





Research Article

The early adoption of East Asian crops in West Asia: rice and broomcorn millet in northern Iran

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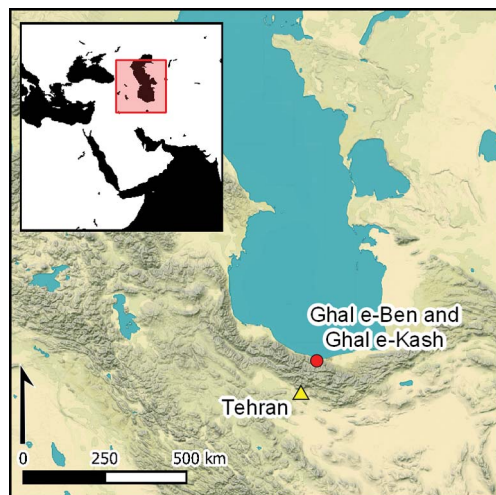
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Following their early domestication, broomcorn millet and rice (in East Asia) and wheat and barley (in South-west Asia) were subsequently adopted across Eurasia during the Bronze Age/early historic period. The precise timing and dispersal routes for this trans-Eurasian exchange, however, remain unclear. Here, the authors present archaeobotanical evidence from sites on the Caspian Sea's southern coast, demonstrating that broomcorn millet reached West Asia by *c.* 2050 BC and rice by *c.* 120 BC. These dispersals relate to two waves of globalisation and were based on two different mechanisms: an 'infiltration' model (broomcorn millet) and a 'leapfrog' model (rice). The results contribute to our understanding of the continental-scale connectivity of the late prehistoric/early historic periods.

Keywords: Eurasia, Silk Route, *Panicum miliaceum*, *Oryza sativa*, *Triticum timopheevii*, agriculture, crop dispersal

Introduction

The transmission and exchange of innovations such as domesticated species, metallurgical technologies and prestige goods have played a significant role in human history, contributing to diverse local trajectories of social evolution (Bentley 1993; Sherratt 2006; Earle 2017). The historical 'Silk Road', linking the Roman, Parthian and Han empires, has long been understood to reflect the cultural interactions that connected much of Eurasia and Africa by the early first century AD (McLaughlin 2016; Cosmo 2020). In recent years, however, a growing body of archaeological scholarship has focused on evidence of transcontinental cultural

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exchange stretching back to the Early Bronze Age, *c.* 2000 BC, seeing it as an early example of globalisation (e.g. Christian 1998; Kuzmina 2008; Jones *et al.* 2011).

At the forefront of these archaeological studies of ancient trans-Eurasian exchange is an interest in the movement of domesticated crops and livestock (e.g. Frachetti *et al.* 2010; Jones *et al.* 2011; Boivin *et al.* 2012; Jones *et al.* 2016; Stevens *et al.* 2016; Liu *et al.* 2019; Spengler 2020). Domesticated species that originated in the Near East, such as wheat, barley, goat and sheep, as well as metallurgical technologies, were introduced into China during the second millennium BC (Mei 2003; Liu *et al.* 2017; Long *et al.* 2018). These exotic elements profoundly changed the economic and social conditions of East Asia in the following millennia. Wheat became the most important staple crop for much of northern China by the time of the Han Dynasty (202 BC–AD 220; Hsu 1980), while pastoralism also attained fundamental importance in the economic system of the north and north-west steppe region of China at this time. The introduction of barley and sheep at higher elevations of the Tibetan Plateau facilitated increased population densities in this area after 1600 BC (Chen *et al.* 2015; d’Alpoim Guedes *et al.* 2016; Tang *et al.* 2021). In terms of new technologies, bronze quickly became central to the ritual system of early states in central China and underpinned the emergence of early Chinese civilisation during the Bronze Age (Linduff & Mei 2009; Jaang 2015; Zhang *et al.* 2019).

By contrast, the early history of the east-to-west diffusion of innovations is less secure. Reports of the discovery in Europe of broomcorn millet (*Panicum miliaceum*) in Neolithic contexts dated as early as the seventh millennium BC would imply either a very early westward transmission of crops from East Asia or a second, alternative origin (Hunt *et al.* 2008). Concerns over the reliability of the inferred ages of these finds, and the absence of millet from southern and South-west Asia until *c.* 2000 BC, however, call these claims into doubt (e.g. Fuller & Boivin 2009; Boivin *et al.* 2012). Recently, direct AMS radiocarbon dating of *Panicum* from sites in Europe, including from supposed Neolithic contexts, has demonstrated these grains to be intrusive. The earliest evidence for the arrival of millet in Europe is now dated to *c.* 1600 BC (Motuzaitė-Matuzevičiūtė *et al.* 2013; Filipović *et al.* 2020), while dates from the Caucasus (Georgia) may go back to as early as 2000 BC (Martin *et al.* 2021). Recent archaeobotanical work in Central Asia has provided growing evidence that Bronze Age agriculture in this region combined summer crops, such as Chinese millets, and winter or spring crops from South-west Asia, such as wheat and barley. Early evidence for the cultivation of both groups of crops in Central Asia includes several sites that have produced wheat or barley and millets (*Panicum miliaceum* and/or *Setaria italica*): Tongtian cave in north-west China (Zhou *et al.* 2020), Begash in Kazakhstan (Frachetti *et al.* 2010; Spengler 2015), Adji Kui in Turkmenistan (Spengler *et al.* 2018) and Pethpuran Teng in the Kashmir Valley (Yatoo *et al.* 2020).

Nevertheless, questions remain regarding how far west these crops spread, how early, and what impact they had on agriculture in these regions. Equally, it remains unclear by which routes these crops moved in any particular period, inhibiting assessment of their impacts in space and time. For example, did millets first reach Europe via the steppe to the north of the Caspian Sea, either through the agency of the pastoral societies who were expanding west into Bronze Age Europe (Kristiansen *et al.* 2017), or, through the populations of Armenia and Asia Minor entering Europe through Greece (the ‘Colchis’ route of the classical sources; McLaughlin 2016)? Alternatively, did millets pass south of the Caspian Sea on an early

version of the classic Silk Route, which traversed the Karakum Desert oases (Turkmenistan) and the Kopet Dagh mountains to northern Iran (later controlled by the Parthians; McLaughlin 2016)? Or perhaps there was a route through eastern Iran (Sistan) to the Persian Gulf and lower Mesopotamia. Each of these various routes implies different cultural contexts, with the steppe route occupied by smaller-scale agro-pastoralist communities, while the Kopet Dagh and Sistan routes were mediated by the urban centres of the Bactria-Margiana Archaeological Complex (or Oxus civilisation).

These contexts are relevant to recent debates about whether the westward spread of summer crops such as millets was largely connected to agricultural intensification and summer irrigation (Miller *et al.* 2016; Spengler 2020), or whether millets were first established on a small scale as risk-buffering crops in a diversified, multi-resource adaptation (Brite *et al.* 2017). The westward spread of rice (*Oryza sativa*) in the first millennium BC or early centuries AD is more clearly associated with irrigation systems (Spengler *et al.* 2021). Related archaeobotanical data are still limited, especially from the Iran region. Here, therefore, we present the results of systematic archaeobotanical analyses and direct dating of assemblages from two sites, Ghal e-Ben and Ghal e-Kash, on the southern coast of the Caspian Sea, in northern Iran, which together document a sequence of crop choices spanning *c.* 3000 BC to AD 200, plus a single medieval sample (*c.* AD 1000).

Study sites and chronologies

Ghal e-Ben (36°23'18"N, 52°34'13"E) is located on the southern coastal plain of the Caspian Sea, approximately 20km south of the present-day city of Babol, Iran (Figure 1A). Due to the construction of modern roads and houses over parts of the mound, less than 3ha currently survives. To inform management of the site and to begin its detailed investigation, in 2019 four trenches were excavated in the northern and central part of Ghal e-Ben (Figure 1B). In places, cultural deposits exceed 10m in thickness, the majority of which were formed during the Bronze Age (*c.* 3000–1500 BC; Figure 1C). Prior to this period, evidence of human occupation during the Late Chalcolithic period has also been identified in the lower levels of the site. After the end of the Bronze Age, an oxbow lake formed around the site and possibly lasted for around 300 years, indicating significant environmental changes. Thereafter, the site was reoccupied at around AD 1000, this later activity disturbing earlier cultural deposits, as indicated, for example, by Bronze Age artefacts retrieved from Islamic-period contexts.

Ghal e-Kash (36°28'11"N, 52°25'35"E) is a small settlement mound near Ghal e-Ben (Figure 1A). During archaeological survey in 2008, large quantities of ceramic material were collected from the surface of this site, including light- and dark-grey and light-red ceramics of Bronze Age date, as well as a few ceramics from the Islamic period, indicating multiple periods of human occupation. Later, in 2009 and 2012, a trench was opened at the top of this site for systematic archaeological excavation, revealing that cultural deposits in this area are more than 13m thick, encompassing the Bronze and Iron Ages.

To confirm the precise dates of the sites and related contexts, 15 charcoal samples and eight carbonised seeds from Ghal-e-Ben, as well as three carbonised seeds from Ghal e-Kash, were selected for accelerator mass spectrometry (AMS) radiocarbon dating. Nineteen samples from Bronze Age contexts and two from Islamic-period contexts were selected from

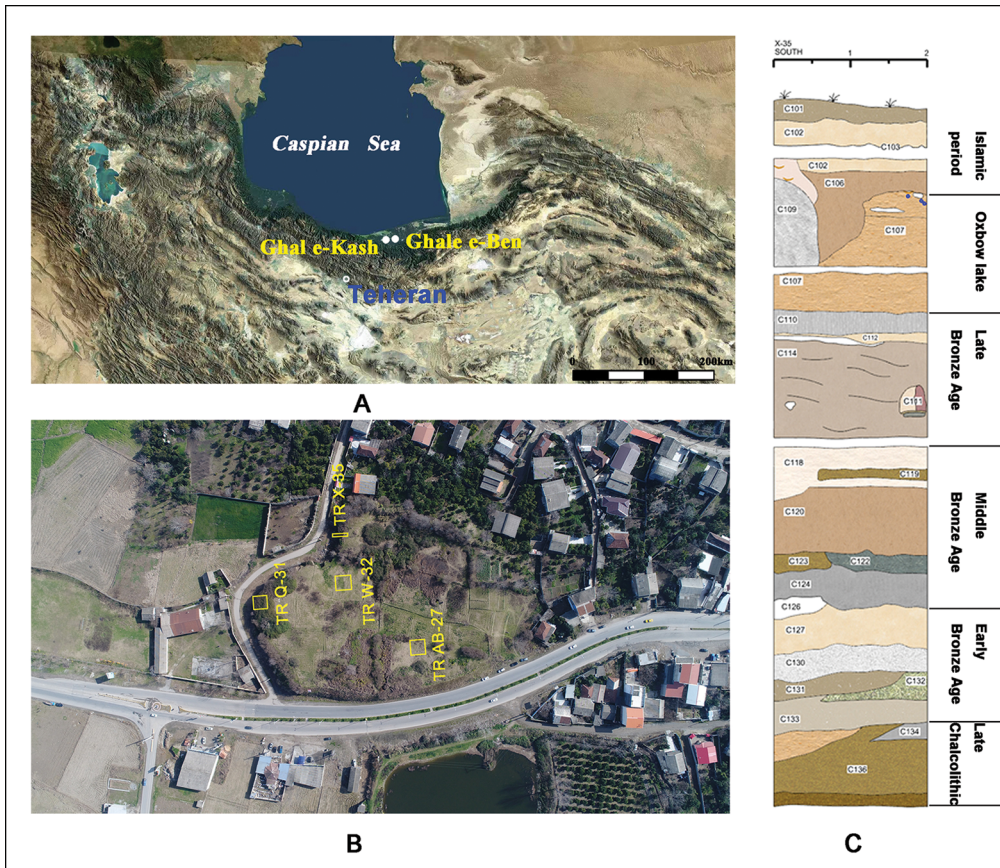


Figure 1. Settings and stratigraphy of Ghal e-Ben and Ghal e-Kash: A) locations of the studied sites; B) modern landscape of Ghal e-Ben, with locations of excavated trenches; C) stratigraphic layers and cultural periods of TR X-35 of Ghal e-Ben (photographs by H.F. Nashli).

Ghal e-Ben, and three from historic-period contexts from Ghal e-Kash (Table 1). All dates were calibrated with OxCal v4.4.4 (Bronk Ramsey 2009), using the IntCal20 atmospheric curve (Reimer *et al.* 2020). With the exception of one sample from an Islamic-period context (306) at Ghal e-Ben, which yielded a Bronze Age date and is therefore residual, all of the other dates are compatible with the stratigraphic matrix and associated artefacts of each site. Broadly, the Late Chalcolithic of Ghal e-Ben extends from *c.* 3300 BC to 3000 BC, and the Bronze Age covers *c.* 3000–1500 BC. Meanwhile, deposits of Islamic date at Ghal e-Ben formed around the tenth-century AD, while the early historic occupation of Ghal e-Kash is much older, dating to between 340 BC and AD 200.

Bronze Age and early historic agricultural systems

For this study, macroscopic plant remains were collected from 18 contexts at Ghal e-Ben and from two at Ghal e-Kash and floated on site. A wide variety of crops and other plant remains

Table 1. AMS radiocarbon dating results of Ghal e-Ben and Ghal e-Kash (all dates calibrated by Oxcal v4.4.4, using the IntCal20 atmospheric curve; Bronk Ramsey 2009; Reimer *et al.* 2020).

Site name	Context/ sample no.	Lab no.	Sample type	Radiocarbon Age (BP)	Calibrated Age (68.3% confidence)	Calibrated Age (95.4% confidence)	Median Age
Ghal e-Ben	CON 306	BA192196	lentil	3210±20	1501–1450 BC	1508–1434 BC	1472 BC
Ghal e-Ben	CON 317	BA190764	charcoal	3245±20	1531–1461 BC	1539–1446 BC	1505 BC
Ghal e-Ben	CON 319	Beta-536438	<i>Triticum aestivum</i>	3280±30	1607–1506 BC	1620–1462 BC	1545 BC
Ghal e-Ben	CON 322	BA190765	charcoal	3820±30	2337–2202 BC	2447–2144 BC	2258 BC
Ghal e-Ben	CON 325	BA190766	charcoal	4010±25	2568–2476 BC	2576–2469 BC	2527 BC
Ghal e-Ben	CON 326	BA192197	<i>Triticum aestivum</i>	3340±20	1629–1543 BC	1686–1535 BC	1601 BC
Ghal e-Ben	CON 334	BA190767	charcoal	4325±20	3003–2899 BC	3011–2893 BC	2918 BC
Ghal e-Ben	CON 337	BA190769	charcoal	4415±20	3095–2940 BC	3263–2925 BC	3041 BC
Ghal e-Ben	CON 109	Beta-559280	<i>Oryza sativa</i>	1080±30	AD 898–1017	AD 892–1023	AD 967
Ghal e-Ben	CON 110	BA192195	<i>Triticum aestivum</i>	3290±20	1608–1516 BC	1613–1508 BC	1556 BC
Ghal e-Ben	CON 111	BA190754	charcoal	3310±20	1612–1539 BC	1621–1518 BC	1574 BC
Ghal e-Ben	CON 113	Beta-536436	<i>Triticum aestivum</i>	3340±30	1667–1541 BC	1735–1532 BC	1606 BC
Ghal e-Ben	CON 114A	BA190755	charcoal	3345±25	1671–1544 BC	1731–1537 BC	1615 BC
Ghal e-Ben	CON 114C	Beta-559281	<i>Panicum miliaceum</i>	3670±30	2133–1980 BC	2141–1951 BC	2057 BC
Ghal e-Ben	CON 115	Beta-536437	<i>Hordeum vulgare</i>	3390±30	1736–1626 BC	1863–1564 BC	1675 BC
Ghal e-Ben	CON 118	BA190756	charcoal	3835±25	2341–2206 BC	2452–2200 BC	2284 BC
Ghal e-Ben	CON 120	BA190757	charcoal	4055±25	2623–2497 BC	2834–2475 BC	2576 BC
Ghal e-Ben	CON 124	BA190758	charcoal	3865±20	2447–2290 BC	2458–2211 BC	2343 BC
Ghal e-Ben	CON 125	BA190759	charcoal	3970±20	2560–2465 BC	2571–2456 BC	2493 BC
Ghal e-Ben	CON 127	BA190760	charcoal	4030±20	2576–2491 BC	2620–2472 BC	2526 BC
Ghal e-Ben	CON 135	BA190763	charcoal	4450±20	3314–3028 BC	3330–3018 BC	3165 BC
Ghal e-Kash	Sample 1	Beta-536434	<i>Oryza sativa</i>	2110±30	168–56 BC	339–46 BC	123 BC
Ghal e-Kash	Sample 2	Beta-536433	<i>Oryza sativa</i>	2090±30	151–51 BC	196 BC–AD 4	102 BC
Ghal e-Kash	Sample 2	BA192194	<i>Hordeum vulgare</i>	1930±20	AD 66–125	AD 25–203	AD 97

attesting ancient agricultural practices are present in nearly all sampled contexts. Details of the plant remains are presented in Table S1 in the online supplementary material (OSM).

Analysis of the 18 samples from Ghal e-Ben indicates that the Bronze Age material resembles that known from elsewhere in the Middle East, being principally based on the cultivation of barley (*Hordeum vulgare*) and wheats; at Ghal e-Ben, the latter are predominantly free-threshing bread wheat (*Triticum aestivum*, identified from rachis segments) rather than the more typical glume wheats. Among glume wheats, however, there are three distinct morphotypes: einkorn (*T. monococcum*), emmer (*T. dicoccon*) and ‘new type’ glume wheat (*T. cf. timopheevii*, or Timopheev’s wheat; Czajkowska *et al.* 2020). The presence of *T. timopheevii* is of note, as this species has a distinctive dispersal pattern in the Neolithic, connecting Anatolia (central Turkey) to northern Iran and Turkmenistan (see OSM1). Meanwhile, barley in the Ghal e-Ben assemblage is dominated by asymmetrical grains, suggesting six-row crops, as does the presence of flared rachis fragments. Grain shapes indicate the presence of both hulled and naked barley varieties (Figures 2 & 3).

Cultivated large legumes comprise a notable proportion in most of the samples. Lentil (*Lens culinaris*) is the most common species among all samples, followed by bitter vetch (*Vicia ervilia*) and grass pea (*Lathyrus sativus*). The generally rounded shape and relatively large size of the *Lathyrus* and *Vicia* material indicate that they are likely to be cultigens. Four examples of pea (*Pisum sativum*) were also identified; their small size (a mean diameter of 3mm) prevents certainty regarding their domesticated status. Most of the pulses are preserved as complete specimens, with a few of the half seeds showing the concave surface of their inner cotyledon side, which can be used as an indicator that the pulses were processed before being charred (Valamoti *et al.* 2011). The remains of fruits and oil/fibre crops are also occasionally present in a few samples, of which *Vitis* seeds are the most common. In addition, a few examples of possible *Vitis* fruit flesh were identified in samples of both Bronze and Iron Age date, indicating the consistent importance of *Vitis*—most likely for winemaking. *Linum* seeds are present in only two samples of Bronze Age date and in low quantity.

In addition to these Near Eastern cultigens at Ghal e-Ben, a notable finding is the presence of three grains of broomcorn millet (*Panicum miliaceum*) from two Bronze Age contexts (Figure 2a). Direct dating of two broomcorn millet grains (combined as one sample) from context 114C confirms that they date to the end of the third millennium BC (2141–1951 cal BC, at 95.4% confidence). This suggests that an East Asian millet and the practice of summer cropping were among agricultural innovations in northern Iran at the start of the Middle Bronze Age.

The composition of samples from the Iron Age levels, post-dating 400 BC, indicates that free-threshing wheat, barley and pulses continued to play a significant role in the overall farming system of the historic period; the absence of glume wheats may be explained by the limited number of Iron Age samples available. The diversification of summer agriculture in this period, however, is suggested by the presence of rice (*Oryza sativa*; Figure 2c). The South Caspian coastal plain of north-western Iran, with its high rainfall and numerous streams flowing from the Alborz and Talesh Mountains, is a significant region for traditional rice production; written sources indicate that the cultivation of rice was established in early historic times (Nesbitt *et al.* 2010). Two direct dates confirm the antiquity of the rice grains from Ghal e-Kash at 339–46 cal BC and 196 cal BC–cal AD 4 (at 95.4% confidence; Table 1).



Figure 2. Cereal grains and chaff from Ghal e-Ben and Ghal e-Kash: a) *Panicum miliaceum*; b) *Setaria italica*; c) *Oryza sativa*; d) *Hordeum vulgare* rachis, six-row, bulled type; e) *Triticum* cf. *timopheevii* glume base; f) *Triticum aestivum*/durum; g) *Triticum* cf. *timopheevii*; h) *Hordeum vulgare* var. *coeleste* (naked, six-row); i) *Triticum aestivum* rachis (photographs by Y. Huang).

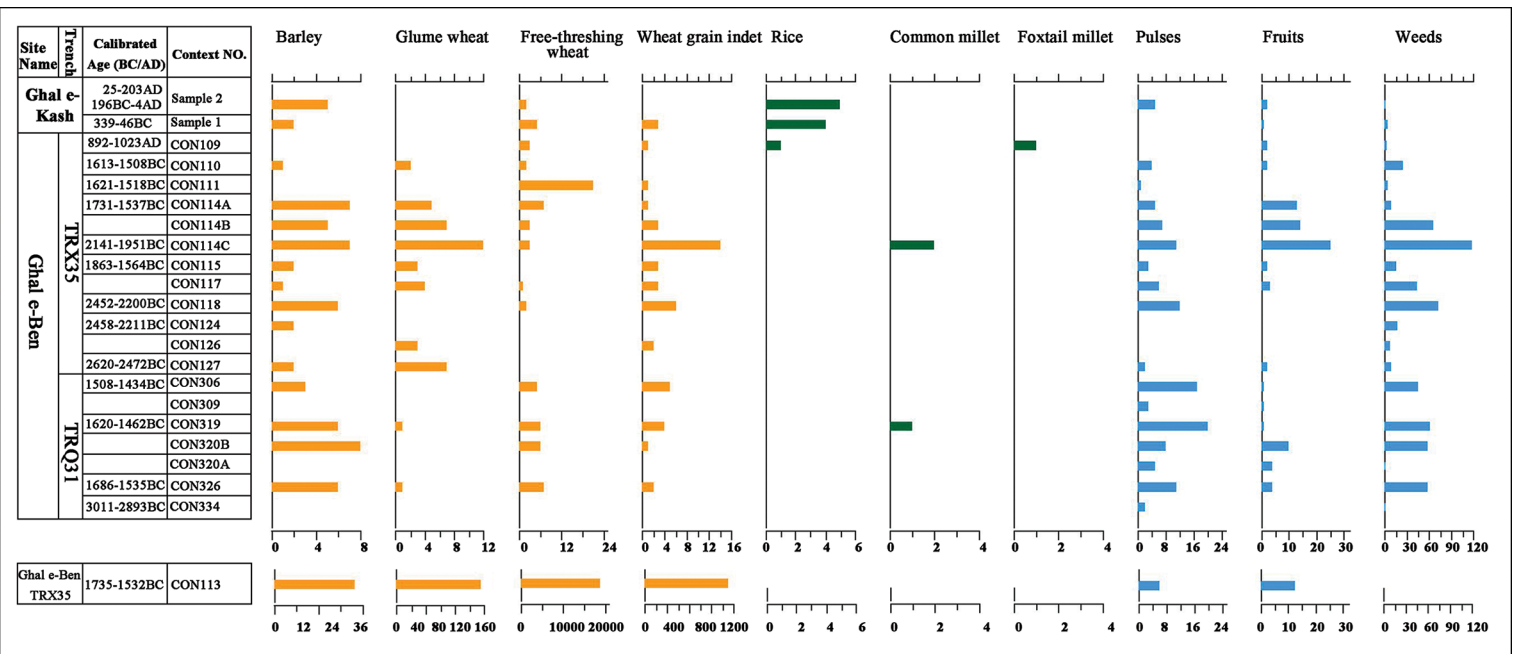


Figure 3. Compositional analysis of plant remains from Ghal e-Ben and Ghal e-Kash (figure by Z. Deng).

Continuity of rice cultivation into the Islamic Period (cal AD 892–1023, at 95.4% confidence) is attested by rice grains from context 109 at Ghal-e-Ben. This context also yielded a single specimen of foxtail millet (*Setaria italica*), another domesticated grain of East Asian origin, which seems to have spread somewhat more selectively and later than *Panicum miliaceum*.

Broomcorn millet in West Asia: the first wave of globalisation

As the earliest East Asian crop incorporated into West Asian and European farming systems, broomcorn millet has long featured as a key element in discussions of early trans-Eurasian communications and prehistoric food globalisation (Jones *et al.* 2011; Boivin *et al.* 2012; Filipović *et al.* 2020; Martin *et al.* 2021). In the North China plain, broomcorn millet had been fully domesticated and become a staple food crop together with foxtail millet, no later than 6500 BC (Lu *et al.* 2009; Liu *et al.* 2018). Broomcorn millet subsequently spread widely through northern China, the Korean Peninsula and south into south-west and south-east China by *c.* 3000–2500 BC (Stevens *et al.* 2016; Deng *et al.* 2018, 2022). The date of dispersal outside of China and into Western Asia and Europe, however, is debated.

It is widely accepted that broomcorn millet was spread into Central Asia through the Hexi Corridor and northern Xinjiang, along the foothills of the Altai, Karakorum and other mountain ranges. Currently, the earliest evidence of broomcorn millet from the Hexi Corridor of north-west China dates to *c.* 2300 BC (Zhou *et al.* 2016), although millet farming communities can be inferred from sedentary settlements in the region as early as 3000 BC (Wang 2012).

Moving into Central Asia, the oldest find of broomcorn millet is currently from the Pethpuran Teng site in the Kashmir Valley, where 100 grains have been recovered, along with wheat, barley and lentils (Yatoo *et al.* 2020). Three direct dates on the broomcorn millet grains are all older than 2000 BC, and the earliest is 2580–2446 cal BC (at 95.4% confidence). The Pethpuran Teng evidence is slightly earlier than that from Kazakhstan at Begash (2458–2199 cal BC, at 95.4% confidence) (Frachetti *et al.* 2010). Somewhat older finds from north-west China are to be expected in the future, as implied by the evidence of the stable isotope data from animal bone for the use of millet crops as fodder at sites in the Dzhungar Mountains (Hermes *et al.* 2019; Motuzaitė Matuzeviciute *et al.* 2022). In consideration of the evidence from Kashmir, a second dispersal route through the foothills of the southern Tibetan Plateau might also be considered. This hypothesis may be supported by the discovery of both foxtail millet and broomcorn millet as early as *c.* 3000–2500 BC at the Karuo site in south-eastern Tibet and other sites such as Guijiabao and Baiyangcun in the Zang-Yi Corridor (Dal Martello *et al.* 2018; Gao *et al.* 2020; Huan *et al.* 2022).

Either or both routes facilitated the adoption of broomcorn millet cultivation in Central Asia by *c.* 2200 BC, as attested by discoveries from Adji Kui in Turkmenistan (Spengler *et al.* 2018), and the evidence from Ghal e-Ben presented here at *c.* 2050 BC. Finds from the Caucasus are marginally later (Martin *et al.* 2021), while finds from Mesopotamia, the Levant, Turkey and Eastern Europe all indicate increasingly widespread cultivation by *c.* 1500 BC (Figure 4). Collectively, these data argue against the older idea that broomcorn millet was dispersed along the so-called ‘Steppe Highway’ from Mongolia to Ukraine, an area where there

are few finds and no direct dating. In addition, recent stable isotope research on human and animal bones shows no detectable signal of C_4 plants, such as millets, contributing to diets before *c.* 2000 BC on the Eurasian Steppe (Ventresca Miller & Makarewicz 2019).

The new finds from Ghal e-Ben provide the first solid evidence of early broomcorn millet in this region, dating to *c.* 2050 BC, which bridges a gap in the evidence for the dispersal route of broomcorn millet into Western Eurasia. Combined with the results of previous research on south-east Central Asia, we argue that it is likely that the main route for crop exchange prior to 2000 BC was the 'Inner Asian Mountain Corridor' (Frachetti 2012) and its western extension through south of the Caspian Sea, northern Iran.

Rice in West Asia: the second wave of globalisation

Asian rice is a typical monsoon cereal crop with high hydrothermal requirements. While millets may be grown with as few as 2000 Growing Degree Days [GDD] and 250–300mm rainfall per annum, rice requires approximately 3000 GDD (d'Alpoim Guedes *et al.* 2016) and more than 800mm of annual rainfall (Fuller *et al.* 2011). Although cultivation of *japonica* rice began in the Yangtzi River basin by 8000 BC, rice agriculture remained confined to the better-watered parts of China until *c.* 3000 BC, before spreading primarily southwards to the tropics (Fuller 2011; Silva *et al.* 2015). Rice cultivation in the Ganges River basin also started around 2500–2000 BC; here, it is hypothesised that hybridisation with introduced *japonica* rice from East Asia after 2000 BC facilitated large-scale agriculture based on *indica* rice (Fuller 2011; Bates *et al.* 2017), and both *indica* and *japonica* forms were widespread throughout the Indian subcontinent by the first millennium BC (Castillo *et al.* 2016; Rahman *et al.* 2020).

The spread of rice agriculture further west, to the oases of Central Asia, Iran or the Mediterranean, was hampered by lower levels of rainfall or the need for irrigation. One region with climatic conditions naturally suited to rice cultivation, however, is the South Caspian coastal plain; another is the (irrigated) alluvial plain of Susiana (modern-day Khuzestan province in south-western Iran; Brice 1966). The present study establishes by direct dating, for the first time, that rice was present in West Asia, at Ghal e-Kash, by at least *c.* 339–46 BC—much earlier than any currently available evidence from elsewhere in Central Asia. It is therefore possible that rice was first adopted in the well-watered regions of Iran, before spreading to irrigated oases in Central Asia.

Based on Mesopotamian written sources, some rice cultivation was perhaps established in Syria by *c.* 1100 BC, while areas of cultivation are indicated in south-western Iran from Achaemenid sources of the sixth or fifth century BC (Muthukumaran 2014). Previously, the earliest widely accepted evidence of rice cultivation in Iran came from Susa, dating to the first century AD (Miller 1981; Nesbitt *et al.* 2010; Spengler *et al.* 2021). The Susa rice finds are short-grained rice (Miller 1981) with a length/width ratio below 2 (mean 1.6), indicative of subspecies *japonica* (see Castillo *et al.* 2016). The earliest evidence for rice in Central Asia is from Khalchayan in the Surkhan Darya Basin of Uzbekistan, directly dated to 236–386 cal AD (at 95.4% confidence), and also probably subspecies *japonica* (Chen *et al.* 2020); this may be regarded as the earliest evidence of irrigated oasis rice cultivation. All these early rice finds from Central Asia are consistent with the rice grain from Ghal

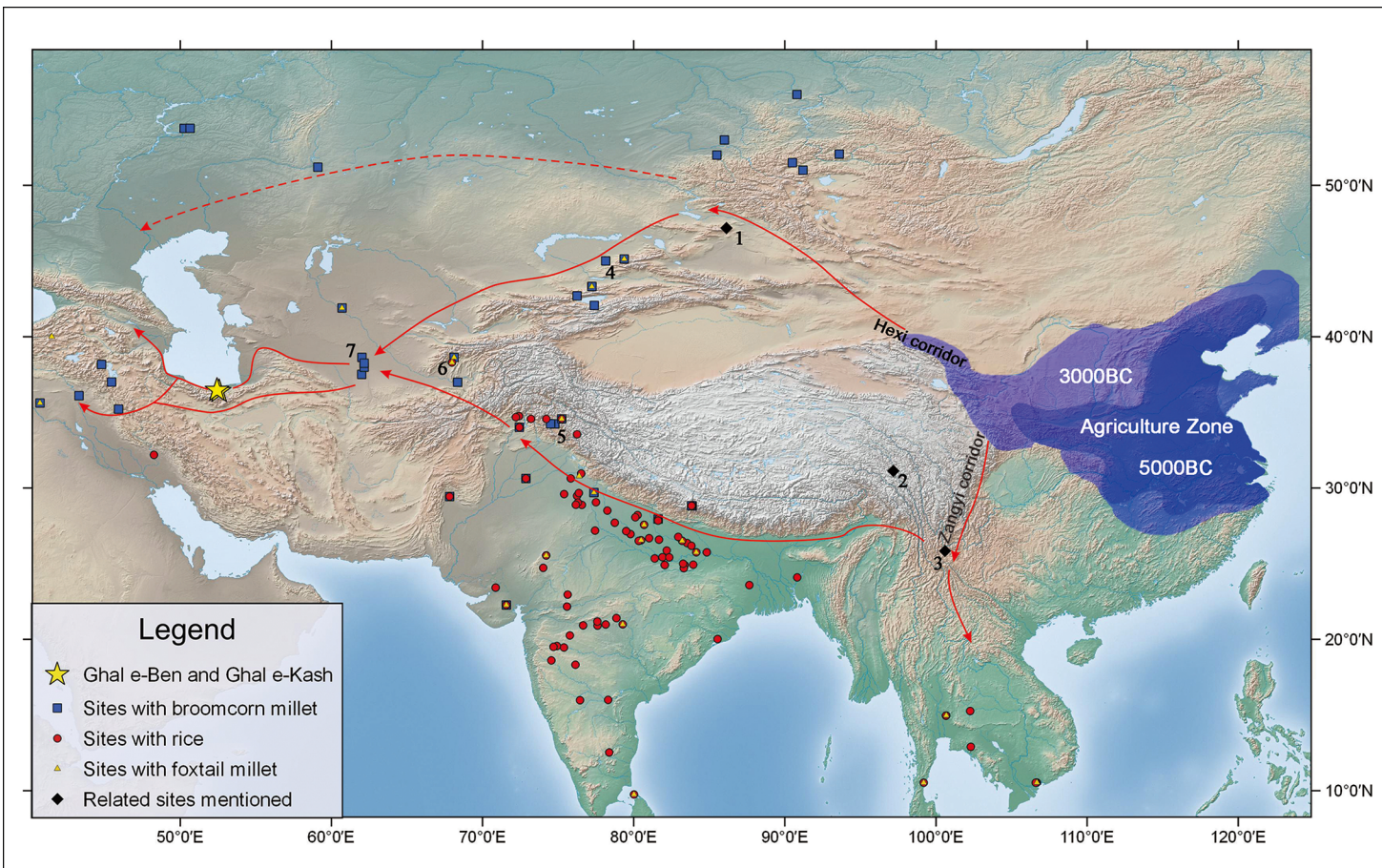


Figure 4. Proposed westward dispersal routes of East Asian crops, along with distribution of sites with early evidence of rice, broomcorn millet and foxtail millet along the routes and important sites mentioned in the text: 1) Tongtian Cave; 2) Karuo; 3) Baiyangcun; 4) Begash; 5) Pethpuran Teng; 6) Khalchayan; 7) Adji Kui. For details of all sites plotted in this map, see Table S2 in the online supplementary material (figure by Z. Deng).

e-Ben with a length/width ratio of 1.75, pointing towards the subspecies *japonica*, a group that includes modern rice varieties such as Iranian *gerdeh* and *berenj loke* in Afghanistan (see OSM2). The available evidence therefore suggests that the earliest rice to spread west was of the *japonica* type, with long-grained *indica* and aromatic rice arriving later.

A second point to emphasise here is that the geographical dispersal of rice was different from that of broomcorn millet. The latter was cultivated in all areas along its dispersal route, adopted by all communities unconstrained by any climatic or environmental conditions. In this way, the seemingly long-distance dispersal of broomcorn millet was probably accomplished through a series of short-distance, local interactions. This is akin to an ‘infiltration’ model, similar to that proposed by Frachetti (2012) in relation to trade and material transfer across South-west and Central Asia in the Bronze Age. By contrast, the spread of rice cultivation followed a ‘leapfrog’ model, in which the adoption of rice farming had to jump across numerous natural barriers (e.g. areas with insufficient rainfall) to arrive at the sparsely distributed habitats suited to its needs. This model is only plausible in the presence of the direct exchange of information between distant places. In other words, the dispersals of broomcorn millet and rice attest to two distinct waves of globalisation based on two different processes. By the time of the second wave, the whole Eurasian continent was much more closely connected, providing the conditions needed for the success of the ‘leapfrog’ model.

Conclusion

Based on the analysis of new archaeobotanical data and direct AMS radiocarbon dating, here, for the first time, we present firm evidence of Bronze Age and historic period farming practices on the southern coast of the Caspian Sea. Crop assemblages from the sites of Ghal e-Ben and Ghal e-Kash are, like at other sites from across the Middle East, dominated by wheat and barley; specifically, free-threshing bread wheat was more important in local farming systems than glume wheats. In addition, the assemblages from these two sites attest to two waves of agricultural change related to the adoption of East Asian crops: broomcorn millet arriving *c.* 2050 BC and rice arriving *c.* 120 BC. A single grain of foxtail millet from Ghal-e-Ben may suggest that this crop was introduced alongside rice.

The new evidence presented here bridges a geographical gap in the westward dispersal route of East Asian crops and offers a refined chronology for their adoption. Moreover, these data suggest that crop dispersal events followed two different models: an ‘infiltration’ model for broomcorn millet and a later ‘leapfrog’ model for rice, the feasibility of the latter illustrating the intensification of connectivity and information exchange across Eurasia during the second wave of globalisation some 2000 years ago.

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Supplementary material

To view supplementary material for this article, please visit <https://doi.org/10.15184/aqy.2023.42>.

References

- D'ALPOIM GUEDES, J., S.W. MANNING & R.K. BOCINSKY. 2016. A 5500-year model of changing crop niches on the Tibetan Plateau. *Current Anthropology* 57: 517–22. <https://doi.org/10.1086/687255>
- BATES, J., C.A. PETRIE & R.N. SINGH. 2017. Approaching rice domestication in South Asia: new evidence from Indus settlements in northern India. *Journal of Archaeological Science* 78: 193–201. <https://doi.org/10.1016/j.jas.2016.04.018>
- BENTLEY, J.H. 1993. *Old World encounters: cross-cultural contacts and exchanges in pre-modern times*. Oxford: Oxford University Press.
- BOIVIN, N., D.Q. FULLER & A. CROWTHER. 2012. Old World globalization and the Columbian exchange: comparison and contrast. *World Archaeology* 44: 452–69. <https://doi.org/10.1080/00438243.2012.729404>
- BRICE, W.C. 1966. *A systematic regional geography. Vol. 8: South-west Asia*. London: University of London Press.
- BRITE, E.B., F.J. KIDD, A. BETTS & M. NEGUS CLEARY. 2017. Millet cultivation in Central Asia: a response to Miller *et al.* *The Holocene* 27: 1415–22. <https://doi.org/10.1177/0959683616687385>
- BRONK RAMSEY, C. 2009. Bayesian analysis of radiocarbon dates. *Radiocarbon* 51: 337–60. <https://doi.org/10.1017/S0033822200033865>
- CASTILLO, C.C. *et al.* 2016. Archaeogenetic study of prehistoric rice remains from Thailand and India: evidence of early *japonica* in South and Southeast Asia. *Archaeological and Anthropological Sciences* 8: 523–43. <https://doi.org/10.1007/s12520-015-0236-5>
- CHEN, F. *et al.* 2015. Agriculture facilitated permanent human occupation of the Tibetan Plateau after 3600 BP. *Science* 347: 248–50. <https://doi.org/10.1126/science.1259172>
- CHEN, G. *et al.* 2020. Kushan Period rice in the Amu Darya Basin: evidence for prehistoric exchange along the southern Himalaya. *Science China Earth Sciences* 63: 841–51. <https://doi.org/10.1007/s11430-019-9585-2>
- CHRISTIAN, D. 1998. *A History of Russia, Central Asia and Mongolia. Volume 1: inner Eurasia from prehistory to the Mongol Empire*. Oxford: Blackwell. <https://doi.org/10.1007/s11430-019-9585-2>
- COSMO, N.D. 2020. The ‘birth’ of the Silk Road between ecological frontiers and military innovation, in J.D. Lerner & Y. Shi (ed.) *Silk Roads: from local realities to global narratives*: 11–20. Oxford: Oxbow. <https://doi.org/10.2307/j.ctv13nb9gn.7>
- CZAJKOWSKA, B.I. *et al.* 2020. Ancient DNA typing indicates that the ‘new’ glume wheat of early Eurasian agriculture is a cultivated member of the *Triticum timopheevii* group. *Journal of Archaeological Science* 123: 105258. <https://doi.org/10.1016/j.jas.2020.105258>
- DAL MARTELLO, R. *et al.* 2018. Early agriculture at the crossroads of China and South-east Asia: archaeobotanical evidence and radiocarbon dates from Baiyangcun, Yunnan. *Journal of Archaeological Science: Reports* 20: 711–21. <https://doi.org/10.1016/j.jasrep.2018.06.005>
- DENG, Z. *et al.* 2018. The ancient dispersal of millets in southern China: new archaeological evidence. *The Holocene* 28: 34–43. <https://doi.org/10.1177/0959683617714603>
- 2022. Early Austronesians cultivated rice and millet together: tracing Taiwan’s first Neolithic crops. *Frontiers in Plant Science* 10: 962073. <https://doi.org/10.3389/fpls.2022.962073>
- EARLE, T.K. 2017. *An essay on political economies in prehistory*. Bonn: Habelt.
- FILIPOVIĆ, D. *et al.* 2020. New AMS ¹⁴C dates track the arrival and spread of broomcorn millet cultivation and agricultural change in prehistoric Europe. *Scientific Reports* 10: 13689. <https://doi.org/10.1038/s41598-020-70495-z>
- FRACHETTI, M.D. 2012. Multiregional emergence of mobile pastoralism and nonuniform institutional complexity across Eurasia. *Current Anthropology* 53: 2–21. <https://doi.org/10.1086/663692>
- FRACHETTI, M.D., R.S. SPENGLER, G.Y. FRITZ & A.N. MAR’YASHEV. 2010. Earliest evidence of

- broomcorn millet and wheat in the central Eurasian Steppe region. *Antiquity* 84: 993–1010.
<https://doi.org/10.1017/S0003598X0006703X>
- FULLER, D.Q. 2011. Pathways to Asian civilizations: tracing the origins and spread of rice and rice cultures. *Rice* 4: 78–92.
<https://doi.org/10.1007/s12284-011-9078-7>
- FULLER, D.Q. & N. BOIVIN. 2009. Crops, cattle and commensals across the Indian Ocean. *Études Océan Indien* 42–43: 13–46.
<https://doi.org/10.4000/oceanindien.698>
- GAO, Y., G. DONG, X. YANG & F. CHEN. 2020. A review on the spread of prehistoric agriculture from southern China to mainland Southeast Asia. *Science China Earth Sciences* 63: 615–25.
<https://doi.org/10.1007/s11430-019-9552-5>
- HERMES, T.R. *et al.* 2019. Early integration of pastoralism and millet cultivation in Bronze Age Eurasia. *Proceedings of the Royal Society B* 286: 20191273.
<https://doi.org/10.1098/rspb.2019.1273>
- HSU, C. 1980. *Han agriculture: the formation of early Chinese agrarian economy (206 BC–AD 220)*. Seattle: University of Washington Press.
- HUAN, X. *et al.* 2022. The emergence of rice and millet farming in the Zang-Yi Corridor of south-west China dates back to 5000 years ago. *Frontiers in Earth Science* 10: 874649.
<https://doi.org/10.3389/feart.2022.874649>
- HUNT, H.V. *et al.* 2008. Millet across Eurasia: chronology and context of early records of the genera *Panicum* and *Setaria* from archaeological sites in the Old World. *Vegetation History and Archaeobotany* 17: 5–18.
<https://doi.org/10.1007/s00334-008-0187-1>
- JAANG, L. 2015. The landscape of China's participation in the Bronze Age Eurasian network. *Journal of World Prehistory* 28: 179–213.
<https://doi.org/10.1007/s10963-015-9088-2>
- JONES, M. *et al.* 2011. Food globalization in prehistory. *World Archaeology* 43: 665–75.
<https://doi.org/10.1080/00438243.2011.624764>
- 2016. Food globalisation in prehistory: the agrarian foundation of an interconnected continent. *Journal of the British Academy* 4: 73–87.
<https://doi.org/10.5871/jba/004.073>
- KRISTIANSEN, K. *et al.* 2017. Re-theorising mobility and the formation of culture and language among the Corded Ware Culture in Europe. *Antiquity* 91: 334–47.
<https://doi.org/10.15184/aqy.2017.17>
- KUZMINA, E.E. 2008. *The prehistory of the Silk Road*. Philadelphia: University of Pennsylvania Press.
<https://doi.org/10.9783/9780812292336>
- LINDUFF, K.M. & J. MEI. 2009. Metallurgy in the ancient Eastern Asia: retrospect and prospects. *Journal of World Prehistory* 22: 265–81.
<https://doi.org/10.1007/s10963-009-9023-5>
- LIU, X. *et al.* 2017. Journey to the east: diverse routes and variable flowering times for wheat and barley en route to prehistoric China. *PLoS ONE* 12: e0187405.
<https://doi.org/10.1371/journal.pone.0187405>
- LIU, X., G. MOTUZAITÉ-MATUZEVIČIUTE & H.V. HUNT. 2018. From a fertile idea to a fertile arc: the origins of broomcorn millet 15 years on, in E. Lightfoot, X. Liu & D.Q. Fuller (ed.) *Far from the hearth: essays in honour of Martin K. Jones*: 155–64. Cambridge: McDonald Institute for Archaeological Research.
<https://doi.org/10.17863/CAM.38305>
- LIU, X. *et al.* 2019. From ecological opportunism to multi-cropping: mapping food globalisation in prehistory. *Quaternary Science Reviews* 206(15): 21–28.
<https://doi.org/10.1016/j.quascirev.2018.12.017>
- LONG, T.W. *et al.* 2018. The early history of wheat in China from ¹⁴C dating and Bayesian chronological modelling. *Nature Plants* 4: 272–79. <https://doi.org/10.1038/s41477-018-0141-x>
- LU, H. *et al.* 2009. Earliest domestication of common millet (*Panicum miliaceum*) in East Asia extended to 10 000 years ago. *Proceedings of the National Academy of Sciences of the USA* 106: 7367–72.
<https://doi.org/10.1073/pnas.0900158106>
- MARTIN, L. *et al.* 2021. The place of millet in food globalization during late prehistory as evidenced by new bioarchaeological data from the Caucasus. *Scientific Reports* 11: 13124.
<https://doi.org/10.1038/s41598-021-92392-9>
- MCLAUGHLIN, R. 2016. *The Roman Empire and the Silk Routes: the ancient world economy and the empires of Parthia, Central Asia and Han China*. Barnsley: Pen & Sword.
- MEI, J. 2003. Cultural interaction between China and Central Asia during the Bronze Age. *Proceedings of the British Academy* 121: 1–39.
<https://doi.org/10.5871/bacad/9780197263037.003.0001>

- MILLER, N.F. 1981. Plant remains from Ville Royale II, Susa. *Cahiers de la Délégation Archéologique Française en Iran* 12: 137–42.
- MILLER, N.F., R.N. SPENGLER & M. FRACHETTI. 2016. Millet cultivation across Eurasia: origins, spread, and the influence of seasonal climate. *The Holocene* 26: 1566–75.
<https://doi.org/10.1177/09596836166641742>
- MOTUZAITE-MATUZEVICIUTE, G. *et al.* 2013. The early chronology of broomcorn millet (*Panicum miliaceum*) in Europe. *Antiquity* 87: 1073–85.
<https://doi.org/10.1017/S0003598X00049875>
- 2022. The integration of millet into the diet of Central Asian populations in the third millennium BC. *Antiquity* 96: 560–74.
<https://doi.org/10.15184/aqy.2022.23>
- MUTHUKUMARAN, S. 2014. Between archaeology and text: the origins of rice consumption and cultivation in the Middle East and the Mediterranean. *Papers from the Institute of Archaeology* 24: 14.
- NESBITT, M., S.J. SIMPSON & I. SVANBERG. 2010. History of rice in Western and Central Asia, in S.D. Sharma (ed.) *Rice: origin, antiquity and history*: 308–40. Boca Raton (FL): CRC Press.
<https://doi.org/10.1201/EBK1578086801-c10>
- RAHMAN, M. *et al.* 2020. Agricultural systems in Bangladesh: the first archaeobotanical results from early historic Wari-Bateshwar and early medieval Vikrampur. *Archaeological and Anthropological Sciences* 12: 1–17.
<https://doi.org/10.1007/s12520-019-00991-5>
- REIMER, P.J. *et al.* 2020. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon* 62: 725–57.
<https://doi.org/10.1017/RDC.2020.41>
- SHERRATT, A. 2006. The trans-Eurasian exchange: the prehistory of Chinese relations with the West, in V. Mair (ed.) *Contact and exchange in the ancient world*: 32–53. Honolulu: Hawaii University Press.
- SILVA, F. *et al.* 2015. Modelling the geographical origin of rice cultivation in Asia using the Rice Archaeological Database. *PLoS ONE* 10: e0137024.
<https://doi.org/10.1371/journal.pone.0137024>
- SPENGLER, R.N. 2015. Agriculture in the Central Asian Bronze Age. *Journal of World Prehistory* 28: 215–53.
<https://doi.org/10.1007/s10963-015-9087-3>
- 2020. Anthropogenic seed dispersal: rethinking the origins of plant domestication. *Trends in Plant Science* 25: 340–48.
<https://doi.org/10.1016/j.tplants.2020.01.005>
- SPENGLER, R.N. *et al.* 2018. The breadth of dietary economy in Bronze Age Central Asia: case study from Adji Kui 1 in the Murghab region of Turkmenistan. *Journal of Archaeological Science: Reports* 22: 372–381.
<https://doi.org/10.1016/j.jasrep.2016.03.029>
- 2021. The southern Central Asian mountains as an ancient agricultural mixing zone: new archaeobotanical data from Barikot in the Swat Valley of Pakistan. *Vegetation History and Archaeobotany* 30: 463–76.
<https://doi.org/10.1007/s00334-020-00798-8>
- STEVENS, C.J. *et al.* 2016. Between China and South Asia: a middle Asian corridor of crop dispersal and agricultural innovation in the Bronze Age. *The Holocene* 26: 1541–55.
<https://doi.org/10.1177/0959683616650268>
- TANG, L. *et al.* 2021. The transition to a barley-dominant cultivation system in Tibet: first millennium BC archaeobotanical evidence from Bangga. *Journal of Anthropological Archaeology* 61: 101242.
<https://doi.org/10.1016/j.jaa.2020.101242>
- VALAMOTI, S.M., A. MONIAKI & A. KARATHANOU. 2011. An investigation of processing and consumption of pulses among prehistoric societies: archaeobotanical, experimental and ethnographic evidence from Greece. *Vegetation History and Archaeobotany* 20: 381–96.
<https://doi.org/10.1007/s00334-011-0302-6>
- VENTRESCA MILLER, A.R. & C.A. MAKAREWICZ. 2019. Intensification in pastoralist cereal use coincides with the expansion of trans-regional networks in the Eurasian Steppe. *Scientific Reports* 9: 8363.
<https://doi.org/10.1038/s41598-018-35758-w>
- WANG, H. 2012. The genealogy and distribution pattern of archaeological cultures in the Neolithic and Bronze Age of Ganqing region. *Archaeological Research* 9: 210–43 (in Chinese).
- YATOO, M.A. *et al.* 2020. New evidence from the Kashmir Valley indicates the adoption of East and West Asian crops in the western Himalayas by 4400 years ago. *Quaternary Science Advances* 2: 100011.
<https://doi.org/10.1016/j.qsa.2020.100011>

ZHANG, C. *et al.* 2019. China's major Late Neolithic centres and the rise of Erlitou. *Antiquity* 93: 588–603.
<https://doi.org/10.15184/aqy.2019.63>

ZHOU, X., X. LI, J. DODSON & K. ZHAO. 2016. Rapid agricultural transformation in the prehistoric Hexi Corridor, China. *Quaternary International*

426: 33–41.
<https://doi.org/10.1016/j.quaint.2016.04.021>

ZHOU, X. *et al.* 2020. 5200-year-old cereal grains from the eastern Altai Mountains redate the trans-Eurasian crop exchange. *Nature Plants* 6: 78–87.
<https://doi.org/10.1038/s41477-019-0581-y>