

Evidence for cultivation and selection of azuki (*Vigna angularis* var. *angularis*) in prehistoric Taiwan sheds new light on its domestication history

Christian Leipe^{a,b,*}, Jou-chun Lu^c, Ko-an Chi^c, Shu-min Lee^c, Hung-cheng Yang^c,
Mayke Wagner^d, Pavel E. Tarasov^b

^a Institute for Space-Earth Environmental Research (ISEE), Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8601, Japan

^b Institute of Geological Sciences, Paleontology Section, Freie Universität Berlin, Malteserstraße 74–100, Building D, 12249, Berlin, Germany

^c Department of Anthropology, National Taiwan University, No. 18, Siyuan St, Zhongzheng District, Taipei City, Taiwan

^d Eurasia Department and Beijing Branch Office, German Archaeological Institute, Im Dol 2–6, 14195, Berlin, Germany

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ABSTRACT

Grain legumes of the *Vigna* genus are important crops in Asia, although their origins and history of domestication and cultivation are less known than that of rice and millet. Azuki (*V. angularis* var. *angularis*) is widely cultivated and consumed across East Asia, especially in China, Korea and Japan, which are considered independent centres of azuki domestication. This study presents the first directly dated archaeobotanical record of *V. angularis* from Taiwan recovered from prehistoric cultural layers at the Sanbaopi 5 archaeological site (23°07'03"N, 120°15'32"E, 3 m above sea level) located in the Tainan Science Park, south-western Taiwan. The archaeological dataset is compared with charred modern reference material and records from other prehistoric sites in East Asia and then discussed in context of cultivation and domestication. The obtained results suggest that *V. angularis* was used in the study area between the first half of the 1st millennium BCE (Wushantou phase) and 6th century CE (Niaosong phase) and that it was an important part of the diet of local populations. The younger specimens appear on average larger than the older ones. It is possibly that during this period the pulse underwent selection for size increase so that at least the specimens dating to the 6th century CE may be addressed as azuki (*V. angularis* var. *angularis*), the domesticated form of *V. angularis* var. *nipponensis*. This indicates that prehistoric Taiwan may have been an independent centre of azuki cultivation/domestication in addition to the previously suggested regions. However, compared to evidence for azuki domestication in Japan, Korea and China, which dates to between ca. 4000 and 1000 BCE, the larger pulses from Taiwan appear quite late (about 4500–1500 years later). An alternative scenario to regional domestication is that azuki was introduced to the island by immigrating farmers or through exchange across the Taiwan Strait.

1. Introduction

Grain legumes of the *Vigna* genus are important crops in Asia. Of the 21 Asian *Vigna* species summarised in the subgenus *Ceratotropis*, six have been fully domesticated (Tomooka et al., 2011). Mung bean (*Vigna radiata* var. *radiata*), urd bean (*Vigna mungo* var. *mungo*), moth bean (*Vigna aconitifolia*), creole bean (*Vigna glabrescens*) and rice bean (*Vigna umbellata*) originate from South or Southeast Asia, whereas azuki (or adzuki) (*Vigna angularis* var. *angularis*), sometimes called red bean, is believed to have been domesticated in East Asia from *Vigna angularis* var. *nipponensis* (Fig. 1A) (Tomooka et al., 2002b). Another crop, which belongs to the African *Vigna* group (subgenus *Vigna*) but is believed to have

been domesticated in Asia from cowpea (*Vigna unguiculata* var. *unguiculata*), is yardlong bean (*Vigna unguiculata* var. *sesquipedalis*) (Kong-jaimun et al., 2012). Unlike the Asian *Vigna* crops, which are mostly cultivated for their seeds, yardlong bean is grown mainly for its pods.

Although azuki is not the most important legume crop, it is widely cultivated and consumed across East Asia (Rawal and Navarro, 2019). The main producers today are China, Japan, Taiwan and South Korea (Sindhu and Manickavasagan, 2020), where azuki beans are used to produce sprouts or consumed dry, boiled or as paste, often sweetened and used in fillings for rice-based confectionary or pastry (Soley, 2019; Takabatake, 2000). In terms of per capita consumption, azuki is the second most important legume crop in Japan, where it is only surpassed

* Corresponding author. Institute for Space-Earth Environmental Research (ISEE), Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8601, Japan.
E-mail address: c.leipe@fu-berlin.de (C. Leipe).

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by soy bean (*Glycine max*) (Uwaegbute, 1996).

From Japan also the oldest evidence for the use of *V. angularis* has been reported. Pulses, morphologically comparable to *V. angularis* var. *nipponensis*, have been found in an Initial Jomon cultural layer at the water-logged Awazu site at the bottom of Lake Biwa (Fig. 1A) dated to around 8000 BCE (Minaki and Nakagawa, 2000). Morphological evidence for domestication (selection for size increase) is documented by assemblages from sites in the Japanese Central Highlands (Nakayama, 2019; Nasu et al., 2015) and Shimoyakebe on the Kanto Plain (Sasaki et al., 2007) in central Japan dating to the Middle Jomon period (3300–2400 BCE). Besides Japan, also northern China and the Korean Peninsula have been suggested as independent centres of azuki domestication (Lee, 2013). Large quantities of *V. angularis*, which show no size increase compared to *V. angularis* var. *nipponensis*, have been reported from sites at the southern coast of the Korean Peninsula (Lee, 2013). Direct dating places the finds in the late phase of the regional Neolithic

Middle Chulmun period (3500–3000/2700 BCE, after Lee, 2017), during which foxtail (*Setaria italica*) and broomcorn (*Panicum miliaceum*) millet cultivation, most likely introduced to Korea during the late Early Chulmun (6000–3500 BCE) period (Leipe et al., 2019), started to play a more important role in regional subsistence economies (Lee, 2017). Larger, azuki-sized assemblages are documented from Middle Mumun (950–450 BCE) context interpreted by Lee (2013) as the results of a prolonged domestication process. In northern China the use and domestication of *V. angularis* is verified by assemblages larger than the wild type from Longshan (2600–1900 BCE) cultural context at the Liangchengzhen site (Crawford et al., 2005) and Shang dynasty (1600–1400 BCE) context at the Wangchenggang site (Fuller and Zhang, 2007) in the Lower Yellow River region. Almost one decade has passed since (Lee's (2013)) overview study on the origin of azuki and despite a continuously growing number of archaeobotanical investigations across Asia, only two new, confidently identified records of *V. angularis* have

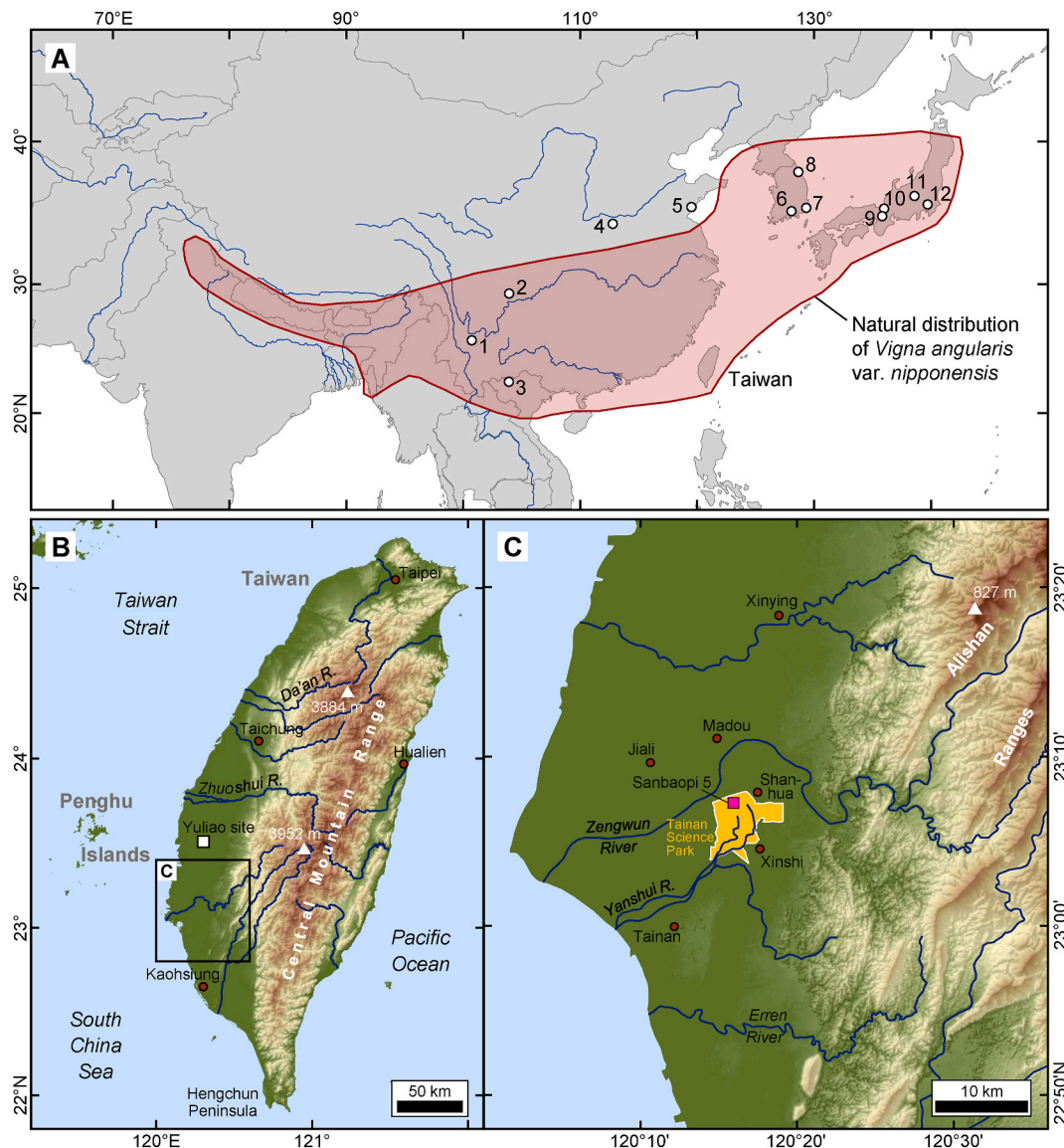


Fig. 1. Map set showing (A) the location of Taiwan and the natural distribution of *Vigna angularis* var. *nipponensis*, the wild progenitor of azuki, after Isemura et al. (2011), and archaeological sites and regions mentioned in the text and Table 1: 1 – Baiyangcun, 2 – Baodun, 3 – Lao Cai Province, 4 – Wangchenggang, 5 – Liangchengzhen, 6 – Okbang and Pyeonggeodong, 7 – Daudong and Bibongri, 8 – Osanri C, 9 – Awazu, 10 – Torihama, 11 – sites in the Japanese Central Highlands, 12 – Shimoyakebe; (B) the location of the study region in south-western coastal Taiwan and (C) the location (23°07'03"N, 120°15'32"E) of the Sanbaopi 5 archaeological site (magenta square) within the Tainan Science Park Special District in the municipality of Tainan City. Digital elevation models are based on the GMTED2010 dataset (Danielson and Gesch, 2011). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

been reported since then. With one from Japan (Obata and Miyaura, 2021) and the other one from South Korea (Kwak et al., 2020) they come from regions, which are long known as early centres of azuki cultivation. That our knowledge about the origin, dispersal and role of azuki in Asian prehistory has not increased is likely due to the difficulties involved in the secure differentiation of *Vigna* species and other legumes, which has limited identification regarding taxonomic depth (e.g., Dal Martello et al., 2018) or led to misidentifications (e.g., Kudo and Sasaki, 2010; Obata et al., 2007) in past studies.

This study is based on archaeological data and a directly dated archaeobotanical record from prehistoric cultural layers at the Sanbaopi 5 archaeological site located in the Tainan Science Park, Tainan City, south-western Taiwan (Fig. 1). We present the records of charred *V. angularis* seeds and correlate them with modern reference material and records from other archaeological sites in East Asia and discuss them in context of cultivation and domestication. For native spelling of romanised Chinese, Korean and Japanese terms in the text the readers are referred to Supplemental Table S1.

2. The Sanbaopi site and archaeological features

Sanbaopi 5 represents one section of the Sanbaopi archaeological site complex, which is located on the flood plains between the Zengwun and Yanshui rivers west of the Alishan Ranges (Fig. 1B and C). The site lies within the Tainan Science Park Special District (Fig. 1C), which is part of the Southern Taiwan Science Park since 2019 and covers about 3350 ha. With over 80 archaeological sites discovered during the last 25 years the district harbours the largest contiguous site complex in Taiwan with a rich archaeological record dating back to ca. 3000 BCE (Tsang and Li, 2015). Most features at Sanbaopi are associated with the Wushantou phase (900–100 BCE) of the Dahu culture (1400 BCE–100 CE), which represents the Late Neolithic in coastal south-western Taiwan stretching from the Zengwun River basin to the Hengchun Peninsula (Fig. 1B and C) (Kuo, 2019). The site is part of the largest known Dahu culture settlement site in Taiwan.

At the time of existence, the Sanbaopi settlement was located in a coastal environment rich in food resources. The archaeological records show that local populations had a broad-range subsistence based on marine and riverine fishing, terrestrial hunting and gathering and cultivation of foxtail millet (*Setaria italica*), broomcorn millet (*Panicum miliaceum*), rice (*Oryza sativa*) and Job's-tears (*Coix lacryma-jobi*) (Tsang et al., 2015). Buildings were erected on pillars and the settlement was well-structured and divided into functional units (e.g., burial grounds, residential space, wells). The burial record, which comprises over 300 graves, demonstrates spatial organisation by gender and social status. Jade ornaments, such as beads and rings, made of nephrite and arrowheads made of slate show long-distance exchange with communities from the southern and eastern parts of the island.

The Dahu culture is noted for the production of grey and black pottery. During the Wushantou phase this pottery rarely shows decoration, which is well reflected by assemblages from Sanbaopi. Grey and black pottery without decoration is a feature which the Longshan culture (2600–1900 BCE) of northern China is especially renowned for (Underhill, 1991), but is also associated with Neolithic cultures from further south on the continent, such as the Liangzhu (3200–2000 BCE) in the Lower Yangtze region (Lu et al., 2013). Such pottery was also produced by the Yinpu culture (1300 BCE–100 CE), which was based on the coastal plains between the Da'an and Zhuoshui rivers north of the Dahu domain (Fig. 1B). However, the pottery production at Sanbaopi appears more advanced with highly polished and partly very thin-walled vessels compared to that documented at all other Dahu and Yinpu culture sites. Because of identified differences from their respective predecessor cultures Niuchuozi and Niumatou Late (2300–1300 BCE), some authors believe that the Dahu and Yinpu cultures mark the arrival of new people (Kuo, 2019; Tsang and Li, 2015). Kuo (2019) notes that the grey and black Yinpu pottery shares many traits with the Taying and Fulingang

types from Shang/Zhou period sites in Fujian Province, which may point to a connection with the continent. However, there is no agreement about the origin of the Dahu and Yinpu cultures and whether they reflect immigration or descended from local indigenous groups (Chen, 2017).

Sanbaopi 5 (23°07'03"N, 120°15'32"E, 3 m above sea level) has a size of 10,648 m² and comprises 221 ash pits, ten shell mounds, seven pottery clusters, 157 human and five dog burials and five wells (Supplemental Fig. S1). Pot sherd records (unpublished excavation report) suggest that the archaeological features represent the Dahu period and the Niaoosong period (100–1400 CE) of coastal south-western Taiwan. Most features at Sanbaopi 5 are associated with the Wushantou phase. Three pits located close to the northern site boundary contained sherds with typological features of the Yuliao phase (100 BCE–100 CE) and/or the Niaoosong period as defined in the chronology for south-western Taiwan (Kuo, 2019). Although stylistic changes are noticeable in the post-Wushantou pottery assemblages, Yuliao type pottery, which is mainly found in the region around the Yuliao type site in Chiayi County (Fig. 1B), is not clearly represented at sites within the Tainan Science Park. Therefore, we relate this pottery and its associated archaeological assemblages to a transitional phase between the Wushantou phase and the Niaoosong period.

Most of the sampled ash pits ($n = 90$) were located between 10 and 70 cm below the modern surface. Stretching from 30 to 136 cm depth pit number 01 (P01) (Supplemental Fig. S1) was comparatively deep. Sampling revealed that P01 comprised three partly overlapping depositional units (Supplemental Fig. S2). It appears that the lower one (ca. 100–136 cm depth) represents a hearth or kiln as indicated by red-coloured soil and the middle (ca. 70–110 cm depth) and upper (ca. 30–80 cm depth) ones represent discarded materials (i.e., ash pits). The pot sherd record from P01 suggests that the bottom depositional unit is associated with the transitional phase (between Wushantou phase and Niaoosong period) and the two units above are related to the beginning of the Niaoosong cultural period.

3. Material and methods

The *V. angularis* records presented in this study were obtained through bucket flotation of deposits from 74 archaeological features (ash pits, human graves, pottery cluster) at Sanbaopi 5. Flotation of 9462 L of sediment was conducted using buckets and nylon meshes with a 250- μ m aperture size. To avoid artificial inflation of the total counts, we omitted seed fragments that comprised less than 50% of the original seed size. Photographs of selected seeds were taken with a Keyence VHX-2000 digital microscope.

To aid identification and size assessment of the recovered *Vigna* seeds, we utilised fresh reference material obtained from the Genetic Resources Center of the National Agriculture and Food Research Organization (NARO) in Tsukuba, Japan. The reference samples comprise seeds of two plants of *Vigna reflexo-pilosa*, one originating from Yonaguni Island (NARO Stock No. 130515) and one from Ishigaki Island (NARO Stock No. 130497), of two plants of *Vigna riukiensis*, one from Ishigaki Island (NARO Stock No. 130487) and one from Taiwan (NARO Stock No. 152418) and two plants of *V. angularis* var. *nipponensis*, one from Nagasaki Prefecture, Japan (NARO Stock No. 137564) and one from Taiwan (NARO Stock No. 153209). Prior to comparison of morphological features, the reference seeds were charred in an RT-25FP Fukushima Yuyaku Co., Ltd. furnace at 350 °C for 3 h under anoxic conditions. For size comparison we mainly relied on the product of length (L), width (W) and thickness (T) dimensions as a measure of seed volume. This was also suggested as more representative for size changes than single dimensions for studying domestication of soy bean in East Asia (Lee et al., 2011).

Direct dating of carbonised seeds from Sanbaopi 5 was done using the AMS ¹⁴C dating facilities at the Poznan Radiocarbon Laboratory, Poland. For conversion of ¹⁴C dates to calendar ages we used the online version of OxCal v4.4 (Bronk Ramsey, 1995) and the Intcal20

calibration curve (Reimer et al., 2020). The same curve was used to re-calibrate previously published ¹⁴C dates mentioned in the discussion. The OxCal software was also used for plotting the probabilities of the calibrated ages.

4. Results and interpretation

4.1. Chronology

Fourteen charred seeds of rice, broomcorn millet, foxtail millet and *Vigna* from ten different ash pits at Sanbaopi 5 were AMS ¹⁴C-dated. The 95% confidence intervals of the calibrated ages are distributed between 776 BCE and 650 CE, which corresponds to between the early Wushantou phase (Dahu period) and the early Niaosong phase (Niaosong period) in the regional archaeological chronology (Fig. 2). Calibrated age ranges for ash pits associated with the Wushantou phase range between ca. 800 and 170 BCE. P01 and P02, located at the northern site boundary, are associated with the transitional phase and/or the Niaosong period (Supplemental Fig. S1). The concentration of pot sherds and a large quantity of charred seeds in P02 are well-confined within the 30–40 cm depth interval, suggesting that these deposits represent a single event. Calibration of Poz-126439 dates this seed assemblage to 436–637 CE (95% confidence interval) with the most likely date of deposition sometime during the 6th century CE (Fig. 2), which is in

agreement with the pottery from P02 assigned to the early Niaosong phase. In contrast, P01 is relatively deep with deposits stretching from 30 to 136 cm depth. Three distinct, partly overlapping infills were identified ranging between 30 and 80, 70–110 and 100–136 cm (Supplemental Fig. S2). Pot sherds from the lowermost infill showing features of a hearth or kiln were assigned to the transitional phase, which is corroborated by the calibrated ages of Poz-121993 from 110 to 120 cm depth and Poz-127724 from 120 to 130 cm depth. The 68% confidence intervals of Poz-121993 (197–60 BCE) and Poz-127724 (88 BCE–20 CE) date to the Wushantou/transitional phase boundary and the first half of the transitional phase, respectively. Poz-127723 from depth interval 100–110 cm appears to represent the two uppermost infills, which contained pot sherds assigned to the beginning of the Niaosong period (equivalent to the beginning of the Anzi phase in the regional periodisation). For this date the 95% confidence interval of the calibrated age ranges between 568 and 650 CE, suggesting that these two infills are at least ca. 650 years younger than the lowermost one and thus more or less coeval with that of P02. In addition, the dating results indicate that the pot sherds of the upper infills represent the early Niaosong phase instead of the beginning of the Niaosong period. The ¹⁴C dating results associate the *V. angularis* assemblages from P02 with the early Niaosong phase, that from P01 with the transitional phase and early Niaosong phase and those from the remaining six pits (P09, P14, P16, P17, P18, P20) with the Wushantou phase.

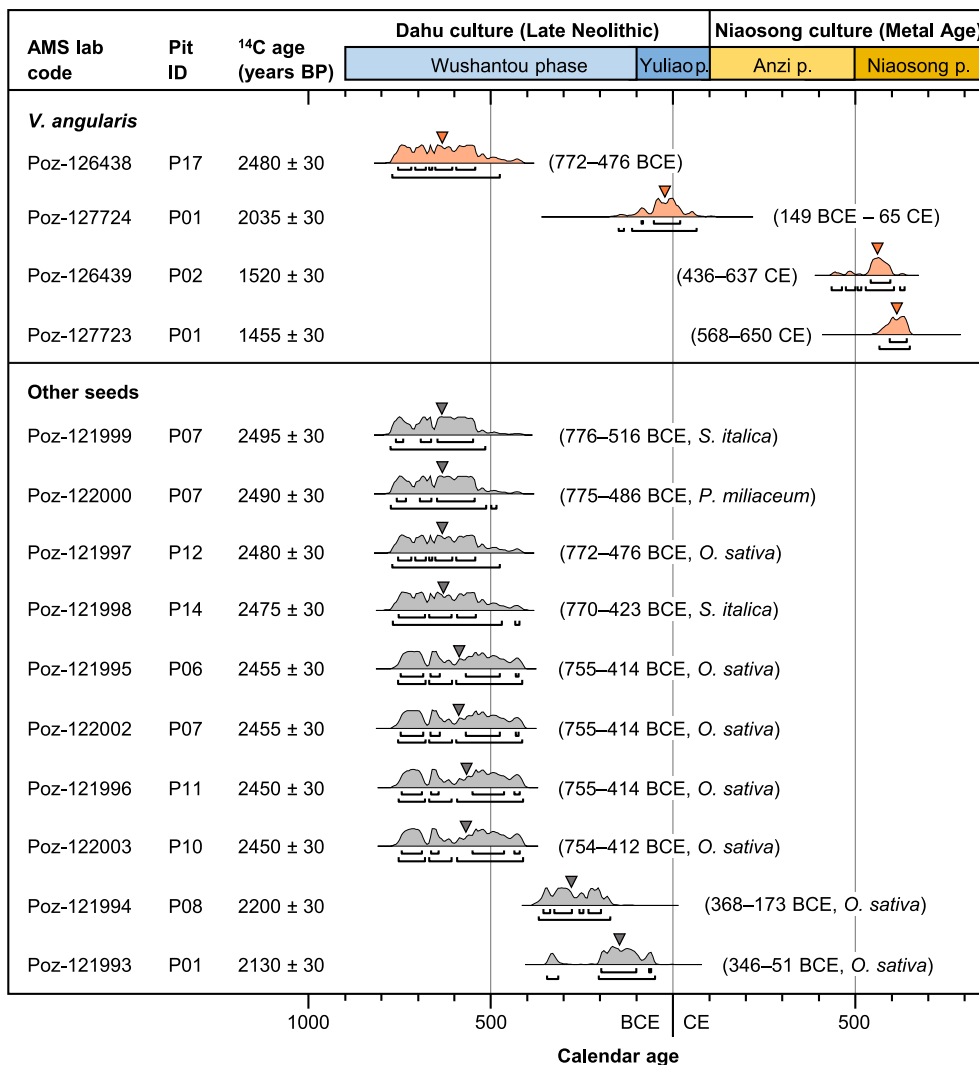


Fig. 2. AMS ¹⁴C dates and probability distributions (silhouettes), probability densities at 68% (upper square brackets) and 95% (lower square brackets and intervals in parentheses) confidence levels and medians (arrows) of calibrated ages of selected carbonised seeds from the analysed ash pit deposits of the Sanbaopi 5 site. Archaeological cultures and phases for south-western Taiwan are drawn according to Tsang and Li (2015). Note that typical Yuliao phase pottery is not represented in the Tainan Science Park area so that this interval between the Wushantou phase and the Niaosong period is termed transitional phase throughout the text. See Supplemental Fig. S1 for location of pits.

4.2. *V. angularis* records

Deposits of 74 archaeological features (jar burials, sherd assemblages and ash pits) at Sanbaopi 5 were processed by flotation. A total of 44 ash pits contained charred remains of wild and cultivated plants described in detail in Leipe et al. (in prep). Cultivated plants comprise cereals, including foxtail millet, broomcorn millet, rice, Job's-tears, and pulses, including soy bean, pigeon pea (*Cajanus cajan*), mung bean (*Vigna radiata* var. *radiata*) and *V. angularis* (Fig. 3), which was identified based on the following criteria. The pulses have a generally cylindrical shape and appear spherocylindrical/ovate to cylindrical in lateral view, which are typical morphological features of Asian *Vigna* species summarised in the subgenus *Ceratotropis* (Fuller and Harvey, 2006). The cross-section (Fig. 3, specimen 3) of most pulses is slightly trianguloid (Fuller and Harvey, 2006). Several split cotyledons still possess the plumule, which appears generally small and short relative to the cotyledon size (Fig. 3, specimens 6 and 7) (Lee, 2013; Yoshizaki, 1992; Yoshizaki and Tsubakisaka, 2001). The hilum of the recorded specimens is not preserved,

although the depressions on preserved ventral sides indicate that it was relatively long (Fuller and Harvey, 2006). The same authors argue that beside its length, its displacement towards one end is another prominent trait of the hilum. This does not seem to be a distinct characteristic in the pulses from Sanbaopi 5. However, the described hilum position may be common in *V. angularis*, but is not a universal feature, at least not in the wild progenitor (*V. angularis* var. *nipponensis*) of azuki (Takahashi et al., 2017).

Since the identification of *Vigna* to species level based on their seeds requires great caution, we also took into account seed morphology of regional species. The Flora of China lists 13 species that are naturally distributed across Taiwan (Wu and Thulin, 2010). Among them, pulses of *V. riukiensis* and *V. reflexo-pilosa* appear morphologically similar to the specimens recorded at Sanbaopi 5. Both belong to the 'azuki bean group', which is a subdivision of the subgenus *Ceratotropis* based on seedling characteristics (Egawa and Tomooka, 1994). Pulses of *V. riukiensis*, which has a relatively small geographic distribution range stretching from the southern Ryukyu Islands (Okinawa Prefecture) to

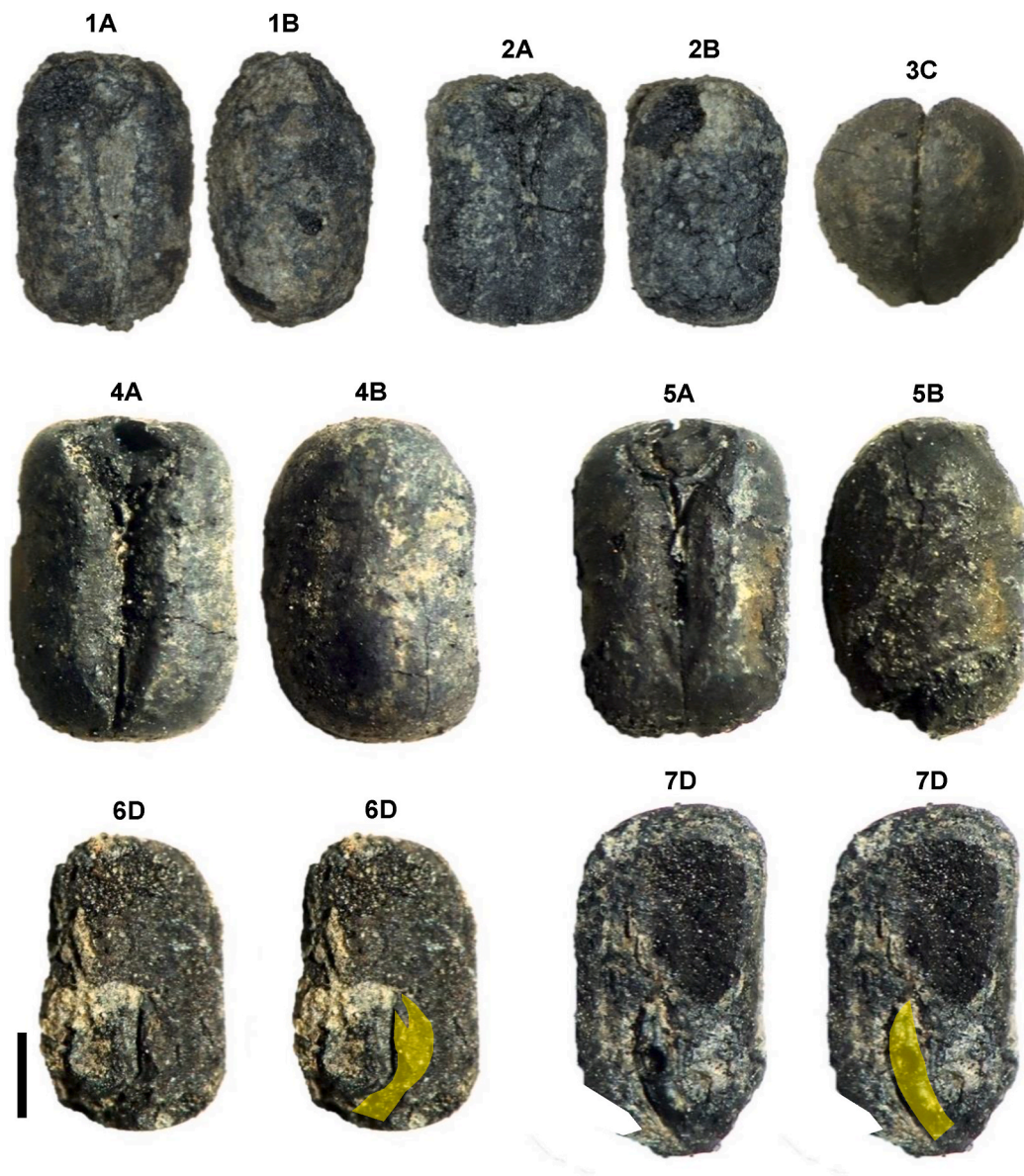


Fig. 3. Carbonised seeds of *Vigna angularis* from Dahu (1, 2, 6) and Niaosong (3, 4, 5, 7) cultural layers dated to ca. 800–170 BCE and the 6th century CE (Fig. 2), respectively. Seeds are shown in ventral (A), lateral (B) and cross-section (C) views; cotyledons with plumules (D) are highlighted in yellow; scale bar = 1 mm. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Taiwan, also have a relatively long hilum (Supplemental Fig. S3) and a small and short plumule (Supplemental Fig. S4). However, the analysed modern specimens from Taiwan and Ishigaki Island demonstrate that the ends of the long axis are more rounded and the overall pulse shape tends to be more elliptic and less oblong (Supplemental Fig. S3) as also noted by Tomooka et al. (2002b).

V. reflexo-pilosa has been identified as the progenitor of *Vigna glabrescens*, a little-known crop commonly called creole bean, probably domesticated somewhere in mainland Southeast Asia (Tomooka et al., 2002a) and today cultivated in Vietnam, the Philippines, Mauritius and West Bengal (eastern India) (Tomooka et al., 2011). The overall oblong pulse shape with rounded to angular ends resembles that of the specimens from Sanbaopi 5 (Supplemental Fig. S3). The hilum, which occupies a central position on the ventral side, is described as ‘narrowly elliptic’ by Tomooka et al. (2002b) and appears relatively short and elliptic to ovate in the modern reference populations. However, this cannot be used as a diagnostic property in this study, since not preserved in the archaeological specimens. A more indicative feature is the plumule, which in *V. reflexo-pilosa* is significantly larger in relation to pulse size than that of the archaeological specimens (Fig. 3) and fresh *V. angularis* var. *nipponensis* (Supplemental Fig. S4). Based on the sum of these traits we assign the *Vigna* morphotype recorded in the Sanbaopi 5 ash pits to *V. angularis*.

A total of 81 *V. angularis* were recorded in pits P09, P14, P16, P17, P18 and P20 (Supplemental Fig. S1) dating to between 800 and 170 BCE, which corresponds to a ubiquity of 16%. One *V. angularis* pulse was recovered from the lowermost infill (100–136 cm) of P01 from the sampling interval of 130–140 cm depth dating to ca. 150 BCE–70 CE and one from the intermediate infill (70–110 cm) at the depth interval of 90–100 cm dating to ca. 570–650 CE (Fig. 2). P02, dated to the 6th

century CE, contained a large number of *V. angularis* seeds, which is, based on volumetric measurements, estimated to around 193,700. In this pit *V. angularis* was admixed with thousands of charred pigeon peas (*Cajanus cajan*) and mung beans (*V. radiata* var. *radiata*), estimated to respectively 2200 and 41,300, and a few remains of wild grasses.

4.3. Size measurements

Visual comparison of both *V. angularis* populations suggested that the seeds from P02 from the 6th century CE (Niaosong phase) are on average larger than those dating to the 800–170 BCE interval (Wushantou phase). To verify this observation, we measured the recorded seeds from the Wushantou phase ($n = 78$) and a selection of representative seeds of the Niaosong assemblage ($n = 50$) for L, W and T dimensions to obtain a volumetric ($L \times W \times T$) measure (Supplemental Table S2). The pulses from ash pits associated with the Wushantou phase have a median $L \times W \times T$ of 11.5 and a mean of 11.9. The interquartile range (IQR) stretches from 10.4 to 13.4 (Fig. 4). The Niaosong assemblage has a median $L \times W \times T$ of 20.1 (mean = 21.0) and an IQR from 17.6 to 22.4. While the single pulse from P01 directly dated to 149 BCE–65 CE has a volume ($L \times W \times T = 13.2$) that is in the upper size range of the Wushantou assemblage, the size ($L \times W \times T = 26.9$) of the single pulse from the same pit dated to 568–650 CE falls into the range of the 75th and 90th percentile of the Niaosong assemblage (Fig. 4).

For size evaluation of the Sanbaopi 5 specimens we charred pulses of modern *V. angularis* var. *nipponensis*. With an IQR from 11.4 to 13.9, an $L \times W \times T$ median of 12.7 and mean of 13.4 the pulses of the plant from Taiwan are on average slightly smaller than that from the Wushantou phase (Fig. 4, Supplemental Table S2). On the other hand, the plant from Kyushu Island produced slightly larger pulses. With a value of 15.0 the L

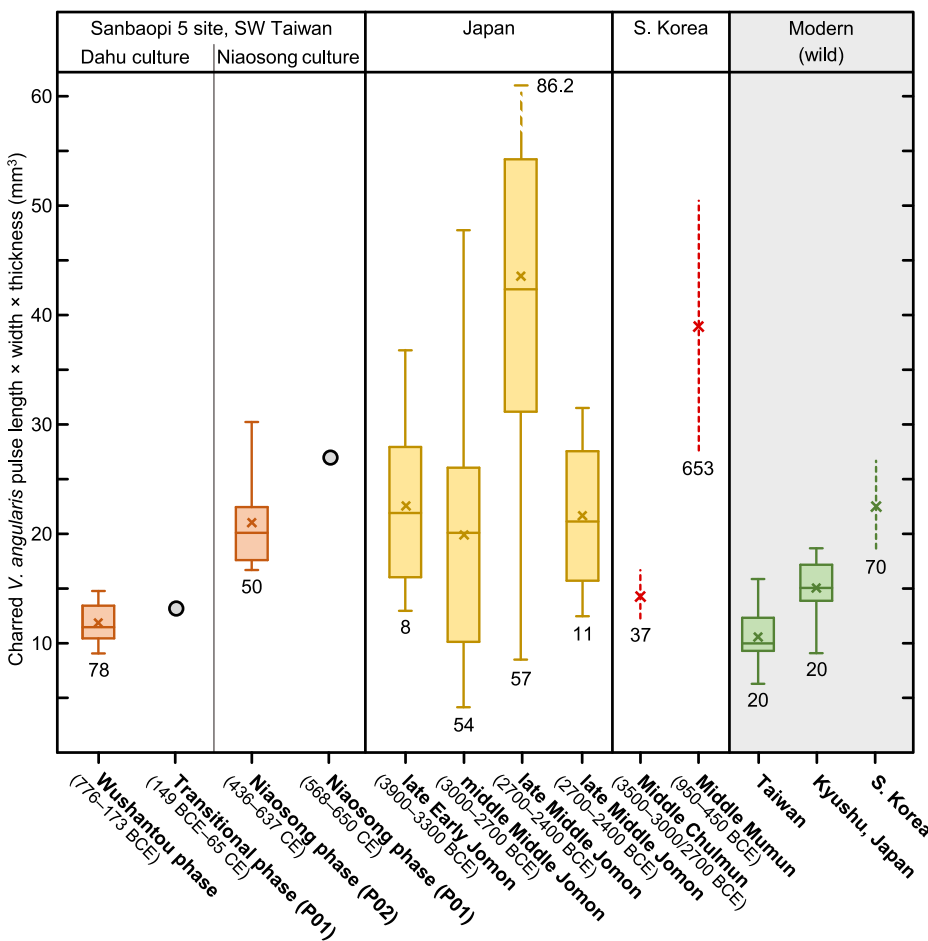


Fig. 4. Length × width × thickness distribution of fossil (carbonised) *Vigna angularis* pulses from Dahu and Niaosong cultural layers at the Sanbaopi 5 site (this study), late Early (Kajoji), middle Middle (Mekiri) and late Middle (Oyokomichiu, larger seed size; Minamione, smaller seed size) Jomon period sites in the Japanese Central Highlands (Nasu et al., 2015), Middle Chulmun and Middle Mumun period sites in South Korea (Lee, 2013) and charred modern reference pulses of *V. angularis* var. *nipponensis* from Taiwan and Kyushu Island (Japan) obtained from the Genetic Resources Center of the National Agriculture and Food Research Organization, Japan (this study) and from South Korea derived from the Rural Development of Agriculture of Korea (Lee, 2013). In the box-and-whisker plots the box’s top and bottom boundaries and inner lines correspond to the 75th percentile, 25th percentile and 50th percentile (median), respectively. Whiskers stretch from the 10th percentile (bottom) to the 90th percentile (top), crosses show arithmetic means and numbers indicate numbers of measured specimens. Crosses in combination with dashed lines represent arithmetic means and standard deviations of the measured pulse populations, respectively. Grey circles show values for single pulses recorded in P01. For the *V. angularis* assemblages from Sanbaopi 5 calibrated age ranges (95% confidence interval) of direct ¹⁴C dates (Fig. 2) are given.

× W × T median and mean are close to the upper whisker of the Wushantou data set. The IQR stretches from 13.9 to 17.2.

5. Discussion

5.1. *V. angularis*' contribution to diet of local populations

The morphological characteristics of the identified *Vigna* pulses from the Sanbaopi 5 cultural deposits suggest that they represent *V. angularis*. Compared to the ubiquities of foxtail millet (59%), broomcorn millet (41%) and rice (61%), *V. angularis* occurs less frequent (16%) in the sampled Wushantou ash pits (Leipe et al., in prep). However, with 81 counted specimens from six different pits the use of these pulses does not seem sporadic, but suggests that it was an inherent part of the local populations' economy during this period. This is advocated by the continuous presence of this pulse between ca. 800–170 BCE and the 6th century CE as suggested by the specimens dating to the transitional phase (ca. 150 BCE–70 CE) (Fig. 2).

Finds of pulses are also documented from other Niasong culture sites in the Tainan Science Park. At Daoye 75 pulses out of 5350 seeds were identified (Tsang and Li, 2010). At Wujiancuo flotation of cultural layers brought to light 774 pulses contained in a total of 163,841 seeds, most of which (94%) are associated with chinaberry (*Melia azedarach*) (Tsang and Li, 2009). If chinaberry is excluded from the sum of identified seeds (including also *Cordia dichotoma*, rice and Job's-tears), pulses account for 20% of this record. The provided photographs in the respective excavation reports do not allow a precise identification, but only indicate that these pulses may belong to the *Vigna* genus and possibly represent *V. angularis*. In addition, unidentified pulses have been

found at other archaeological sites associated with the Wushantou phase. At Youxianfang South 2 and Wangang 22 out of 348 seeds and four out of 59 seeds were assigned to the legume family, respectively (Tsang and Li, 2010). The use of legumes in the Tainan Science Park area can be traced back even further. Undifferentiated pulses were found in Dabengkeng cultural (3000–2200 BCE) layers (Tsang et al., 2006). 'Many varieties of legumes' have been reported from the Youxianfang site dated to the Niuchuozi period (Tsang and Li, 2015). Although the published photographs do not allow size assessment or more precise identification, they suggest that the shown pulses may represent *V. angularis* and were recorded in large numbers (Tsang and Li, 2008).

5.2. *V. angularis* origin and domestication

Considering a long-term use of *V. angularis* at the study site raises the question whether this plant underwent domestication. Azuki has been widely cultivated in East Asia since the Neolithic (Lee, 2013). Its wild ancestor (*V. angularis* var. *nipponensis*) is distributed across a wide area in South and East Asia (Fig. 1A), which largely corresponds to the Asian warm-temperate evergreen broadleaved forest zone (Isemura et al., 2011). Evidence for early domestication of *V. angularis* var. *nipponensis* comes from northern China, the Korean Peninsula and Japan (Table 1). The earliest appearance is reported from Jomon cultural layers in Japan. Evidence of relatively large azuki comes from the early Middle Jomon (3300–3000 BCE) Shimoyakebe site in the Kanto region, central Japan (Sasaki et al., 2007). One pulse was directly dated (MTC-05837, 4515 ± 45 ¹⁴C BP) to 3366–3035 BCE (95% confidence interval) (Kudo and Sasaki, 2010). Although the recorded *Vigna* pulses with L of 3.3–5.8 and W of 2.4–3.8 mm could not be unequivocally identified as *V. angularis*.

Table 1

Records of *V. angularis* from cultural layers of archaeological sites across East Asia mentioned in the text and/or shown in Fig. 4 and, if available, radiocarbon dates directly obtained from *V. angularis* remains. Archaeological sites with equivocally identified *V. angularis* remains are marked by an asterisk.

Site name, location	Material	Cultural period	Conventional age of cultural period	Radiocarbon date, uncal yr BP	Calendar age, BCE (95% probability range)	Reference
<i>Japan</i>						
Awazu, Kansai region	charred seeds	Initial Jomon	9000–5000 BCE			Minaki and Nakagawa (2000), Nasu (2018) Nakagawa (1997), Nasu (2018)
	charred seeds	Middle Jomon	3300–2400 BCE			
Torihama shell mound, Hokuriku region	uncharred seeds	Early Jomon	5000–3300 BCE			Yoshizaki and Tsubakisaka (2001)
Kajoji, Central Highlands	charred seeds	late Early Jomon	3900–3300 BCE	5385 ± 25	4334–4066	Nasu et al. (2015)
Shimoyakebe*, Kanto region	charred seeds	early Middle Jomon	3300–3000 BCE	4515 ± 45	3366–3035	Sasaki et al. (2007)
Mekiri, Central Highlands	charred seeds, seed impressions	middle Middle Jomon	3000–2700 BCE	4390 ± 25	3092–2917	Nasu et al. (2015)
Oyokomichiue, Central Highlands	charred seeds	late Middle Jomon	2700–2400 BCE	4025 ± 25	2621–2469	Nasu et al. (2015)
Minamione, Central Highlands	charred seeds	late Middle Jomon	2700–2400 BCE	4005 ± 25	2574–2468	Nasu et al. (2015)
Motonobaru, south-eastern Kyushu	seed impressions	Late Jomon	2400–1300 BCE			Obata and Miyaura (2021)
<i>Korean Peninsula</i>						
Osanri C*, Gangwon Province	seed impressions	Initial Chulmun	6000–5000/4500 BCE			Lee et al. (2019)
Bibongri, South Gyeongsang Province	seed impressions	Early Chulmun	5000/4500–3500 BCE			Kwak et al. (2020)
Daundong, South Gyeongsang province	charred seeds	Middle Chulmun	3500–3000/2700 BCE	2510 ± 70	797–417	Crawford and Lee (2003)
Okbang, South Gyeongsang province	charred seeds	Middle Chulmun	3500–3000/2700 BCE			Crawford and Lee (2003)
Pyeonggeodong, South Gyeongsang province	charred seeds	Middle Chulmun	3500–3000/2700 BCE	4350 ± 25	3072–2901	Lee (2013)
				4175 ± 25	2884–2637	
<i>China</i>						
Liangchengzhen, southern Shandong Peninsula	charred seeds	late Longshan	2600–2000 BCE			Crawford et al. (2005)
Wangchenggang, northern Henan Province	charred seeds	Shang dynasty	1600–1400 BCE			Fuller and Zhang (2007)

Evidence for azuki was also reported from several sites in different parts of the Japanese Central Highlands dating to the Early, Middle and Late Jomon periods (Fig. 4) (Nakayama, 2019; Nasu et al., 2015) and the waterlogged Torihama shell mound site (western Hokuriku region, central Honshu) dating to the Early Jomon period (5000–3300 BCE) (Yoshizaki and Tsubakisaka, 2001). The earliest use of *V. angularis* is indicated by a sample of relatively small pulses indistinguishable from wild ones found in a 10,000-year-old cultural layer (Initial Jomon period) at the waterlogged Awazu site located within the modern extent of Lake Biwa (Minaki and Nakagawa, 2000). This site also has evidence for size increase with larger pulses excavated from layers dating to the Middle Jomon period (Nasu, 2018). *V. angularis* use is also documented by archaeobotanical records from Middle Chulmun cultural layers at the Okbang and Daundong sites on the south-eastern Korean Peninsula dating to ca. 3000 BCE (Crawford and Lee, 2003). A single *V. angularis* seed impression on a pot sherd associated with the Early Chulmun period (5000–3500 BCE) from the Bibongri site suggests that use of this pulse started even earlier (Kwak et al., 2020). However, the earliest evidence for larger, azuki-type pulses dates to the 1st half of the 1st millennium BCE (Middle Mumun period). Older are finds of azuki-type pulses from late Longshan (2600–2000 BCE) cultural layers at the Liangchengzhen site on the southern Shandong Peninsula in China (Crawford et al., 2005).

The available archaeobotanical evidence for at least three geographical origins of azuki (Lee, 2013) is corroborated by a phylogenetic investigation of cultivated and wild form accessions across the natural distribution zone of *V. angularis* var. *nipponensis* (Zong et al., 2003). The latter study also revealed a potential for further independent domestication centres, such as the Nepal-Bhutan region from where analysed modern seeds show a high genetic diversity. A more recent study (Xu et al., 2008) discovered genetic distinctness also for azuki accessions collected in northern Vietnam (Lao Cai Province). The authors suggest that the Vietnamese azuki originated from regions further north, as they are genetically most closely related to analysed accessions from the Middle Yangtse River basin. Although their size (L = 4.9 mm; W = 3.9 mm) is relatively small, which raises the question when, and if as cultivated populations, at what stage of domestication, these cultivars may have found their way to northern Southeast Asia. Although archaeobotanical data from south of the Yellow River region is extremely limited, there is scant evidence for *Vigna* use in southern mainland China during prehistoric times. Small pulses that may potentially represent *V. angularis* based on the provided descriptions and photographs are documented from the Baiyangcun site in Yunnan Province (Dal Martello et al., 2018) dating to the late 3rd millennium BCE and the Baodun site in central Sichuan Province dating to the middle of the 3rd millennium BCE (D'Alpoim Guedes et al., 2013).

An increase in seed/fruit size is one of the most common traits associated with plant domestication (Hancock, 2012) and probably the most important and obvious criterion for detecting this process in archaeobotanical studies. This also applies to pulses, with those of domesticated specimens being generally larger than those of their wild progenitors. However, archaeological pulses with a size that falls within the range of wild forms does not rule out that plants underwent human management including selection and cultivation. This phenomenon is discussed by Fuller and Harvey (2006) regarding the domestication of mung bean in India. The authors assume that during the Neolithic selection was first targeted towards seed dispersal, such as loss of dormancy and non-dehiscent pods (Butler, 1989; Zohary and Hopf, 2000). Distinction from modern populations of its wild progenitor (*V. radiata* var. *sublobata*) by larger size is only feasible for mung bean that was cultivated not before Early Historic times. From the occurrence of *V. radiata* at high sample ubiquities and in regions where *V. radiata* var. *sublobata* does not grow Fuller and Harvey (2006) inferred that this legume was cultivated and underwent domestication during the Neolithic and proposed that mung bean seed enlargement postdates initial cultivation and selection for other genetic traits by perhaps

1500–2000 years. An even longer delay in seed enlargement of about 2000–4000 years has been recognised in the domestication process of the Near East pulses lentil (*Lens culinaris*) and pea (*Pisum sativum*) (Fuller, 2007 for discussion and references).

The current *V. angularis* record from Sanbaopi 5 allows to assess pulse size and to evaluate whether it had changed over the represented period. The volumetric (L × W × T) measurements (Fig. 4, Supplemental Table S2) demonstrate that the size of the Niaocong specimens is on average 1.7 times larger compared to those of the Wushantou phase, which may reflect a response to selection for size increase that happened over a period of ca. 600–1400 years (Fig. 2). Although statistically less significant, the two dated specimens from P01 agree with this interpretation. The size of the pulse dating to ca. 150 BCE–70 CE falls into the larger half of the Wushantou size range and thus may represent an intermediate stage towards the development of larger pulses. The size of the younger specimen coincides both in age and size with the Niaocong assemblage from P02. The size distributions of *V. angularis* var. *nipponensis* may differ markedly from each other. The set of modern wild seeds from Taiwan is slightly smaller than the Wushantou pulses, the wild seeds from Japan have a size that ranges between the Wushantou and Niaocong sets and the mean size of the wild seed set from the Korean Peninsula slightly exceeds that from the Niaocong period (Fig. 4). Although the three *V. angularis* assemblages from late Early (Kajoji site), middle Middle (Mekiri site) and late Middle (Minamione site) Jomon period sites in the Japanese Central Highlands have a wide size distribution (Nasu et al., 2015), the mean and median values of around 20 mm³ are comparable with those from the Niaocong period (Fig. 4). Of relatively small size (mean = 14.5 mm³) within the range of wild specimens are also the pulses from Chulmun cultural layers (Lee, 2013). Pulses that are clearly larger than the measured wild populations are reported from the late Middle Jomon Oyokomichiu site (mean = 43.6 mm³; Nasu et al., 2015) and Middle Mumun (mean = 39.1 mm³; Lee, 2013) contexts, although they are still much smaller than modern azuki (mean volume around 180 mm³; Lee, 2013). Charred *V. angularis* (n = 9) are also reported from the Longshan culture Liangchengzhen site in Shandong Province (Crawford et al., 2005). Based on the given L and W measurements their volume can be estimated to around 40 mm³, which is similar to that of the larger late Middle Jomon (Nasu et al., 2015) and Mumun (Lee, 2013) specimens (Fig. 4) dating approximately to the first half of the 3rd millennium BCE and 950–450 BCE, respectively.

In accordance with the evolution of bean crops from India and the Near East, Lee (2013) concluded that cultivation/domestication of azuki cannot be tied to seed size alone. Despite their small size, which is within the range of wild specimens, it is possible that the Wushantou phase *V. angularis* records represent cultivars, which underwent selection for morphological changes. Like their counterparts from Chulmun period Korea (Lee, 2013) and likely Initial Jomon period Japan (Minaki and Nakagawa, 2000) as well as other grain legumes from India and the Near East, they already appear in the local archaeobotanical records from Wushantou cultural layers, which are much older than those from the Niaocong phase marked by a larger mean size, thus suggest a long history of use in the study region. Another evidence suggesting that the smaller-sized *V. angularis* from Chulmun period Korea and the Wushantou phase were cultivated is that they are associated with fully domesticated crops, such as rice and broomcorn and foxtail millet. Domestication of different plants during the Jomon period has been also widely accepted (Crawford, 2011; Nasu, 2018). One of them is soy bean, which has been domesticated from *Glycine soja*. Although there is evidence that both *V. angularis* and *G. soja* were used since the onset of the Jomon period, a substantial increase in size reaching volumes of modern cultivars by the Middle Jomon period is only documented for the latter species (Lee et al., 2011; Nasu et al., 2015). This finding has led to the hypothesis that domestication of both pulses was underway already long before the Middle Jomon period, but size increase in *V. angularis* was delayed (Nakayama, 2019; Nasu et al., 2015).

Knowledge about the domestication of different legumes in Asia

demonstrates that it is difficult to identify and track the genetic transformations in *V. angularis* var. *nipponensis* leading to the development of azuki. However, there seems to be sufficient indication that the *V. angularis* from Sanbaopi 5 were cultivated and that the specimens from P02 dating to the 6th century CE are the result of selection for larger seed size. Additional evidence that the assemblage from P02 may be classified as azuki is provided by the archaeobotanical composition of this pit. The pulses are accompanied by two fully domesticated legume crops (mung bean and pigeon pea) and represent the biggest share both in absolute numbers and volume.

While it is clear that mung bean and pigeon pea were domesticated on the Indian Subcontinent, the origin of *V. angularis* found in the cultural layers at Sanbaopi 5 remains unresolved. It is possible that the legume or the traditions of its use were introduced along with broom-corn/foxtail millet and rice by farmers, who started to spread from continental China to Taiwan from the early 3rd millennium BCE (Deng et al., 2018, 2020; He et al., 2017). Alternatively, it is possible that the larger *V. angularis* from the 6th century CE represent cultivated azuki, which was introduced to the study region by exchange or immigration. This seems plausible since these azuki-type pulses appear relatively late, i.e., about 4500 years later than domesticated azuki in Japan or 1500 years later than those on the Korean Peninsula, and at a time, which is marked by enhanced exchange activities in East and Southeast Asia (Hung et al., 2007). This scenario would be also in agreement with genetic studies that see a potential origin of northern Vietnamese azuki in the Middle Yangtze region (Xu et al., 2008). However, archaeobotanical records from Japan and the Korean Peninsula also indicate that *V. angularis* was used long before azuki-type pulses appeared. On the Korean Peninsula the oldest reliable evidence for *V. angularis* use predates the appearance of domesticated forms by around 4500 to 2500 years (Lee, 2013; Kwak et al., 2020). In Japan the oldest record of wild-size *V. angularis* predates a marked size increase by around 6000 years (Nasu et al., 2015; Nasu, 2018). Thus, it appears possible that cultivation of *V. angularis* var. *nipponensis* started independently at the study site or elsewhere in the region by the beginning of agriculture during the Dabengkeng period or earlier. To address these open questions, further archaeobotanical studies on Taiwan and in continental China that pay careful attention to legume remains are needed. This may also provide further information about the motivation of *V. angularis* cultivation and whether azuki domestication in early cereal-based agricultural societies was a consequence of the use of its wild progenitor as manure as hypothesised by Lee (2013) regarding the early millet farmers of the Chulmun period on the Korean Peninsula.

6. Conclusions

The current study provides evidence for the use of *V. angularis* by early agricultural populations in the south-western part of Taiwan. The pulse was used at Sanbaopi 5 for at least one millennium, i.e., between the 6th century BCE and 6th century CE, which indicates that it was an inherent part of the food economy of local populations. The specimens from the end of this period are substantially larger than those dating to the beginning of this period and may be addressed as azuki, the domesticated form of *V. angularis* var. *nipponensis*.

The background of this comparatively late occurrence of azuki on Taiwan remains unclear and needs to be addressed in future archaeobotanical investigations on Taiwan and in continental China. One scenario is that the pulse underwent selection for size increase, i.e., was domesticated in the study region. This would mean that prehistoric Taiwan was an independent centre of azuki cultivation/domestication in addition to previously suggested northern China, the Korean Peninsula and Japan. On the other hand, it is possible that azuki was introduced from regions outside Taiwan, such as continental China, by exchange or immigrants. The current finds emphasise the widespread use of *V. angularis* and its economic importance across prehistoric East Asia. It appears that the pulse maintained its importance in roughly the same

places as in prehistory.

Documentation of existing archaeobotanical records from Tainan Science Park sites suggest that cultivation of pulses (possibly *V. angularis*) may have started much earlier there, perhaps around the beginning of agriculture ca. 3000 BCE or even before. Future morphological studies will clarify the identity of these prehistoric pulse records. This study demonstrates once more the difficulty in unambiguous identification of charred pulses from archaeobotanical assemblages, especially those of *Vigna*. The sum of existing evidence hints at geographically more widespread azuki cultivation during East Asia's prehistory than is known today and calls for cautious and thorough examination of archaeobotanical records regarding pulse remains.

Author contributions

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

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Data availability

All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Data.

Declaration of competing interest

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

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Appendix A. Supplementary data

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