoshinogari, (Middle and Late Yayoi - Green).

sherds, all derived from Korean sites but was absent in all the vessels from Northern Kyushu, including the Early Yayoi vessels with adequate preservation of other classes of lipid and the 15 foodcrusts from Nabatake and Sasai (Table 1). As there is archaeobotanical evidence for the millet cultivation in Kyushu (33), it is interesting that millet was not frequently processed in pottery. One explanation may be that foxtail millet (*Setaria italica*) which contains negligible amounts of miliacin was more prevalent than broomcorn in Northern Kyushu than in Korea. In Northern Kyushu, broomcorn millet has only been identified at a single site as seed impressions in pottery out of nine sites investigated whereas foxtail millet was more prevalent (4/9 sites) (4).

To investigate the use of pottery more broadly we conducted isotope analysis of the major saturated fatty acids ($C_{16:0}$, $C_{18:0}$) where preservation permitted (n = 94). These are compared with a selection of authentic reference fats and oils (Fig. 2). Also plotted are the previously published fatty acid isotope data from Korean Bronze Age pottery from Songwon-ri, Songguk-ri, Songdam-ri, Misa-ri, Majeon-ri, Kwanchang-ri, Jukyo-ri, and Daepyoeng-ri (32) but where the presence/absence of molecular biomarkers was not reported. As C_4 plants, both broomcorn and foxtail millet follow a different photosynthetic pathway, and their lipids are ^{13}C-enriched compared to other animal and C_3 plant products, as shown for modern millets in Fig. 2*A*. Fatty acid isotope values corresponding to these reference values were identified in three Late Bronze Age vessels from the site of Majeon-ri in Korea, miliacin was identified in two of these, confirming the presence of broomcorn millet. Nevertheless, other Korean vessels with

Table 1. Summary of lipid residue analysis on all samples

Location	Site Name	Cultural phase	Approx. Date (BCE)	Pottery types	n	C_{lipid} (μg g^{-1}), $\bar{x}$– X(σ)	Samples with lipids (%)	Miliacin (%)	Aquatic (%)
Kyushu	Obaru D	Late Jomon	1670–1530	Kurokawa	31	20 (56)	61%	0%	5%
	Ryumatsu Mizota	Final Jomon	1200–900	Tottaimon	30	7 (15)	20%	0%	0%
	Shimotsukiguma C	Initial–Early Yayoi	830–380	Yusu-Itaduke	29	108 (327)	69%	0%	15%
	Sasai	Early Yayoi	900–390	Itaduke	33	14 (15)	79%	0%	0%
	Nabatake	Initial–Early Yayoi	900–800	Yusu-Itaduke	13	–	100%	0%	38%
Korea	Misari	Early Bronze	1740–1520	Misari	10	26 (19)	100%	40%	0%
	Daepyongri	Early Bronze	1270–790	Misari	34	15 (22)	94%	22%	3%
	Songdamri	Early Bronze	1270–800	Heunamri-Yeoksamdong	7	14 (7)	100%	0%	0%
	Songwonri	Early Bronze	1260–530	Heunamri-Yeoksamdong	5	11 (5)	100%	0%	0%
	Jukyori	Early Bronze	1190–590	Heunamri-Yeoksamdong	12	17 (17)	92%	9%	0%
	Kwanchangri	Late Bronze	830–390	Pre-Songgukri/ Songgukri	10	7 (3)	80%	0%	0%
	Majeonri	Late Bronze	800–380	Pre-Songgukri/ Songgukri	44	36 (44)	98%	37%	16%

C_{lipid}–extractable lipid concentration on absorbed residues only. n–number of samples analyzed. Samples with lipid–% samples with C_{lipid} > 5 μg g^{-1}, % Miliacin–% of samples with interpretable amounts of lipid with miliacin. % Aquatic–% of samples with interpretable amounts of lipid with aquatic biomarkers.

miliacin did not have correspondingly enriched fatty acid values. This must be attributable to mixing to various degrees with other foodstuffs with different fatty acid carbon isotope values.

As broomcorn millet contains only 3.3% lipid by weight (34), it is far less likely to be identifiable isotopically, if, for example, it were mixed with more lipid-rich animal products. Indeed, biomarkers derived from heating aquatic animal oils, i.e. fish, shellfish, and marine mammals (35) were occasionally encountered (Fig. 2*B*), including on pottery from early agricultural sites, implying that animal fats were prevalent (Fig. 2*B*). To illustrate the issue of mixing, a concentration-dependent Bayesian mixing model was used to estimate the contribution of lipids from the major food sources prevalent (rice, millet, marine products, and ruminant animal fat, such as deer) (36). Given the absence of suitable biomarkers, a key aim was to determine the possible contribution of rice and millet to vessels based on their fatty acid δ^{13}C values. The model considers both the carbon isotope range of C_{16} and C_{18} fatty acid in each foodstuff (Dataset S2) and crucially their relative concentrations (Dataset S3), expressed as a % of total fatty acid, (*Materials and Methods*) following the approach of Fernandes (37) but using the MixSIAR package (38). The maximum credible intervals (i.e., 95% confidence) for each product are plotted in Fig. 2*C*.

Based on the isotope data alone, credibly, millet may have been processed in a range of pots from both Kyushu and Korea (Fig. 2*C*). However, due to equifinality, millet and marine products cannot be well differentiated based on isotopic analysis alone, except for those with the most extreme ^{13}C enriched values (Fig. 2*C*). Interestingly, a single Initial Yayoi vessel from Sasai (SAS07) is predicted to have a high contribution of millet-derived fatty acids and negligible marine, despite the absence of miliacin. Given the absence of wild C_4 plants, this provides the only clear evidence for agricultural products in vessels from Northern Kyushu. In other cases, marine-derived lipids provide a better explanation for the enriched ^{13}C values from Kyushu as many of these vessels also had distinctive lipid profiles formed from protracted heating of aquatic products [(35), Fig. 2*B* and Table 1].

Turning to rice, it is clear that theoretically rice lipids could have made a substantial contribution to the majority of vessels (Fig. 2*C*), regardless of period, and rice is only improbable for vessels with more enriched carbon isotope values. Nonetheless, there was very little evidence that pottery was used exclusively for processing rice following its introduction, as some scholars have long predicted based on vessel forms and ethnographic analogy (39). Interestingly, samples with the most depleted $\delta^{13}C_{FA}$ consistent with rice were found in Yayoi contexts in Northern Kyushu. Caution must be exercised however, as other wild C_3 plants such as chestnut or acorn would also produce similar estimates. This is almost certainly the case for Late Jomon pottery where there is no archaeobotanical evidence to support the assumption that rice was used and without a clear biomarker for rice, we can only identify vessels where rice was not the dominant food input.

Discussion

The archaeobotanical evidence shows that both broomcorn and foxtail millet along with rice were cultivated in Northern Kyushu during the Final Jomon and Initial Yayoi phase, where they are found as seed impressions on Tottaimon and Fusenmon pottery (4). Wet rice cultivation is supported by evidence for paddy fields during the early part of the 1st millennium BC (Yusu 1) (40) and overall supports the narrative that rice and millet agriculture were introduced as a package from Southern Korea to Northern Kyushu (41), marking a clear shift in subsistence and material culture (42). It is therefore intriguing that there is little evidence for the millet use in pottery at the point when agriculture arrived in Japan, despite its common occurrence in contemporary Korean Bronze Age (Mumun) pottery (Fig. 1*A*). Similarly, the available human stable isotope data show that while millet made a major contribution to the diet of individuals from Korea, it was, at most, only a negligible contributor to the diet of humans buried during the early phases of agricultural adoption in Japan. There is no obvious environmental reason for this discrepancy, as millet (along with

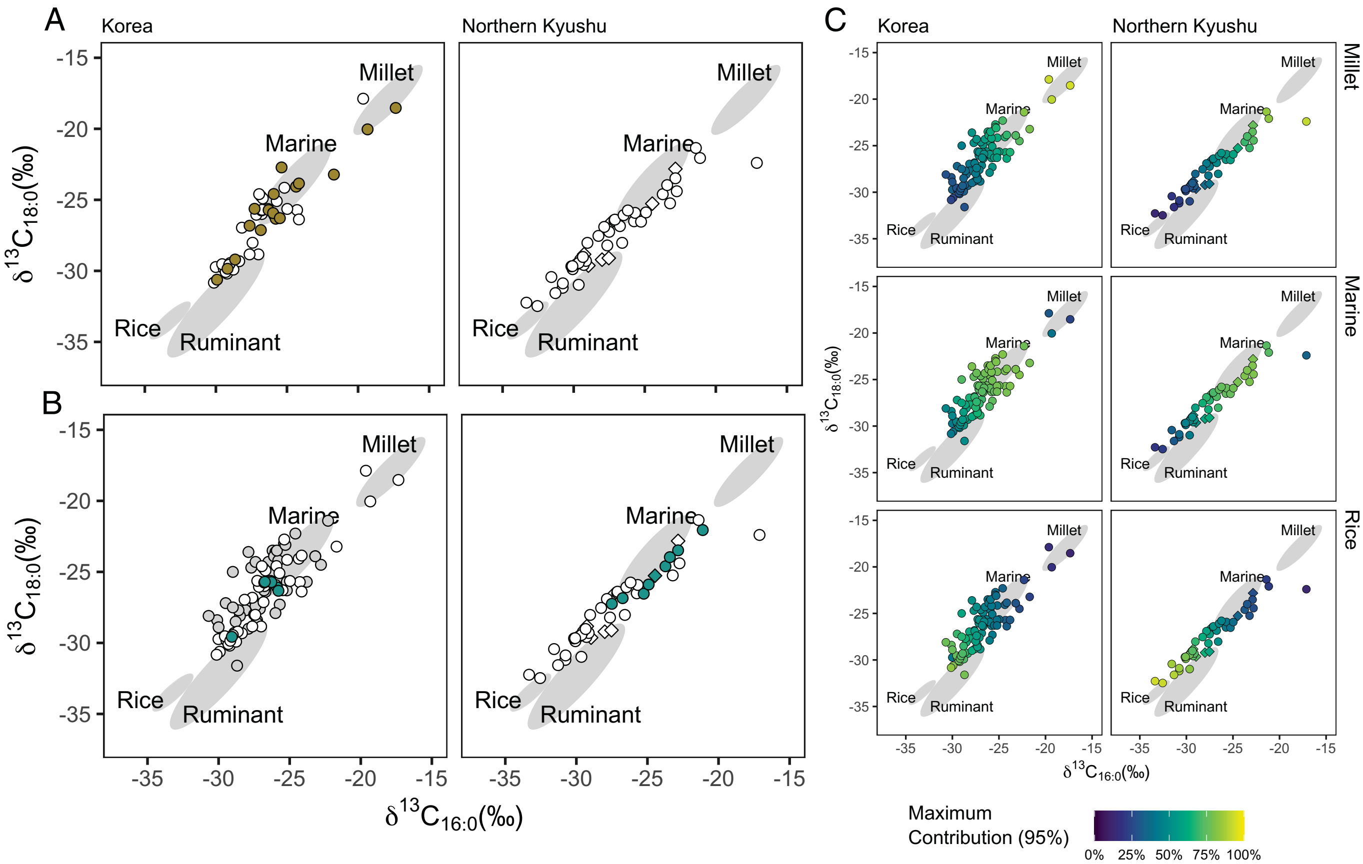

Fig. 2. Stable carbon isotope values of $C_{16:0}$ and $C_{18:0}$ fatty acids Korean Bronze Age (*Left*), Late/Final Jomon (diamonds–*Right*), and Initial/early Yayoi pottery (ellipses–*Right*) from Northern Kyushu. The values are plotted against reference ellipses (68%) derived from modern authentic reference products corrected for the Suess effect (Dataset S2). (*A*) Presence of biomarkers for Broomcorn millet (miliacin). (*B*) Presence of biomarkers for aquatic products. Gray shaded points represent vessels where no biomarker data were reported (32). (*C*) Maximum credible limits for the contribution of fatty acids from millet, marine resources, and rice to vessels against their stable carbon isotope values. The shaded color scale shows the maximum credible contribution (95% confidence) of each product (expressed as % fatty acid to total fatty acid). Note, that the limits for ruminant fats are not shown but available in Dataset S6.

rice) could be easily grown in most regions of Korea and Japan at this time. Conceivably, millet might have been better suited for cultivation in upland central inland areas where the Korean human isotope data are drawn from (10) but could have been easily grown in the coastal regions of Northern Kyushu (Fig. 1*B*).

A number of explanations are offered to explain this discrepancy. First, it is perhaps not surprising that millet was more deeply embedded in Bronze Age Korean culinary practices, considering it had a much longer cultivation history in Korea than Japan, dating back to the Neolithic period (43). This is illustrated by a Bayesian analysis of the available radiocarbon evidence for both crops (Fig. 3). Millet was introduced to the Korean peninsula from northeast China as early as the Middle Neolithic (Chulmun) period (90% HPDI: 5,772 - 3,490 cal BCE) with rice only appearing in the Bronze Age (Early Mumun) around 2,000 y later (90% HPDI: 1,677–1,161 cal BCE), although earlier dates have been proposed (44, 45). Overall therefore, the difference in arrival time of rice in South Korea and Japan was less than 1,000 y (90% HPDI: 279 to 808 y), whereas foxtail and broomcorn millet which were delayed in Korea by several millennia (90% HPDI: 2,001 to 4,838 y) before reaching the Japanese islands.

The different arrival times signal radically different dispersal dynamics between rice and millet. Conceivably, millet was picked up in Korea during the dispersal of rice and carried along with rice to Japan, a process analogous to "cultural hitchhiking" (46, 47). In this scenario, rice was the primary driver for this dispersal process and consequently millet was of only minor significance to early Japanese farmers. A variation on this scenario is that rice cultivation intensified in specific regions of Korea, as has been suggested for the Songguk-ri cultural group from the south-west of the peninsula, and it was these specific groups that expanded to Northern Kyushu (48). However, our analysis of 44 Songguk-ri vessels from the site of Majeon-ri in South-western Korea showed a high prevalence of miliacin, as well as aquatic derived lipids (Table 1), inconsistent with intensive rice use. More likely, therefore while millet continued to be cultivated across the Korean peninsula, it was perhaps rice that promoted the expansion into Japan and became the dominant crop.

A second hypothesis is that agriculture was adopted by indigenous fisher-hunter-gatherers in Japan but incorporated into their existing, highly developed broad-spectrum economy. While new pottery styles, with clear elements of continental design and production techniques (42), began to be produced in the first few centuries of the 1st millennium BCE, we found no evidence for a radical change in use from the Jomon pots they superseded. Contrary to the standard interpretation in Japanese archaeology (e.g., ref. 49), we found no radical shift in pottery use between the Jomon and Yayoi (Fig. 2) and only limited evidence of C_3 plants, potentially including rice, as a major contributor to the residues in early agricultural pottery from Kyushu, albeit that identification is hampered by mixing (Fig. 2*C*). There is scant

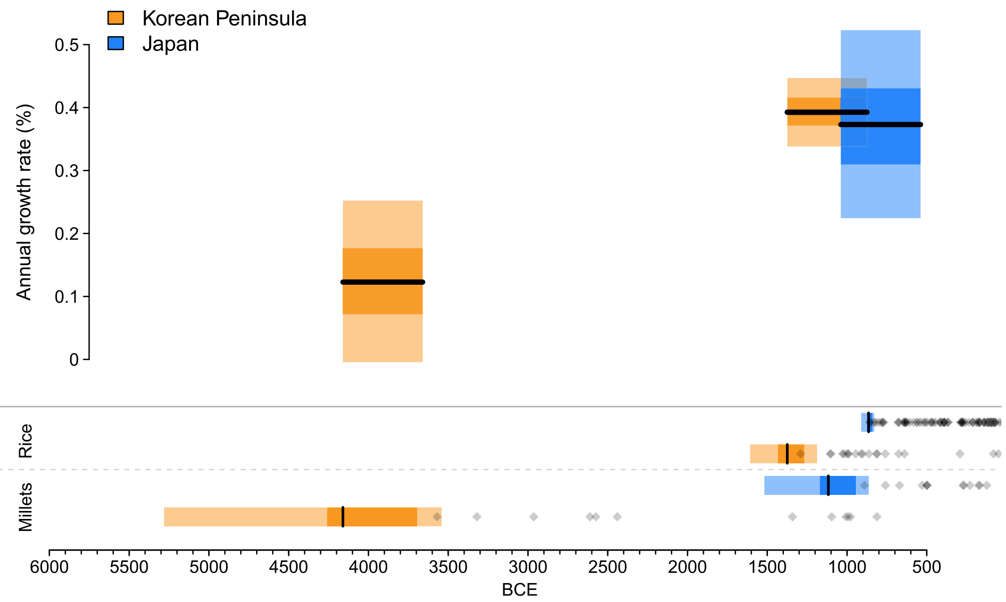

Fig. 3. Growth rates and arrival times. Posterior estimates of population growth rates during the first 500 y of millet and rice farming in the Korean peninsula and Japan (*Top*) and the arrival time of rice and millets in Korea and Japan (*Bottom*). Color shades represent the highest posterior density intervals (90% for darker shade, 50% for lighter shade), while the dark lines represent median posteriors; diamonds depict the median calibrated date of each plant macrofossil remains.

evidence that Initial Yayoi pottery from Kyushu was dedicated for cooking rice, as asserted based on vessel forms and ethnographic analogy (39).

Available to our study were thirteen foodcrusts associated with Initial/Early Yayoi pottery from the key site of Nabatake (Datasets S1 and S7) with botanical evidence for rice and where both broomcorn and foxtail millet have been identified as seed impressions (4). Unlike analysis of absorbed lipids in the ceramics which have a greater propensity to integrate inputs over the use-life of the vessel, lipids in foodcrusts derive a narrower period of use and therefore are less influenced by mixing (50). Interestingly, three of these samples yielded depleted $\delta^{13}C$ values potentially derived from the processing of C_3 plants, such as rice. However, at least a further five of the vessels from Nabatake were used for processing marine foods, including one sample of Yusu I pottery, (Table 1 and Datasets S1 and S7) indicative of a much broader economy. The human isotope evidence of marine consumption during the Early Yayoi, at least from the Ohtomo site, supports this view but without further ancient genomic data from the Initial Yayoi period, it is not possible to assess the degree of demographic change (11). Even if there were substantial movement of people from the Korean peninsula to Japan this would not negate economic continuity if they simply adapted their subsistence strategy in-line with that of the dense groups of Jomon fisher-hunter-gatherers they encountered.

Demographic growth estimates based on the time-frequency of radiocarbon dates can provide further insights into the impact of rice and millet agriculture. Previous studies (51) have indicated major differences in the population sizes between the Chulmun (millet cultivation) and the Mumun (rice and millet cultivation) periods. Bayesian reanalyses of these data focused on the first 500 y of the introduction of millet (6,109–5,609 BP) and rice (3,323–2,823 BP) in Korea indicate major differences in annual growth rate, with the former yielding a posterior median of 0.12% (95% HPDI: −0.004 ~ 0.25%) and the latter of 0.4% (95% HPDI: 0.34 ~ 0.47%; Dataset S5). Notwithstanding the fact that, a) these figures represent the average growth for a considerably wide and potentially demographic heterogeneous areas (see, for example ref. 52), and b) growth rates are the result of both the speed of the uptake and demographic impact, the difference in the demographic impact of millet and rice farming appears clear. Indeed, growth rates estimated for millet are comparable in magnitude to the demographic boom experienced by Jomon foragers during the Middle Jomon period (53), whereas the much higher growth rate following the introduction of rice is of similar magnitude to other cereal-based transitions [e.g., the British Neolithic (54)].

Assessing differences in growth rates following the introduction of rice and millet to the Japanese archipelago is more complex, as the two crops were introduced at the same time. Crema and Shoda (55) have identified a significant delay in demographic growth and the timing of the population uptake following the arrival of agriculture in Kyushu, with an estimated change point around the end of the 8th century BCE, several hundred years after the estimated arrival time of rice and millets. This would support the second hypothesis that agriculture initially only had a minor demographic impact in Kyushu, as there was no radical change in food production from the Final Jomon period. However, a more recent study by Crema et al. (56) suggests that this may be due to a substantial slowdown in the dispersal of rice farming in southern Kyushu, possibly related to local topographic and soil conditions. Indeed, their estimate of the growth rate for Northern Kyushu yields a relative posterior mean of 0.37%, comparable to the Korean peninsula following the arrival of rice, although with greater uncertainty owing to smaller sample sizes (90% HPDI: 0.22 ~ 0.52%). As the economic importance of rice is hard to assess using botanical methods, dietary isotopes, or food residues, we cannot yet rule out the possibility that the arrival of rice agriculture had a similar demographic impact on population growth in Northern Kyushu as it had in Korea a few centuries earlier.

The impact of the arrival of agriculture on demography, diet, and material culture in Japan provides an interesting contrast to other world regions. In Japan, there was a clear cultural transformation at the start of the 1st millennium BCE, evidenced by a change in pottery styles and other forms of material culture (42), coinciding with the earliest evidence for rice and millet. The degree to which these monumental changes can be attributed to the movement of people is unclear from the limited ancient genomic data so far available (15). While further genetic data will surely emerge, we show here that early Yayoi pottery had a range of uses including for processing fish, that was not unlike the use of Final Jomon pottery. Furthermore, there is scant evidence that Yayoi pots were dedicated for cooking rice and there is very little evidence of millet, which we suggest was not of major importance at this juncture. Overall, despite changes in material culture, there is little evidence for a radical change in culinary practice.

The process is analogous to Southern Scandinavia which was heavily occupied by Ertebolle (EBK) hunter-gatherers prior to the arrival of cereal agriculture and domesticated animals in the Neolithic funnel beaker period (TRB) at ca. 4,000 BCE. Here too, there was a rapid cultural transition in pottery styles from EBK to TRB but continuity in the use of wild foods (22). In the Danish case, however, the process seems to be entirely driven by the movement of people with little evidence for the persistence of hunter-gatherer ancestry into the Neolithic period (57), as is observed in the Yayoi period in Japan (15, 17, 57).

In other parts of Europe, including Britain, there is stronger evidence for a more dramatic shift in diet and culinary practices with the introduction of agriculture concomitant with population expansion and demographic growth (54, 58, 59), although increased admixture with local hunter-gatherers is observed in southern Europe after the arrival of farming (60). Unlike East Asia, Mesolithic hunter-gatherers in Southern, Central, and Western Europe were "aceramic." Pottery was therefore an introduced technology entirely within the farmer worldview and it is perhaps not surprising that evidence for its use for processing wild foods is scant (61). Conversely, in Northern Europe and East Asia, the pottery residue evidence shows that culinary habits and traditions persisted beyond the arrival of farming. These data reinforce the notion that culinary practice, a set of behaviors conditioned by the local "foodscape", was a deeply embedded and persistent social tradition. This may be particularly true of foraged, collected, and hunted products that served to buffer the risk of establishing new forms of agriculture. But in the case of Korea, long-standing production of millet might have also served this purpose, therefore facilitating the establishment of rice agriculture.

Materials and Methods

Organic Residue Analysis. Lipids were extracted from pottery vessel sherds and charred deposits associated with vessel surfaces using acidified methanol (H_2SO_4) following established methods as previously described (27). The results of Gas Chromatography-Mass Spectrometry analysis and isotopic values acquired from GC-combustion-Isotope Ratio Mass Spectrometry are reported in Datasets S1 and S7. Detailed methods and instrument specifications are described in the *SI Appendix, Supporting text*.

Mixing Models. Modeling was carried out using the MixSIAR (62). The model was implemented using $\delta^{13}C_{16:0}$ and $\delta^{13}C_{16:0}$ values as proxies. Four food groups were selected as potential sources (marine, ruminant adipose, rice, and millet) and $\delta^{13}C$ values for each were obtained from modern authentic reference fats and oils (Dataset S2). Palmitic and stearic acid concentration values (Dataset S3) were obtained from the United States Department of Agriculture Food Composition Databases (https://ndb.nal.usda.gov/ndb/). The source concentrations, and therefore model outputs, are expressed as % of total lipid by weight. The trophic discrimination factor was set to 0 and assumes fatty acids from all the sources will have equal probability of contributing to the residue. The model used a generalist prior and a "process error" to reflect the fact that the source inputs to any of the pots could be drawn from across the distribution. "Extreme" (number of chains = 3; chain length = 3,000,000; burn in = 1,500,000; Thin = 500) was set as the Markov Chain Monte Carlo (MCMC) chain length; convergence was tested using the Gelman–Rubin and Geweke statistics.

Arrival Time Estimations. Estimated dates of the introduction of millets (Broomcorn, *P. miliaceum,* and Foxtail, *S. italica*) and rice (*Oryza sativa*) in the Korean peninsula and Japan were obtained via Bayesian analyses of ^{14}C dated macrofossil remains. A total of 277 dates (rice: $n_{japan} = 221$; $n_{korea} = 30$; millets: $n_{japan} = 14$; $n_{korea} = 12$; see Dataset S5) were modeled using a hierarchical model that accounts for sample interdependence (i.e. macrofossil remains recovered from the same site) (see ref. 7 for details). The Bayesian models were built and fitted using nimble (63) and nimbleCarbon (55) R packages using four chains for each crop and running a sufficient number of iterations (0.5 million sampled every 25 steps for millets, six million sampled every 300 steps for rice; in both cases have the iterations discarded for burn-in) to reach satisfactory convergence (i.e., a Gelman–Rubin statistic below 1.01) for all parameters. Posterior estimates on the delay of the arrival of rice were obtained by subtracting estimates from the MCMC samples of millet and rice.

Population Growth Rate Estimates. Population growth rates after the estimated introduction date of millets and rice for the Korean peninsula were inferred from the time-frequency of radiocarbon dates by fitting a Bayesian growth model described in ref. 55. Samples were obtained from previous studies focusing on demographic analyses of radiocarbon dates. In the case of millet, we used the dataset compiled and published by ref. 52, while for rice, we used the ^{14}C dates from ref. 51. Both datasets were filtered by considering: 1) samples with a cumulative calibrated probability mass above 0.5 during the first 500 y from the posterior median estimate of the arrival time of each crop (i.e., 6,109–5,609 BP for millet and 3,323–2,823 BP for rice); 2) randomly selecting one radiocarbon date from each site-phase, the latter defined using the *binPrep* function in the *rcarbon* (64) using bin sizes of 50 y, to account for intersite variations in sampling intensity. The final datasets ($n = 46$ for millet and $n = 663$ for rice) were modeled by fitting an exponential growth model (55), using four chains with 500,000 iterations (half discarded for burn-in and sampled every 25 steps). Model convergence was assessed using the Gelman–Rubin statistic.

Data, Materials, and Software Availability. R script, R markdown files, csv files, MS datafiles (.mzxml); raw GCMS data have been deposited in Zenodo [10.5281/zenodo.15641871 (36) and 10.5281/zenodo.15003335 (29)]. Previously published data were used for this work. In Fig. 1 the stable isotope data is previously published and all the references are provided in Dataset S4.

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