New data from Northern Iran demonstrates early adoption of East Asian crops in West Asia: broomcorn millet at 2050 BC and rice at 120 BC

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Abstract

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: *Panicum miliaceum*, *Oryza sativa*, *Triticum timopheevi,* agriculture, crop dispersal, trans-Eurasian communication, Silk Road

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 Reference Bentley1993; Sherratt Reference Sherratt and Mair2006; Earle Reference Earle2017). 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 Reference McLaughlin2016; Cosmo Reference Cosmo, Lerner and Shi2020). In recent years, however, a growing body of archaeological scholarship has focused on evidence of transcontinental cultural exchange stretching back to the Early Bronze Age, c. 2000 BC, seeing it as an early example of globalisation (e.g. Christian 1998; Kuzmina Reference Kuzmina2008; Jones et al. Reference Jones2011).

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. Reference Frachetti, Spengler, Fritz and Mar'yashev2010; Jones et al. Reference Jones2011; Boivin et al. Reference Boivin, Fuller and Crowther2012; Jones et al. Reference Jones2016; Stevens et al. Reference Stevens2016; Liu et al. Reference Liu2019; Spengler Reference Spengler2020). 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 Reference Mei2003; Liu et al. Reference Liu2017; Long et al. Reference Long2018). 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 Reference Hsu1980), 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. Reference Chen2015;

d'Alpoim Guedes et al. Reference d'Alpoim Guedes, Manning and Bocinsky2016; Tang et al. Reference Tang2021). 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 Reference Linduff and Mei2009; Jaang Reference Jaang2015; Zhang et al. Reference Zhang2019).

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. Reference Hunt2008). 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 Reference Fuller and Boivin2009; Boivin et al. Reference Boivin, Fuller and Crowther2012). 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 (Motuzaite-Matuzeviciute et al. Reference Motuzaite-Matuzeviciute2013; Filipović et al. Reference Filipović2020), while dates from the Caucasus (Georgia) may go back to as early as 2000 BC (Martin et al. Reference Martin2021). 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. Reference Zhou2020), Begash in Kazakhstan (Frachetti et al. Reference Frachetti, Spengler, Fritz and Mar'yashev2010; Spengler Reference Spengler2015), Adji Kui in Turkmenistan (Spengler et al. Reference Spengler2018) and Pethpuran Teng in the Kashmir Valley (Yatoo et al. Reference Yatoo2020).

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. Reference Kristiansen2017), or, through the populations of Armenia and Asia Minor entering Europe through Greece (the 'Colchis' route of the classical sources; McLaughlin Reference McLaughlin2016)? 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 Reference McLaughlin2016)? 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. Reference Miller, Spengler and Frachetti2016; Spengler Reference Spengler2020), or whether millets were first established on a small scale as risk-buffering crops in a diversified, multi-resource adaptation (Brite et al. Reference Brite, Kidd, Betts and Negus Cleary2017). 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. Reference Spengler2021). 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).

Studied 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.

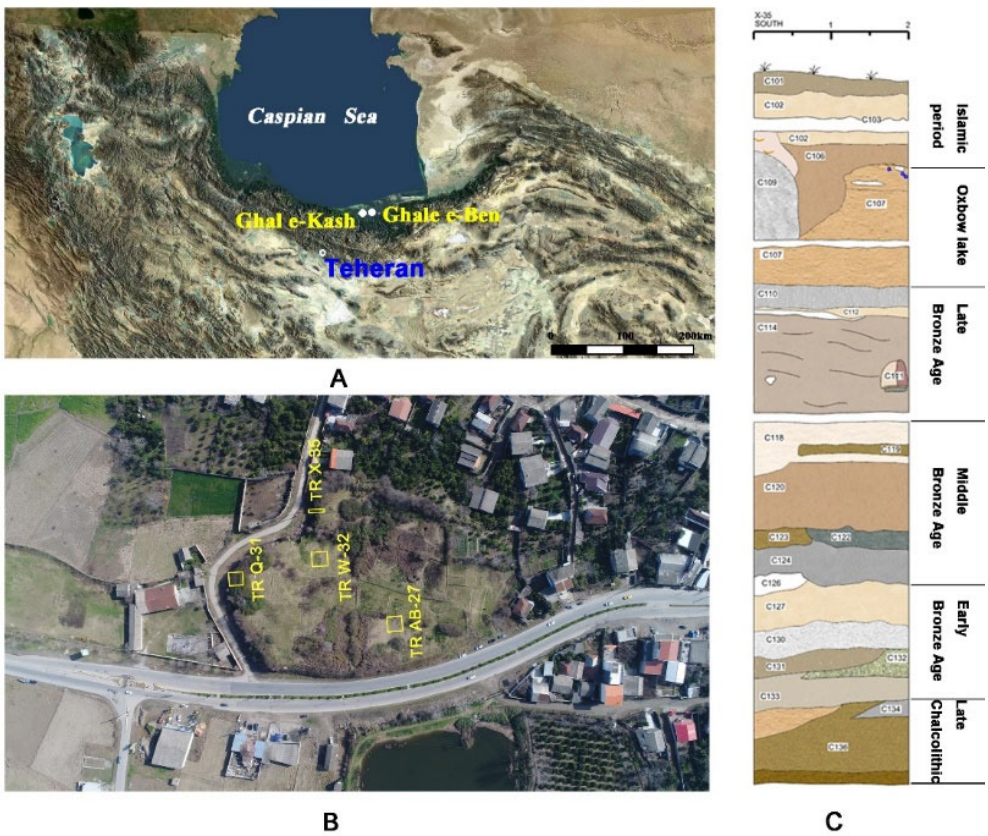

Figure 1. Settings and stratigraphy of Ghal e-Ben and Ghal e-Kash (A. locations of the studied sites B. modern landscape of Ghal e-Ben with locations of excavated trenches C. stratigraphic layers and cultural periods of TR X-35 of Ghal e-Ben)

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 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 Reference Bronk Ramsey2009), using the IntCal20 atmospheric curve (Reimer et al. Reference Reimer2020). 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.*Table 1. AMS radiocarbon dating results of Ghal e-Ben and Ghal e-Kash (all dates calibrated by Oxcal 4.4.4, using the IntCal20 atmospheric curve)*

Site name	Context/ Sample NO.	Lab NO.	Sample type	Radiocarbon Age（BP）	Calibrated Age (BC/AD) (1δ，68.3%)	Median Age	Calibrated Age (BC/AD) (2δ，95.4%)	Median Age
Ghal e-Ben	CON 306	BA192196	Lentil	3210±20	1501-1450 BC	1508BC	1508-1434BC	1472BC

Ghal e-Ben	CON 317	BA190764	charcoal	3245±20	1531-1461 BC	1539BC	1539-1446BC	1505BC
Ghal e-Ben	CON 319	Beta-536438	*Triticum aestivum*	3280±30	1607-1506 BC	1620BC	1620-1462BC	1545BC
Ghal e-Ben	CON 322	BA190765	charcoal	3820±30	2337-2202 BC	2447BC	2447-2144BC	2258BC
Ghal e-Ben	CON 325	BA190766	charcoal	4010±25	2568-2476 BC	2576BC	2576-2469BC	2527BC
Ghal e-Ben	CON 326	BA192197	*Triticum aestivum*	3340±20	1629-1543 BC	1686BC	1686-1535BC	1601BC
Ghal e-Ben	CON 334	BA190767	charcoal	4325±20	3003-2899 BC	3011BC	3011-2893BC	2918BC
Ghal e-Ben	CON 337	BA190769	charcoal	4415±20	3095-2940 BC	3263BC	3263-2925BC	3041BC
Ghal e-Ben	CON 109	Beta-559280	*Oryza sativa*	1080±30	AD 898-1017	AD 892	AD 892-1023	AD 967
Ghal e-Ben	CON 110	BA192195	*Triticum aestivum*	3290±20	1608-1516 BC	1613BC	1613-1508BC	1556BC
Ghal e-Ben	CON 111	BA190754	charcoal	3310±20	1616-1539 BC	1621BC	1612-1518BC	1574BC
Ghal e-Ben	CON 113	Beta-536436	*Triticum aestivum*	3340±30	1667-1541 BC	1735BC	1735-1532BC	1606BC
Ghal e-Ben	CON 114a	BA190755	charcoal	3345±25	2133-1980 BC	1731BC	1731-1537BC	2057BC
Ghal e-Ben	CON 114c	Beta-559281	*Panicum miliaceum*	3670±30	1671-1544 BC	2141BC	2141-1951BC	1615BC
Ghal e-Ben	CON 115	Beta-536437	*Hordeum vulgare*	3390±30	1736-1626 BC	1863BC	1863-1564BC	1675BC
Ghal e-Ben	CON 118	BA190756	charcoal	3835±25	2341-2206 BC	2452BC	2452-2200BC	2284BC
Ghal e-Ben	CON 120	BA190757	charcoal	4055±25	2623-2497 BC	2834BC	2834-2475BC	2576BC
Ghal e-Ben	CON 124	BA190758	charcoal	3865±20	2447-2290 BC	2458BC	2458-2211BC	2343BC
Ghal e-Ben	CON 125	BA190759	charcoal	3970±20	2560-2465 BC	2571BC	2571-2456BC	2493BC
Ghal e-Ben	CON 127	BA190760	charcoal	4030±20	2576-2491 BC	2620BC	2620-2472BC	2526BC
Ghal e-Ben	CON 135	BA190763	charcoal	4450±20	3314-3028 BC	3330BC	3330-3018BC	3165BC
Ghal e-Kash	Sample 1	Beta-536434	*Oryza sativa*	2110±30	168-56 BC	339 BC	339-46BC	123 BC
Ghal e-Kash	Sample 2	Beta-536433	*Oryza sativa*	2090±30	151-51 BC	196 BC	196BC- AD 4	102 BC
Ghal e-Kash	Sample 2	BA192194	*Hrodeum vulgare*	1930±20	AD 66-125	AD 25	AD 25-203	AD 97

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 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. Reference Czajkowska2020). 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).

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, hulled type e. *Triticum* cf. *timopheevi* glume base f. *Triticum aestivum/durum* g. *Triticum* cf. *timopheevi* h. *Hordeum vulgare* var. *coeleste* (naked, six-row) i. *Triticum aestivum* rachis.

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. Reference Valamoti, Moniaki and Karathanou2011). 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.

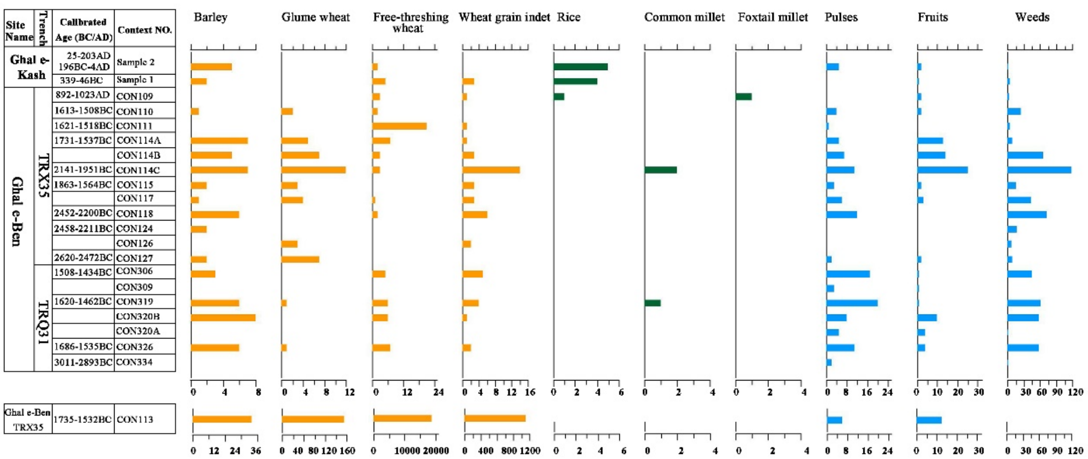

Figure 3. Compositional analysis of plant remains from Ghal e-Ben and Ghal e-Kash

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. Reference Nesbitt, Simpson, Svanberg and Sharma2010). 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). 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. Reference Jones2011; Boivin et al. Reference Boivin, Fuller and Crowther2012; Filipović et al. Reference Filipović2020; Martin et al. Reference Martin2021). 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. Reference Lu2009; Liu et al. Reference Liu, Motuzaite-Matuzeviciute, Hunt, Lightfoot, Liu and Fuller2018). 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. Reference Stevens2016; Deng et al. Reference Deng2018, Reference Deng2022). 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. Reference Zhou, Li, Dodson and Zhao2016), although millet farming communities can be inferred from sedentary settlements in the region as early as 3000 BC (Wang Reference Wang2012).

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. Reference Yatoo2020). 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. Reference Frachetti, Spengler, Fritz and Mar'yashev2010). 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. Reference Hermes2019; Motuzaite Matuzeviciute et al. Reference Motuzaite-Matuzeviciute2022). 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. Reference Dal Martello2018; Gao et al. Reference Gao, Dong, Yang and Chen2020; Huan et al. Reference Huan2022).

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. Reference Spengler2018), and the evidence from Ghal e-Ben presented here at c. 2050 BC. Finds from the Caucasus are marginally later (Martin et al. Reference Martin2021), 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 C4 plants, such as millets, contributing to diets before c. 2000 BC on the Eurasian Steppe (Ventresca Miller & Makarewicz Reference Ventresca Miller and Makarewicz2019).

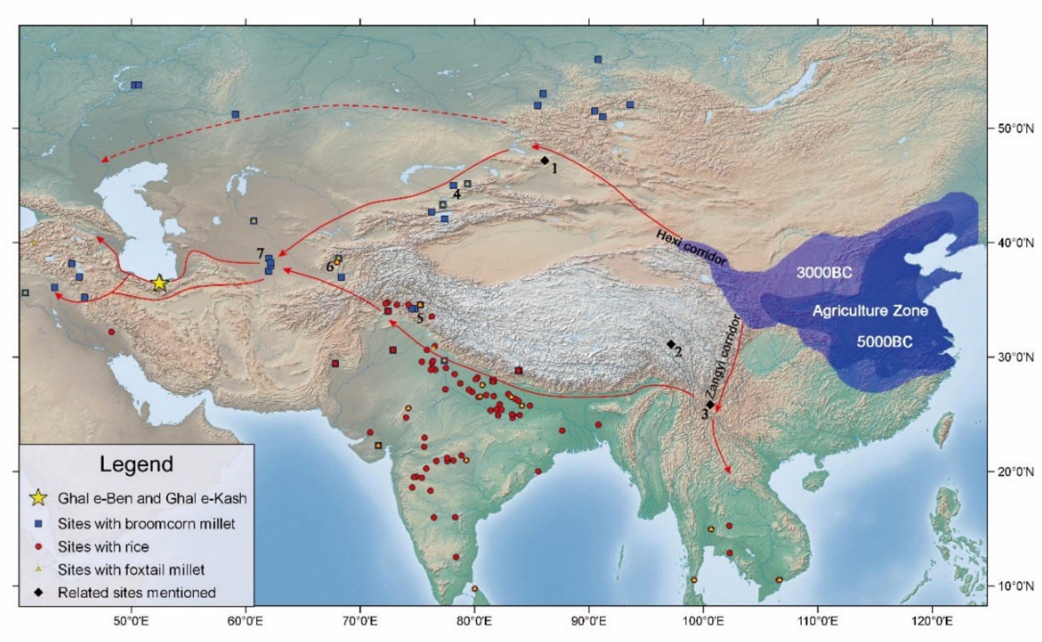

Figure 4. Proposed westward dispersal routes of East Asian crops along with distribution of sites with early evidence of rice, broomcorn millet and foxtail millet along the routes and important sites mentioned in the text (1. Tongtian cave 2. Karuo 3. Baiyangcun 4. Begash 5. Pethpuran Teng 6. Khalchayan 7. Adji Kui; Details of all sites plotted in this map are presented in Supplementary Table 2)

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 Reference Frachetti2012) 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. Reference d'Alpoim Guedes, Manning and Bocinsky2016) and more than 800mm of annual rainfall (Fuller et al. Reference Fuller2011). 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 Reference Fuller2011; Silva et al. Reference Silva2015). 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 Reference Fuller2011; Bates et al. Reference Bates, Petrie and Singh2017), and both indica and japonica forms were widespread throughout the Indian subcontinent by the first millennium BC (Castillo et al. Reference Castillo2016; Rahman et al. Reference Rahman2020).

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 Reference Brice1966). 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 Reference Muthukumaran2014). Previously, the earliest widely accepted evidence of rice cultivation in Iran came from Susa, dating to the first century AD (Miller Reference Miller1981; Nesbitt et al. Reference Nesbitt, Simpson, Svanberg and Sharma2010; Spengler et al. Reference Spengler2021). The Susa rice finds are short-grained rice (Miller Reference Miller1981) with a length/width ratio below 2 (mean 1.6), indicative of subspecies japonica (see Castillo et al. Reference Castillo2016). 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. Reference Chen2020); 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 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 (Reference Frachetti2012) 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 Text 1. On the presence of two tetraploid glume wheat species, *Triticum* cf. *timopheevi* and *T. dicoccon*

In addition to emmer we recognize *Triticum* cf. *timopheevi,* the "new type glume wheat" (Jones et al., 2000). This is recognized by glume bases that are more striate than standard emmer, have a more adaxial (straight forward) keel (compared to more recurved in emmer), and a much taller abscission scar; its grains lack a pronounced shoulder, have an elongate shape and have a blunt apex (Kohler-Schneider, 2003; Ulas & Fiorentino, 2020; Bogaard et al., 2021). This "new type" wheat only became widely recognized as a distinct form, or taxon, at the end of the 1990s (Jones et al., 2000), referred as the "new glume wheat" over the past decades, by De Moulins (1997) as "Machoid emmer", and by Fuller et al. (2011) as "striate emmeroid". The presence of the distinct AAGG genome of *timopheevi/araraticum,* was already suggested by early aDNA work at Assiros in Greece (Brown et al., 1998), and confirmed by more recent methods (Czajkowska et al., 2020).

The wild AAGG wheat, *Triticum araraticum* is likely to have been domesticated in modern day Turkey towards the southeastern region, based on chloroplast genetic diversity in relict modern crops and wild populations (Mori et al., 2009). The earliest archaeological finds are ninth millennium BC, including from Cafer Hoyuk, levels IX-X (De Moulins 1997), which probably date to the Middle Pre-Pottery Neolithic, probably from 8400-8000 BC, presumably cultivated, and in small quantities of similar age from Boncuklu Höyük in the Konya plain, which are morphologically wild but perhaps under pre-domestication cultivation (Baird et al., 2018). The next finds come from all sampled phases as Aşikli Höyük in central Anatolia (8400-7500 BC), although standard emmer wheat (*T. dicoccum*) dominates over this wheat type (Ergun 2018; Ergun et al. 2018). Preliminary chaff data, suggest a mixture of morphologically wild and domesticated forms, indicating that this cultivar was undergoing domestication. Recently, the study by Charles et al. (2021) has clarified how spikelet scar morphologies vary between wild and domesticated forms in this wheat, which is subtly different to standard emmer (*T. dicoccumi)*. At Çatalhöyük in the early levels (7100-6500 BC) this wheat still shows a large minority of the shattering/wild form but becomes fixed for the domesticated morphology by the upper levels (Charles et al., 2021); it is also in these upper levels (6500-6000 BC) where this species becomes the dominant wheat (Bogaard et al., 2017; 2021). Studies on grain metrices from Yumuktepe on the southern coast of Turkey and Yenikapi in Instabul indicate increase in average grain size took place between the 7th and 6th millennia BC (Ulas & Fiorentino, 2020); this follows a pattern seed in other cereals in which grain size continued to increase for a millennium or more after non-shattering is fixed.

Beyond this core area this species of wheat spread both west and east. It is widely reported from southeastern and central Europe in the Neolithic and Bronze Age (Kohler-Schneider, 2003; Czajkowska et al., 2020). Its westward dispersal is marked by 6th Millennium BC evidence from Yenikapi (Istanbul) (Ulas & Fiorentino, 2020). It is found in the eastern Middle East by Late PPNB times. It is present in the second phase at Sheikh-e Abad, Iran (ca. 7600 BC) (Whitlam et al., 2018), and somewhat later at Jarmo (7500-7000 BC) alongside emmer (Fuller unpublished data). In the Late Neolithic (6000-5000 BC) it is present at Tepe Khalesh, Iran (Whitlam et al., 2020), but prior to this time it had reached northeastern Iran in the 7th millennium BC at Sang-i Chakmak and beyond to Jeitun in Turkmenistan (Charles & Bogaard, 2010). Recent evidence from Ghal e-Ben near the Caspian Sea indicates that this wheat continued to be cultivated in this area of northern Iran until at least the Late Bronze Age, ca. 1500 BC (this study).

Supplementary Text 2. A note on traditional rice varieties in Iran

Traditional rice cultivars in Iran are numerous but include subspecies *japonica*, *indica* and the aromatic group. The aromatic sadri rices of Iran are related to Indian basmati and placed genetically in the aromatic group, which is regarded as evolving in India from hybridization between *japonica* and *circum-aus* cultivars (Civan et al 2019); these are usually long grained and a high L:W ratio (>2.2). Short-grained arid adapted cultivars include gerdeh, conventionally classed as "*indica*" (Rabiei et al. 2004), but shown through recent genomics to fall into a *japonica* clade with some admixture (Wang et al 2018). These *japonica* rices are likely related to the short, starchy grained rice in Afghanistan termed *loke* (Krochmal 1958), and other Central Asian short-grain rices. Long-grained, true *indica* cultivars include khazar and domsephid, and Afghan rices referred to as mai-een by Krochmal (1958).

Supplementary Table 1. Plant remains from Ghal e-Ben and Ghal e-Kash

Site Name		Ghal e-Ben	Ghal e-Ben	Ghal e-Ben	Ghal e-Ben	Ghal e-Ben	Ghal e-Ben
Sample Number		**CON334**	**CON326**	**CON320-A**	**CON320-B**	**CON319**	**CON309**
Volume of soil processed (litres)		6.2	13.7	15.5	15.5	13	5.4
context description		kiln	pit	kiln	kiln	pit	soil layer
period		early bronze age	early bronze age	late bronze age	late bronze age	late bronze age	late bronze age
Wheat	*Triticum monococcum*						
	Triticum monococcum/ dicoccum						
	Triticum dicoccum		1				
	Triticum cf. *timopheevi*						
	Triticum cf. *timopheevi /dicoccum*						
	glume wheat indet.						
	Triticum aestivum/durum		7		6	6	
	Triticum indet.		2		1	4	
barley	Hulled *Hordeum vulgare*(straight)					(1)	
	Hulled *Hordeum vulgare* (twisted)						
	Hulled *Hordeum vulgare*						
	Hordeum vulgare var. *nudum* (twisted)		3		3	1	
	Hordeum vulgare var. *nudum* (straight)				1		
	Hordeum vulgare var. *nudum*		1				
	Hordeum indet.		2		3(1)	2(2)	
rice	*Oryza sativa*						
broomcorn millet	*Panicum miliaceum*					1	
foxtail millet	*Setaria italica*						
Wild/cultivated cereal grain	*Triticum baeoticum*		1				
	Hordeum spontaneum						
	Secale cereale						
	Avena sp.		1				
Glume bases	*Triticum monococcum*					1	
	Triticum dicoccum						
	Triticum dicoccum/timopheevi						
	Triticum timopheevi						
	glume wheat indet.						
Rachis internodes	*Triticum aestivum*						

Site Name		Ghal e-Ben	Ghal e-Ben	Ghal e-Ben	Ghal e-Ben	Ghal e-Ben	Ghal e-Ben
Sample Number		**CON334**	**CON326**	**CON320-A**	**CON320-B**	**CON319**	**CON309**
Volume of soil processed (litres)		6.2	13.7	15.5	15.5	13	5.4
context description		kiln	pit	kiln	kiln	pit	soil layer
Barley rachis	*Hordeum vulgare* subsp. *vulgare*						
	Hordeum sp.						
Pulses	*Lens culinaris*		(1)	1*	1*	3*	(1)
	Lathyrus sativus		1			1	
	Vicia ervilia		2*(1)	1*	1*	2*1	
	Vicia sativa					1*	
	Lathyrus sativus/Vicia ervilia				1*	2*1	
	Pisum sativum					1*	
	large legume indet.	(2)	2(4)	1(2) *	3 (2)	7 (2)	(2)
Possibly cultivated, collected	*Linum usitatissimum*						
	Coriandrum sativum		1				
	Vitis sp. pip		2	2	9	1	
	Cucumis sp.						
	Brassicaceae type		1				
	fruit flesh				1		1
	fruit pip			1			
	fruit coat			1			
	unidentified - nut fragments / fruit pip					2	
Wild/weed Taxa	*Sambucus* sp.						
	Lolium spp. (not *temulentum*)	1	36	1	27	28	
	Setaria viridis						
	Panicaceae		1				
	Aegilops sp.		(1)		(1)		
	Digitaria sp.						
	Setaria sp.						
	Phalaris sp.		8		24	9	
	Poaceae		4		4	5	
	Melilotus/Trifolium sp.						
	Medicago sp.		2				
	small seeded legume					1	
	Polygonaceae		2			1	
	Cyperaceae						
	Bellevalia sp.						
	Humulus sp.						
	Apiaceae						
	Amaranthus sp.						
	Chenopodium album						
	Ornithogalum sp.						
	Solanum sp.						
	small seeded weed indet.					1	
	unidentified		3		2	16	
Total		3	90	10	91	102	4

Supplementary Table 1. Plant remains from Ghal e-Ben and Ghal e-Kash (continued)

Site Name		Ghal e-Ben	Ghal e-Ben	Ghal e-Ben	Ghal e-Ben	Ghal e-Ben	Ghal e-Ben
Sample Number		CON306	CON127	CON126	CON124	CON118	CON117
Volume of soil processed (litres)		27.9	2.8	6.2	9	5.9	4.5
context description		soil layer	soil layer	kiln	soil layer	soil layer	hearth & pit & floor
period		Historic period	early bronze age	middle bronze age	middle bronze age	middle bronze age	late bronze age
Wheat	*Triticum monococcum*						
	Triticum monococcum/ dicoccum						
	Triticum dicoccum						
	Triticum cf. *timopheevi*		(1)	1			
	Triticum cf. *timopheevi /dicoccum*						1
	glume wheat indet.						
	Triticum aestivum/durum	5				2	
	Triticum indet.	5		2		4(2)	1
barley	Hulled *Hordeum vulgare*(straight)						
	Hulled *Hordeum vulgare* (twisted)						
	Hulled *Hordeum vulgare*						1
	Hordeum vulgare var. *nudum* (twisted)						
	Hordeum vulgare var. *nudum* (straight)						
	Hordeum vulgare var. *nudum*					4	1
	Hordeum indet.	3	2		2	1(1)	1
rice	*Oryza sativa*						
broomcorn millet	*Panicum miliaceum*						
foxtail millet	*Setaria italica*						
Wild/cultivated cereal grain	*Triticum baeoticum*						
	Hordeum spontaneum						1
	Secale cereale						
	Avena sp.						(1)
Glume bases	*Triticum monococcum*						
	Triticum dicoccum						
	Triticum dicoccum/timopheevi		4	1			1
	Triticum timopheevi			1			2
	glume wheat indet.		2				
Rachis internodes	*Triticum aestivum*						1
Barley rachis	*Hordeum vulgare* subsp. *vulgare*						

Site Name		Ghal e-Ben	Ghal e-Ben	Ghal e-Ben	Ghal e-Ben	Ghal e-Ben	Ghal e-Ben
Sample Number		**CON306**	**CON127**	**CON126**	**CON124**	**CON118**	**CON117**
Volume of soil processed (litres)		27.9	2.8	6.2	9	5.9	4.5
context description		soil layer	soil layer	kiln	soil layer	soil layer	hearth & pit & floor
period		Historic period	early bronze age	middle bronze age	middle bronze age	middle bronze age	late bronze age
	Hordeum sp.						
Pulses	*Lens culinaris*	4	2*			7*	3*
	Lathyrus sativus	1*				1*	
	Vicia ervilia	2*					
	Vicia sativa						
	Lathyrus sativus/Vicia ervilia						
	Pisum sativum	1*				1*(1)*	
	large legume indet.	5(4)				(2)	3
Possibly cultivated, collected	*Linum usitatissimum*						
	Coriandrum sativum						
	Vitis sp. pip	1	2				3
	Cucumis sp.						
	Brassicaceae						
	fruit flesh						
	fruit pip						
	fruit coat						
	unidentified - nut fragments / fruit pip						
Wild/weed Taxa	*Sambucus* sp.						
	Lolium spp. not *temulentum*	25	3	6	9	62	31(1)
	Setaria viridis						
	Panicaceae						
	Aegilops sp.						
	Digitaria sp.						
	Setaria sp.						1
	Phalaris sp.	3	5	1	3	4	4
	Poaceae	1	1		2		2
	Melilotus/Trifolium sp.						
	Medicago sp.	1					1
	small seeded legume	1					
	Polygonaceae	(1)	1	1		2	1
	Cyperaceae						1
	Bellevalia sp.	1			1		
	Humulus sp.	(1)					
	Apiaceae					1	
	Amaranthus sp.						
	Chenopodium album						
	Ornithogalum sp.						
	Solanum sp.						
	Small-seeded weed indet.						
	unidentified	10			3	4	1
Total		75	23	13	20	99	63

Supplementary Table 1. Plant remains from Ghal e-Ben and Ghal e-Kash (continued)

Site Name		Ghal e-Ben	Ghal e-Ben	Ghal e-Ben	Ghal e-Ben	Ghal e-Ben
Sample Number		**CON115**	**CON114A**	**CON114B**	**CON114C**	**CON113**
Volume of soil processed (litres)		7.1	25	15	20	
context description		soil layer	soil layer	soil layer	soil layer	special context
period		late bronze age	late bronze age	late bronze age	late bronze age	late bronze age
Wheat	*Triticum monococcum*					2
	Triticum monococcum/ dicoccum					19
	Triticum dicoccum		2			32
	Triticum cf. *timopheevi*				1(4)	1
	Triticum cf. *timopheevi /dicoccum*			3	2	73
	glume wheat indet.		3			
	Triticum aestivum/durum		7	3	3	18451
	Triticum indet.	3	2		14	1150
barley	Hulled *Hordeum vulgare*(straight)				1	
	Hulled *Hordeum vulgare* (twisted)		1	1	3	
	Hulled *Hordeum vulgare*		2	1		
	Hordeum vulgare var. *nudum* (twisted)		3			7
	Hordeum vulgare var. *nudum* (straight)	1				7
	Hordeum vulgare var. *nudum*		(1)			4
	Hordeum indet.	1	2	(6)	3	7(4)
rice	*Oryza sativa*					
broomcorn millet	*Panicum miliaceum*				2	
foxtail millet	*Setaria italica*					
Wild/cultivated cereal grain	*Triticum baeoticum*					4
	Hordeum spontaneum			2		2
	Secale cereale		(1)			
	Avena sp.					
Glume bases	*Triticum monococcum*					(3)
	Triticum dicoccum			2	2	11
	Triticum dicoccum/timopheevi			1		13
	Triticum timopheevi	3			1	2(1)
	glume wheat indet.			1	2	
Rachis internodes	*Triticum aestivum*					30
Barley rachis	*Hordeum vulgare* subsp. *vulgare*					1

Site Name		Ghal e-Ben	Ghal e-Ben	Ghal e-Ben	Ghal e-Ben	Ghal e-Ben
Sample Number		**CON115**	**CON114A**	**CON114B**	**CON114C**	**CON113**
Volume of soil processed (litres)		7.1	25	15	20	
context description		soil layer	soil layer	soil layer	soil layer	special context
period		late bronze age	late bronze age	late bronze age	late bronze age	late bronze age
	Hordeum sp.					3
Pulses	*Lens culinaris*	2*	1*(1)*	2		
	Lathyrus sativus			1*2	3*	1*
	Vicia ervilia		1*		4*	1*3
	Vicia sativa					
	Lathyrus sativus/Vicia ervilia	1				
	Pisum sativum		1			
	large legume indet.		1*	(2)	(4)	(1)
Possibly cultivated, collected	*Linum usitatissimum*			5	6	
	Coriandrum sativum					
	Vitis sp. pip	2	13	9	16	11
	Cucumis sp.					
	Brassicaceae					2
	fruit flesh				1	
	fruit pip				1	
	fruit coat				1	
	unidentified - nut fragments / fruit pip				2	23
Wild/weed Taxa	*Sambucus* sp.					
	Lolium spp. not *temulentum*	13	1	44	50	1714
	Setaria viridis	1				
	Panicaceae					1
	Aegilops sp.				(3)	(7)
	Digitaria sp.					2
	Setaria sp.			1		
	Phalaris sp.	1		2	13	20
	Poaceae	1	3	7	5	25
	Melilotus/Trifolium sp.					
	Medicago sp.				5	
	small seeded legume		1			1
	Polygonaceae			3	1	29
	Cyperaceae					1
	Bellevalia sp.				1	
	Humulus sp.					
	Apiaceae					1
	Amaranthus sp.				1	
	Chenopodium album			6	27	
	Ornithogalum sp.					12
	Solanum sp.			2	2	
	small seeded weed indet.				1	
	unidentified		1		7	10
Total		29	49	106	192	21692

Supplementary Table 1. Plant remains from Ghal e-Ben and Ghal e-Kash (continued)

Site Name		Ghal e-Ben	Ghal e-Ben	Ghal e-Ben	Ghal e-kash	Ghal e-kash
Sample Number		**CON111**	**CON110**	**CON109**	**CON 10**	**L.F.**
Volume of soil processed (litres)		1.6	26	8.9	/	/
context description		architectural space	architectural space	pit	soil layer	soil layer
period		late bronze age	late bronze age	Historic period	Historic period	Historic period
Wheat	*Triticum monococcum*					
	Triticum monococcum/ dicoccum					
	Triticum dicoccum					
	Triticum cf. *timopheevi*		(1)			
	Triticum cf. *timopheevi /dicoccum*		1			
	glume wheat indet.					
	Triticum aestivum/durum	21	2	3	5	(2)
	Triticum indet.	1		1	2(1)	
barley	Hulled *Hordeum vulgare* (straight)				1	
	Hulled *Hordeum vulgare* (twisted)					(1)
	Hulled *Hordeum vulgare*					(1)
	Hordeum vulgare var. *nudum* (twisted)					3
	Hordeum vulgare var. *nudum* (straight)					
	Hordeum vulgare var. *nudum*		(1)			
	Hordeum indet.				1	
rice	*Oryza sativa*			1	4	5
broomcorn millet	*Panicum miliaceum*					
foxtail millet	*Setaria italica*			1		
Wild/cultivated cereal grain	*Triticum baeoticum*					
	Hordeum spontaneum					
	Secale cereale					
	Avena sp.					
Glume bases	*Triticum monococcum*					
	Triticum dicoccum					
	Triticum dicoccum/timopheevi					
	Triticum timopheevi					
	glume wheat indet.					
Rachis internodes	*Triticum aestivum*					
Barley rachis	*Hordeum vulgare* subsp. *vulgare*					

Site Name		Ghal e-Ben	Ghal e-Ben	Ghal e-Ben	Ghal e-kash	Ghal e-kash
Sample Number		**CON111**	**CON110**	**CON109**	**CON 10**	**L.F.**
Volume of soil processed (litres)		1.6	26	8.9	/	/
context description		architectural space	architectural space	pit	soil layer	soil layer
period		late bronze age	late bronze age	Historic period	Historic period	Historic period
	Hordeum sp.					
Pulses	*Lens culinaris*					1*
	Lathyrus sativus					
	Vicia ervilia	1*	1*			2*
	Vicia sativa					
	Lathyrus sativus/Vicia ervilia					
	Pisum sativum					
	large legume indet.		(3)*			1(1)
Possibly cultivated, collected	*Linum usitatissimum*					
	Coriandrum sativum					
	Vitis sp. pip		2		1	2
	Cucumis sp.			2		
	Brassicaceae					
	fruit flesh					
	fruit pip					
	fruit coat					
	unidentified - nut fragments / fruit pip					
Wild/weed Taxa	*Sambucus* sp.	1				
	Lolium spp. not *temulentum*	3	19	1	1	2
	Setaria viridis					
	Panicaceae					
	Aegilops sp.					
	Digitaria sp.					
	Setaria sp.					
	Phalaris sp.		3			
	Poaceae			1		
	Melilotus/Trifolium sp.					1
	Medicago sp.					
	Small-seeded legume					
	Polygonaceae		1			
	Cyperaceae					
	Bellevalia sp.					
	Humulus sp.					
	Apiaceae					
	Amaranthus sp.					
	Chenopodium album					
	Ornithogalum sp.					
	Solanum sp.					
	Small-seeded weed indet.	1				
	unidentified		2	1	4	2
Total		28	35	11	20	24

Supplementary Table 2. Occurrence of broomcorn millet, foxtail millet and rice in regions between East Asia and West Asia (Sites plotted in Figure 4)

Site	Region	Latitude	Longitude	Date	West Asian Crops			East Asian Crops			References
					Wheat	Barley	Pea	Foxtail millet	Broomcorn millet	Rice	
Chap I	Central Asia	42.70	76.25	1000-600 BC	√	√			√		Motuzaite et al., 2020
Tasbas [2A]	Central Asia	45.13	79.37	1500-1200 BC	√	√	√	√	√		Doumani et al., 2015; Spengler et al., 2014a
The Uch-kurbu	Central Asia	42.07	77.39	1700-1100 BC	√	√			√		Matuzeviciute et al., 2017;2018
Ojakly	Central Asia	38.25	62.16	1700-1600 BC	√	√			√		Spengler et al., 2014b; Rouse & Cerasetti, 2014
Adji Kui-1	Central Asia	38.63	62.02	2000-1600 BC	√	√	√		√		Spengler et al., 2018
Begash 1a	Central Asia	45.01	78.14	2500-2000 BC	√				√		Spengler, 2015; Frachetti & Rouse, 2012
Tuzusai	Central Asia	43.31	77.23	400-150 BC	√	√		√	√		Spengler et al., 2013
Tseganka 8	Central Asia	43.32	77.24	400-50 BC	√	√			√		Chang et al., 2003; Spengler et al., 2017
Kyzyltepa	Central Asia	38.63	68.12	600-300 BC	√	√	√	√	√		Wu et al., 2015
Khalchayan	Central Asia	38.29	67.98	AD 200-400	√	√	√	√		√	Chen et al., 2020
Shortughai	Central Asia	36.99	68.35	2500-1500 BC	√	√	√		√		Willcox, 1991
Site 1211/1219	Central Asia	37.99	62.17	1700-1500 BC	√	√	√		√		Spengler et al, 2014a
Takhirbai-Depe	Central Asia	37.51	62.00	1800-1350 BC		√			√		Herrmann & Kurbansakhatov, 1994
Arzhan	North Asia	52.07	93.60	1000-600 BC					√		Miller & Makarewicz, 2019
Maima I	North Asia	52.00	85.50	AD 100-500		√			√		Abdulganeyev & Vladimirov, 1997
Novy Kumak-2	North Asia	51.20	59.10	500-100 BC	√				√		Akbulatov, 1999

Site	Region	Latitude	Longitude	Date	West Asian Crops			East Asian Crops			References
					Wheat	Barley	Pea	Foxtail millet	Broomcorn millet	Rice	
Serebryakovsky	North Asia	56.00	90.80	1000-100 BC		√			√		Martynov, 1979
Ushlep-5	North Asia	53.00	86.00	AD 100-500		√			√		Abdulganeyev, 1997
Russkaya Selitba	North Asia	53.77	50.65	2000-1000 BC	√				√		Ryabogina & Ivanov, 2011
Lipovy Ovrag	North Asia	53.76	50.26	2000-1000 BC	√				√		Ryabogina & Ivanov, 2011
Qasim Bagh	South Asia	34.25	74.50	2000-1300 BC	√		√		√		Spate et al., 2017; Betts et al., 2019
Pethpuran Teng	South Asia	34.24	74.78	2500-1900 BC	√	√	√		√		Yatoo et al., 2020
Hulas	South Asia	29.70	77.37	2000-1700 BC	√	√		√	√		Saraswat, 1993a
Saunphari	South Asia	28.21	80.25	1000 BC- AD 300		√	√			√	Chanchala, 2004a
Bhagimohari	South Asia	21.40	78.85	1000-100 BC		√	√			√	Kajale, 1989
Sringaverapura	South Asia	26.59	81.67	1000-700 BC		√				√	Saraswat, 1986
Barikot	South Asia	34.57	73.20	1200 BC- AD 50	√	√	√			√	Spengler et al., 2020
Imlidh-Khurd	South Asia	26.51	83.20	1300-800 BC	√	√		√		√	Saraswat, 1993b; Fuller & Boivin, 2009
Daimabad	South Asia	19.50	74.69	1500-1100 BC	√	√	√			√	Kajale, 1977
Semthan	South Asia	33.55	76.25	1500 BC- AD 1000	√	√	√			√	Lone et al., 1993
Nevasa	South Asia	19.56	74.91	150 BC- AD 200	√	√	√			√	Sankalia et al., 1960
Bir-Kot-Ghwandai	South Asia	34.68	72.20	1700-1400 BC	√	√	√			√	Costantini, 1987
Loebanhr 3	South Asia	34.75	72.41	1700-1400 BC	√	√	√			√	Costantini, 1987
Harappa	South Asia	30.63	72.87	1900-1300 BC	√	√			√	√	Weber, 2003; 2010b
Koldihwa	South Asia	24.91	82.05	1900-1500 BC	√	√	√			√	Harvey et al., 2005
Pirak	South Asia	29.44	67.82	1950-1550 BC	√	√			√	√	Costantini, 1979; Kenoyer, 1995
Mahagara	South Asia	24.91	82.05	2000-1300 BC	√	√	√			√	Harvey et al., 2005; 2006

Site	Region	Latitude	Longitude	Date	West Asian Crops			East Asian Crops			References
					Wheat	Barley	Pea	Foxtail millet	Broomcorn millet	Rice	
Mitathal	South Asia	28.89	76.17	2000-1400 BC	√	√				√	Willcox, 1992
Dangwada	South Asia	22.95	75.63	2000-1500 BC 300 BC- AD 300	√		√			√	Vishnu-Mittre et al., 1984
Sangol	South Asia	30.78	76.39	2000-1700 BC	√	√	√	√			Margabandhu & Gaur, 1986
Bhokardan	South Asia	20.26	75.77	200BC- AD 300	√		√			√	Kajale, 1974
Ter (Thair)	South Asia	18.32	76.14	200BC- AD 400	√	√	√			√	Vishnu-Mittre et al., 1971
Lahuradewa	South Asia	26.77	82.95	2400-2200 BC	√	√				√	Joglekar et al., 2007; Tewari et al., 2008
Hetapatti	South Asia	25.42	82.35	2500-1500 BC		√	√			√	Pokharia et al., 2017
Tokwa	South Asia	24.91	83.37	2500-1500 BC	√	√	√			√	Pokharia, 2008a
Balu	South Asia	29.67	76.37	2500-1900 BC	√	√	√			√	Saraswat & Pokharia, 2002
Banawali	South Asia	29.60	75.39	2500-2000 BC	√	√	√			√	Lone et al., 1987
Ahirua Rajarampur	South Asia	27.15	79.50	2500 BC- AD 200		√	√			√	Chanchala, 2005; 2006
Babar Kot	South Asia	22.27	71.57	2600-1300 BC	√	√	√	√	√	√	Reddy, 2003
Farmana	South Asia	29.04	76.31	2600-1300 BC	√	√	√			√	Weber et al., 2011
Alamgirpur	South Asia	29.06	77.50	2600-2200 BC	√	√	√			√	Singh et al., 2013
Kunal	South Asia	29.48	76.25	3000-2500 BC	√	√	√			√	Saraswat & Pokharia, 2003
Mebrak	South Asia	28.82	83.87	400 BC- AD 100	√	√	√		√	√	Knörzer, 2000
Phudzeling	South Asia	28.83	83.82	400 BC- AD 100	√	√			√	√	Knörzer, 2000
Veerapuram	South Asia	16.00	78.31	500 BC- AD 400		√	√			√	Kajale, 1984
Adam	South Asia	20.99	79.27	500 BC- AD 50	√	√	√	√		√	Kajale, 1994
Balathal	South Asia	24.72	74.01	500 BC- AD 300	√	√	√			√	Kajale, 1996b
Khairadih	South Asia	26.18	83.82	700-200 BC	√	√	√			√	Saraswat et al., 1990; 2005

Site	Region	Latitude	Longitude	Date	West Asian Crops			East Asian Crops			References
					Wheat	Barley	Pea	Foxtail millet	Broomcorn millet	Rice	
Hulaskera	South Asia	26.68	81.02	700-500 BC		√				√	Chanchala, 1992
Charda	South Asia	27.95	81.61	900-600 BC		√	√		√	√	Chanchala, 2002
Bhatkuli	South Asia	20.91	77.60	200 BC- AD 200			√			√	Vishnu-Mittre & Gupta, 1968
Bhon	South Asia	20.92	76.65	200 BC- AD 200	√		√			√	Deotare, 2006
Chirand	South Asia	25.75	84.83	2500BC- AD 30	√	√	√			√	Vishnu-Mittre, 1972
Damdama	South Asia	25.87	82.18	5500-5200 BC	√					√	Saraswat, 2004a; 2005
Golbai Sassan	South Asia	20.02	85.55	2500-300 BC			√			√	Harvey et al., 2006
Hund	South Asia	34.01	72.43	300 BC- AD 600	√	√	√		√	√	Cooke, 2002
Inamgaon	South Asia	18.61	74.55	1800-1200 BC	√	√	√			√	Vishnu-mittre & Savithri, 1976; Vishnu-Mittre, 1977
Jhusi	South Asia	25.43	81.90	7100-5900 BC	√	√	√			√	Pokharia et al., 2009; Misra et al., 2009
Kandarodai	South Asia	9.75	80.02	420 BC- AD 20				√		√	Murphy et al., 2018
Kanispur	South Asia	34.57	75.23	AD 100-300	√	√	√	√	√	√	Pokharia et al., 2018
Kanmer	South Asia	23.42	70.86	2600-1900 BC	√	√	√			√	Kharakwal et al., 2008
Kaundinyapura	South Asia	20.98	78.14	300BC- AD 400			√			√	Vishnu-Mittre, 1968a
Kausambi	South Asia	25.34	81.39	1000 BC- AD 600	√	√				√	Chanchala, 1995
Kokhrakot	South Asia	28.88	76.57	100- AD 300		√				√	Sahni, 1936
Lal Quila	South Asia	28.51	78.25	2600-1200 BC	√	√				√	Kajale, 1995; Pokharia et al., 2015
Saunphari	South Asia	28.06	80.11	800BC- AD 100	√	√				√	Chanchala, 2004b
Malhar	South Asia	25.00	83.27	1000-350 BC	√	√	√			√	Tewari et al., 2000; Saraswat, 2004b
Mallapadi	South Asia	12.53	78.38	500-100 BC						√	Moorti, 1994

Site	Region	Latitude	Longitude	Date	West Asian Crops			East Asian Crops			References
					Wheat	**Barley**	**Pea**	**Foxtail millet**	**Broomcorn millet**	**Rice**	
Naimisharanya	South Asia	27.57	80.68	100- AD 300		√		√		√	Chanchala, 2009
Narhan	South Asia	26.36	83.53	1300 BC- AD 300	√	√				√	Saraswat et al., 1994
Navdatoli	South Asia	22.16	75.58	1500-1000 BC	√		√			√	Vishnu-Mittre, 1961
Noh	South Asia	27.19	77.44	1000 BC- AD 300		√				√	Vishnu-Mittre & Savathri, 1974
Paithan I	South Asia	19.46	75.38	1500-1000 BC	√	√	√			√	Cooke & Fuller, 2015
Pandu Rajar Dhibi	South Asia	23.58	87.65	1600-750 BC	√					√	Vishnu-Mittre, 1968b
Piklihal IIIB/IV	South Asia	15.98	76.44	2000-1500 BC	√	√				√	Fuller et al., 2007
Pirvitani Sariff	South Asia	27.84	81.61	800 BC- AD 300	√	√				√	Chanchala, 2003
Radhan	South Asia	26.51	80.33	1100-50 BC		√	√			√	Kajale & Lal., 1989
Raja-Nala-Ka-Tila	South Asia	24.70	83.31	1400-800 BC	√	√				√	Saraswat, 2005
Rohira	South Asia	30.63	75.83	2000-1700 BC	√	√	√			√	Saraswat, 1986; 1988
Ropar	South Asia	30.96	76.52	1800-1600 BC	√					√	Vishnu-Mittre, 1979a; 1979b
Sanchankot/Ramkot	South Asia	26.55	80.48	800 BC- AD 300		√		√		√	Chanchala, 2007; 2008
Senuwar	South Asia	24.93	83.94	2000-500 BC	√	√	√			√	Saraswat, 2004
Siyapur	South Asia	26.95	79.79	1000-100 BC		√				√	Chanchala, 2006
Tuljapur Garhi	South Asia	21.18	77.59	1600-700 BC	√	√	√			√	Kajale, 1988; 1996a
Waina	South Asia	25.75	84.14	7000-100 BC	√			√		√	Saraswat, 2005
Wari-Bateshwar	South Asia	24.09	90.82	400-100 BC		√	√			√	Rahman et al., 2020
Atranjikhera	South Asia	27.70	78.74	2000-1500 BC	√	√	√			√	Chpwdhury et al., 1977; Sarawat, 1980
Ojiyana	South Asia	25.54	74.21	1800-800 BC	√	√	√	√		√	Pokharia, 2008b
Non Nok Tha	Southeast Asia	12.90	102.30	1500-1000 BC						√	Hedges et al., 1991
Ban Non Wat	Southeast Asia	15.26	102.26	1800-1500 BC						√	Silva et al., 2015
Nil Kham Haeng	Southeast Asia	14.96	100.66	1800-1500 BC				√		√	Pigott et al., 2006; Weber et al., 2010a

Site	Region	Latitude	Longitude	Date	West Asian Crops			East Asian Crops			References
					Wheat	**Barley**	**Pea**	**Foxtail millet**	**Broomcorn millet**	**Rice**	
Loc Giang	Southeast Asia	10.53	106.60	2000-1300 BC						√	Barron et al., 2017
An Son	Southeast Asia	10.53	106.60	2300-1100 BC						√	Bellwood et al., 2011
Non Pa Wai	Southeast Asia	14.97	100.68	2500-2200 BC				√			Weber et al., 2010
Khao Sam Kaeo	Southeast Asia	10.53	99.19	400-100 BC				√		√	Castillo & Fuller, 2010
Non Mak La	Southeast Asia	14.96	100.67	2000-500 BC				√		√	Pigott et al., 2006; Weber et al., 2010a
Rach Nui	Southeast Asia	10.54	106.67	1500-1200 BC				√		√	Oxenham et al., 2015; Castillo et al., 2018
Aşvan Kale	West Asia	38.83	38.87	100 BC- AD 100				√	√		Nesbitt & Summers, 1988
Gurgachiya TRC	West Asia	35.21	45.92	1400-1300 BC	√	√	√		√		Wengrow et al., 2016
Haftavan Tepe	West Asia	38.17	44.79	1900-1500 BC	√	√	√		√		Nesbitt & Summers, 1988
Tell Schech Hamad	West Asia	35.62	40.72	2000-100 BC	√	√	√	√	√		van Zeist, 1994; 2001
Hasanlu	West Asia	37.00	45.46	1250 BC- AD 300					√		Nesbitt & Summers, 1988
Sos Höyük	West Asia	40.00	41.50	1000-300 BC	√	√	√	√			Longford et al., 2009
Tille	West Asia	37.70	38.90	900-600 BC				√			Nesbitt & Summers, 1988
Ville Royale of Susa Level 3A	West Asia	32.19	48.26	250 BC- AD 220	√	√	√			√	Miller, 1981
Burzahom III-IV	South Asia	34.57	74.22	1000 BC- AD 200	√	√	√			√	Lone et al., 1993
Kazylgan	North Asia	51.50	90.50	200BC- AD 100					√		Vainshtein, 1980
Kokel	North Asia	51.00	91.20	200BC- AD 100					√		Vainshtein, 1980
Kara-Tepe	Central Asia	41.90	60.70	AD 300-500		√	√	√	√		Brite & Marston, 2012
Nimrud	West Asia	36.10	43.30	700 BC					√		Helbaek 1966: 615

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