Research paper

The Holocene
1–10

DOI: 10.1177/0959683616641742
hol.sagepub.com
SAGE

Millet cultivation across Eurasia: Origins, spread, and the influence of seasonal climate

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Abstract
The two East Asian millets, broomcorn (*Panicum miliaceum*) and foxtail millet (*Setaria italica*), spread across Eurasia and became important crops by the second millennium BC. The earliest indisputable archaeobotanical remains of broomcorn millet outside of East Asia identified thus far date to the end of the third millennium BC in eastern Kazakhstan. By the end of the second millennium BC, broomcorn millet cultivation had spread to the rest of Central Eurasia and to Eastern Europe. Both millets are well suited to an arid ecology where the dominant portion of the annual precipitation falls during the warm summer months. Indeed, the earliest sites with millet remains outside of East Asia are restricted to a narrow foothill ecocline between 800 and 2000 m a.s.l., where summer precipitation is relatively high (about 125 mm or more, from May through October). Ethnohistorically, millets, as fast-growing, warm-season crops, were commonly cultivated as a way to reduce agricultural risk and were grown as a low-investment rain-fed summer crop. In Eurasian regions with moist winters and very low summer precipitation, the prevailing agricultural regime had long depended on winter wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*) cultivated with supplemental irrigation. We propose that the secondary wave of millet cultivation that spread into the summer-dry regions of southern Central Asia is associated with an intensification of productive economies in general, and specifically with the expansion of centrally organized irrigation works.

Keywords
agriculture, irrigation, *Panicum miliaceum*, plant domestication, seasonality, *Setaria italica*

Received 12 December 2015; revised manuscript accepted 20 February 2016

Introduction

There are many factors involved in decision-making regarding the adoption or rejection of a new crop variety. These driving mechanisms include environmental constraints and phenotypical adaptive traits of available landraces, cultivation and processing technology, nutritional and agronomic qualities, social relationships between source and receiving regions, and cultural associations of status, ritual, and appropriateness to the local cuisine, including concepts of taste. In this article, we assess some of the factors that played a role in the acceptance of broomcorn (*Panicum miliaceum*) and foxtail (*Setaria italica*) millet as a key component in an array of different productive economies across the Old World, focusing on their early spread out of East Asia a little over four millennia ago. Both Panicoid species are well known as warm-season, drought-resistant crops, for they require relatively little water and have a short growing season. It is, therefore, paradoxical that they are often grown under irrigation over much of West and Central Asia today, where the prevailing climatic regime is Mediterranean in nature – characterized by cold wet winters and hot dry summers. While we acknowledge that cultural factors played an important role in the spread of these two millets, in this paper we investigate how climatic constraints changed over time. (Here, we use the term ‘millet’ to refer only to broomcorn and/or foxtail millet.) Our approach maps the archaeobotanical data in relation to seasonal climate and vegetation.

Origins of broomcorn and foxtail millet

The Chinese evidence

The origins of broomcorn and foxtail millet have long been a topic of debate. The earliest evidence for domesticated broomcorn millet from charred seed remains comes from the site of Dadiwan (*c*. 5900 cal. BC) in northeastern China (Liu et al., 2004). The earliest remains of foxtail millet grains that show the morphological changes associated with domestication come from the Yuezhuang site and date to 6000–5700 cal. BC (Crawford et al., 2013). Directly dated grains from the Early Neolithic site of Xinglonggou, Inner Mongolia, produced a date of 5670–5610 cal. BC (Zhao, 2011). In the Neolithic layers at Xinglonggou, 1400 charred grains of broomcorn millet and about 60 grains of foxtail

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millet were recovered, directly AMS-dated, and verified by three independent laboratories (Zhao, 2011). As we lay out in the next paragraph, millet ash or decomposed grains were excavated over 35 years ago and reported from the site of Cishan (6100–5600 cal. BC; see Zhao, 2011 for a discussion and critique of these data), which also fits into the general chronology. Based on stable isotope biochemistry (δ^{13}C), Barton et al. (2009) support the existing macrobotanical data and note that there was a process of low-investment cultivation at Dadiwan (what they call a phase of domestication) from 5900–5200 cal. BC, but that intensive millet cultivation did not commence at the site until 3900 cal. BC. Zhao (2011) notes that 5000–3000 cal. BC marked a period of intensification of millet cultivation in northern China that coincided with significant cultural development.

One month following Barton et al.'s (2009) publication, an article published in the same journal by Lu et al. (2009a) boasts that their data 'extended to 10,000 years ago' millet 'domestication' at the Cishan site. The authors support this bold statement citing their claim, published a month earlier, that '[a] species-specific identification of phytoliths is possible for *S. italica* and *P. miliaceum* because they have typically well-defined silica skeletons that are distinguishable from those in *P. bisulcatum*, *S. viridis*, and *S. plicata*, which have no such demonstrable patterns' (Lu et al., 2009b: 7). They correctly acknowledge that 'additional studies are needed to confirm the observations' because the new criteria are based on a single wild *Setaria viridis* specimen and two wild *Panicum bisulcatum* specimens (Lu et al., 2009a: 7368–7369, 2009b: 12). Even if the dating of the Cishan occupation to 10,000 years ago were generally accepted, the interpretation of the material is problematic. Lu et al. (2009a) claim that '>50,000 kg of grain crops' was recovered in situ from 88 storage pits at the site. They say that the grains were both 'well-preserved' and poorly preserved, having 'been oxidized to ashes soon after they were exposed to air' (Lu et al., 2009a: 7367). Thus, their analysis is based on problematic phytolith identification, rather than seed morphology. Subsequent work by Yang et al. (2012), which identified starch grains, supports a similarly early date, but this microbotanical evidence is also problematic (as noted by Bestel et al., 2014: 261; see Zhao, 2011 for a more comprehensive critique of identification and dating of the Cishan data). It should also be noted that starch analysis by Liu et al. (2010) and Yang et al. (2012), both on starch grains recovered from grindstones at the site of Donghulin (9000–7500 cal. BC), has produced contradictory results. Liu and her colleagues argue that there was intensive acorn processing at the site and, based on use wear analysis, note that low-silica plant material was processed with the grindstones. In contrast, Yang et al. (2012) claim to have found considerable quantities of millet starch on the grindstones, and argue that this further 'extend[s] the record of millet use in China by nearly 1,000 y'.

Whether we follow the macrobotanical results for the East Asian millets, which suggest a domestication date around 5900 cal. BC, or the phytolith data, which place millet domestication at 8300–6700 cal. BC, it is clear that the earliest evidence for both broomcorn and foxtail millet domestication comes from northeastern China. Both species were domesticated on the grasslands of China in the broad Yellow River catchment (An, 1988; Bellwood, 2005: 111–127; Crawford, 1992; Kimata and Sakamoto, 1992) or, as Liu et al. (2009) note, on the hilly flanks or dry grasslands north of the Yellow River. The 'dry grasslands' domestication scenario could explain why those millets are so drought-tolerant, as they are naturally adapted to dry-grass meadows.

Single or multiple origins: Monophyly versus polyphyly

Despite the ongoing discussion regarding the origins of millets in East Asia, the narrative of the origins of broomcorn millet, specifically, has had a longer, much deeper history of debate. In 1977, Lisitsyna and Prishepenko argued, based on archaeological material association, that domesticated millet grains from sites in Georgia and Azerbaijan dated to the fifth millennium BC (Kjultepe, Arukhlo, Imirisgora, and Chokh). Referencing these finds, Lisitsyna (1984) claimed that the Soviet Union was home to a center of domestication as proposed by NI Vavilov. Following this work, discoveries of early millet have been reported from sites across Eastern Europe. If, indeed, these claims were to prove true, it would imply one of two scenarios: (1) that broomcorn millet was domesticated twice, once in eastern China and once, possibly, in the Caucasus or elsewhere in Eurasia; or (2) somehow, before 5000 cal. BC, broomcorn millet crossed two continents without the transmission of any other crops or clear evidence of material culture across the vast Eurasian steppe and mountainous expanses. Either scenario would make a fascinating story, incidentally featuring broomcorn millet as the only crop to have been independently cultivated at the far ends of Eurasia before the third millennium BC.

Discussions about millet domestication take place in the broader context of crop domestication worldwide. Despite a lack of evidence for pre-domestication cultivation of millet, macrobotanical remains of *wild* Panicoid grass seeds were recovered from the Shizitan Locality 9 site (11,800 and 9600 cal. BC) in Shanxi province, northeastern China (Bestel et al., 2014). While only eight seeds or seed fragments, including two *Echinochloa* and two *Setaria*, were identifiable below the family clade, a few Poaceae and 'Chenopodiaceae' (also referred to in the article as chenopods) seed fragments were also found. All of these taxa, however, represent the dominant wild seed categories found in most macrobotanical assemblages across Northern Asia and are likely incidental inclusions. Regardless, they are still significant in that they are the first evidence actually linking these plants to early, pre-cultivation human contexts. Bestel et al. (2014) also observe that in southwest Asia, as in other areas of the world, extensive evidence exists for the process of grain domestication, in many cases, arguably, in a protracted model. The paucity of evidence for early Panicoid cultivation in northeastern China has helped fuel the current debate.

Cho et al. (2010) spurred a new wave of interest in the monophyly of broomcorn millet by sequencing its genome and providing the primers used by Hunt et al. (2011) in a subsequent population study. The results of that genetic study show that there are two distinct populations of broomcorn millet, roughly separated by the mountainous regions of Central Asia. However, the study concludes that these populations could either be the result of independent domestication events or an early bottle-necking of the population as a result of the spread of the crop across Eurasia and subsequent genetic isolation. Ultimately, the Hunt et al. (2011) genetic study, while providing a significant contribution to the field, was unable to distinguish between the two above-mentioned scenarios for the presence of early millet in Europe.

The claims of early millet grains across Eastern Europe are not trivial, as Hunt et al. (2008) point out; there are numerous archaeobotanical identifications of both *Setaria* and *Panicum* grains (not always identified as domesticated; see also Motuzaite-Matuzeviciute et al., 2013). Hunt et al. (2008) note that there are 31 published sites with reports of broomcorn millet pre-dating 5000 cal. BC from across Eastern Europe. However, despite this seemingly overwhelming evidence, at least some of these claims are spurious (for a discussion, see Boivin et al., 2012). Motuzaite-Matuzeviciute et al. (2013) point out that it is impossible to test many of these claims because reports were published as much as 50 years ago and the original material in many cases no longer exists. However, they were able to discredit or call into question many of these reports and collected 10 specimens for direct AMS dating. In an unprecedented publication in 2013, Motuzaite-Matuzeviciute and her colleagues reported that '[t]he dates indicate that the chronology previously proposed for the substantial number of Central and Eastern European broomcorn millet macrofossils was too early by at least 3500 years'. This article directly refutes numerous previously published site studies, implies that all 31 published accounts are unreliable, and completely reshapes our understanding of early agriculture in Eurasia, rewriting the narrative for the spread of the millets. The AMS dates underline the general observation that small botanical remains may readily move through the soil column, making inferences about chronology unreliable without direct dating. Ultimately, neither of the above-mentioned scenarios for explaining early broomcorn millet in Eastern Europe appears to hold up.

One reason for the ongoing dispute over the polyphyly and timing of origin for broomcorn millet is that the wild progenitor has never been identified and may no longer exist. Therefore, many scholars have simply written off the range of this wild progenitor as somewhere in the vast *terra incognita* of Central Eurasia (e.g. Hunt et al., 2014; Zohary et al., 2012: 69). In addition, differentiating between wild and domesticated species of macrobotanical remains is difficult because the earliest trait of domestication was a loss of the natural seed dispersal (i.e. brittle rachises); millet rachises are usually too delicate to preserve after charring. Other early traits of domestication include reduced tillering and increased overall size of the condensed panicle (De Wet, 1995), neither of which would show up archaeologically. The spread of foxtail millet outside of China is even more complicated than that of broomcorn millet, due in part to issues of morphological overlap between wild *Setaria viridis* (and other wild Panicoids) and between both domesticated foxtail and broomcorn millet. As Zohary et al. (2012) note, 'Identifying *Setaria italica* remains, and differentiating it from those of *Panicum miliaceum*, can be problematic' (p. 71). It is also the case that foxtail is less common outside of its homeland, for reasons that are not yet known. A first millennium AD Chinese text points out that there are many varieties of millets with many different agronomic and culinary properties (Wang, 2015: 29), which might have resulted in the observed apparent differential adoption of the two types.

Spread of broomcorn and foxtail millet from China

If we accept the Motuzaite-Matuzeviciute et al. (2013) conclusions that broomcorn millet did not reach Europe until the second millennium BC, we are still confronted with the question of how broomcorn millet made its way across two continents (roughly 7000 km) to ultimately become an important crop across Europe by roughly 3000 years ago.

The Inner Asian Mountain Corridor

After the third millennium BC, broomcorn millet cultivation spread rapidly through the mountain foothills of Central Asia, ultimately funneling broomcorn millet into Europe and wheat and barley into East Asia (Spengler et al., 2014c). First proposed by Frachetti (2012), the 'Inner Asian Mountain Corridor' relates the spread of commodities, new ideas, and new technologies by mobile and semi-mobile people to the ecological potential of the foothill zones of the Hindu Kush, Pamir, Tian Shan, Dhzungar, Kunlun, and Altai Mountains as early as the third millennium BC. The Corridor roughly coincides with the mountain foothill ecotone of Central Asia, an arable swath of land that connects the disparate ends of Asia. It enjoys the benefit of both winter precipitation brought by the westerlies across Eurasia and some summer precipitation falling at the edge of the Asian monsoon region (Figure 1a). In Eurasia, where continentality, winter temperature, and seasonality of precipitation are the main determinants of vegetation zones (Djamali et al., 2012), the unique ecological character of this zone is reflected by its distinctive natural vegetation cover (Figure 1b; Table 1). Although the boundaries of the vegetation and climate zones are not sharp and they have shifted over time, modern conditions inform the discussion of the spread of millet.

Seasonally transhumant populations utilized resources in the mountains valleys, and communication and trade with neighboring valleys led to a broadly similar productive economy across the region (Frachetti, 2012). Evidence from the sites of Begash and Tasbas, which lie squarely in the mountain corridor zone, suggests that wheat and barley moved through this corridor toward the northeast and that broomcorn millet spread in a reverse direction by the tail end of the third millennium BC (see Spengler et al., 2014c). By the second millennium BC, a new group of crops came to dominate the piedmont zone, and the local cultivation of crops is clearly archaeologically visible. Macrobotanical remains of broomcorn millet grains from numerous sites across Central Asia illustrate that the grain was present by the end of the third millennium BC and spread south through the mountain river valleys into southern Central Asia by the mid-second millennium BC (Frachetti et al., 2010; Miller, 2010; Spengler, 2015). For a summary of these archaeobotanical remains, see Table 2. The diffusion of other aspects of material culture and ideas through this region intensified through time, ultimately culminating in the Silk Road by the end of the first millennium BC.

Isotope evidence for millet consumption across northern Eurasia

Carbon isotope studies have rapidly increased in popularity across North Asia in the past few years and are complementing macrobotanical data sets. In 2013, Svyatko and her colleagues conducted an isotope study on 354 human and faunal bones from 37 archaeological sites (spanning 2700 to 1 BC) from across the Minusinsk Basin, Russia, mostly excavated in the 1920s. They noted a slight enrichment in the $\delta^{13}C$ values after 1500 BC, arguing that it is an indicator of the beginnings of millet cultivation. The merit of the Svyatko et al. (2013) article is its long time scale, providing baseline readings before and after the proposed introduction of millet. Following on this, Murphy et al. (2013) analyzed human remains from cemeteries at Ai-Dai on the west bank of the Yenisey River (8th through 3rd centuries BC) and Aymyrlyg in the Ulug-Khemski region of the Autonomous Republic of Tuva (mostly 5th through 2nd centuries BC). They also found enriched $\delta^{13}C$ values.

Another study in this recent wave of carbon isotope research looked at human populations from the cemeteries of Bestamak (2032–1640 cal. BC) on the Buruktal tributary of the Ubagan River and Lisakovsk (1860–1680 cal. BC) along the Tobol River (Ventresca Miller et al., 2014). The sites are about 100 km apart and located in the Kostanai oblast of northern Kazakhstan. The study found no enriched $\delta^{13}C$ values, thus providing a temporal and geographic boundary for the westward spread of this trend. Following up on this study, Motuzaite-Matuzeviciute et al. (2015) analyzed bone collagen from 25 archaeological sites, including 127 human and 109 animal bones, spanning all of Kazakhstan and temporally stretching from roughly 2920 BC to AD 1155. Ultimately, their results illustrate that starting in the early second millennium BC, higher $\delta^{13}C$ values appear in the mountains of Central Asia and spread along southerly routes, not taking root on the steppe proper (i.e. northern Kazakhstan). Ultimately, if we assume that the higher $\delta^{13}C$ values correlate with millet consumption and not another possible dietary or ecological shift, then these data support and build on previously published macrobotanical studies. Therefore, these corollary data reflect the introduction of millet cultivation into Central Asia and its widespread distribution in the foothill zone by the first millennium BC.

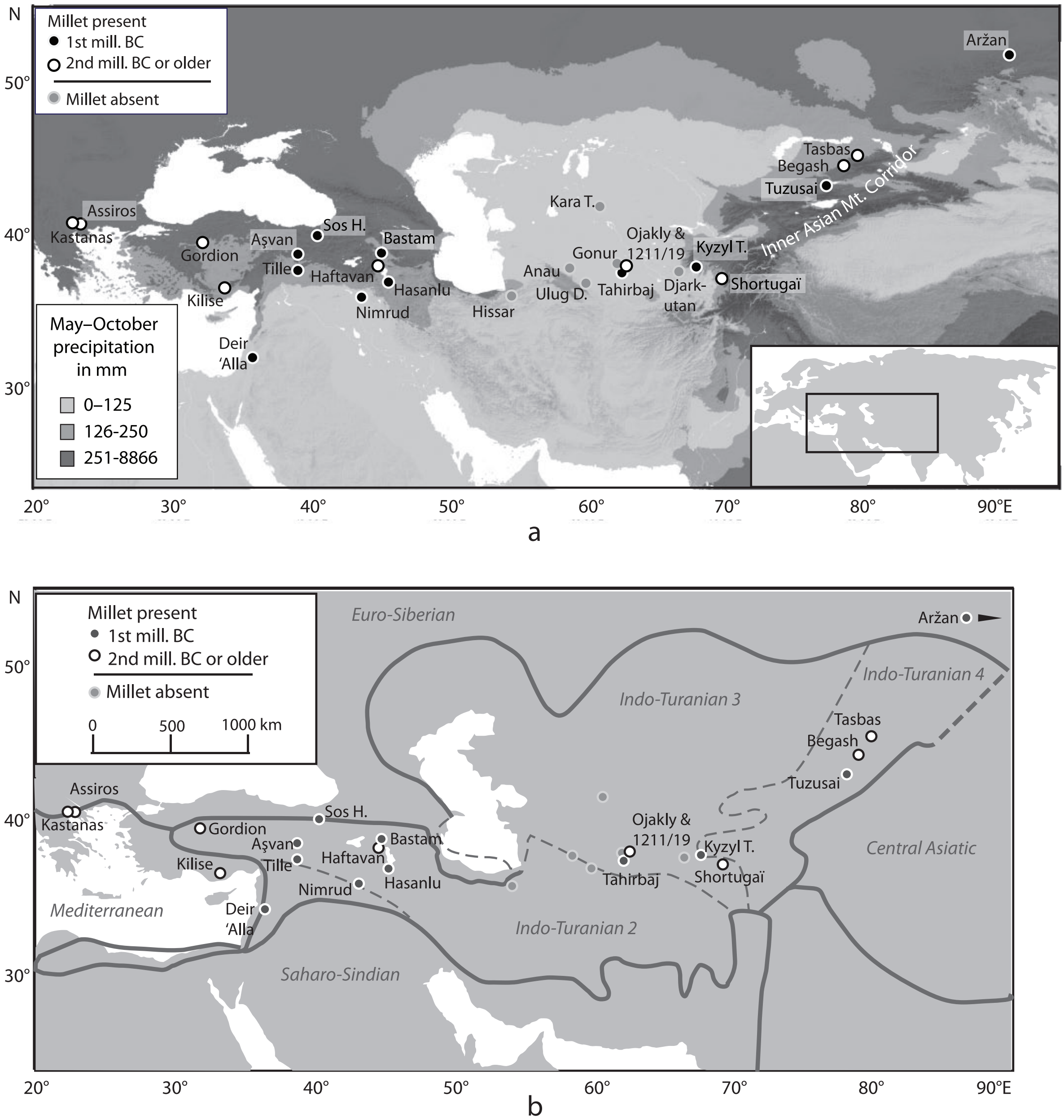

Figure 1. (a) Map showing location of sites mentioned in text in relation to warm-season (May–October) precipitation (precipitation data 1950–2000: http://WorldClim.org; Hijmans et al., 2005). (b) Location of sites mentioned in text in relation to vegetation zones (base map for vegetation zones: Djamali et al., 2012).

Mitigating risk through millet cultivation

Agricultural risk reduction strategies help small-scale independent farmers and mobile pastoralists stabilize their food supplies. Thanks to its low water needs and fast maturation, a catch crop of millet can supplement low food supplies in bad years, so dryfarming or light irrigation of millet in the Mountain Corridor zone would help farmers reduce the risk of harvest failure in the event of drought. Broomcorn millet is often associated with pastoralists in Eurasia and with low-investment agriculture (Pashkevich, 2003; Vainshtein, 1980). Three traits make millets especially suited for mobile pastoralists, whose primary food stores are on the hoof (Pashkevich, 1984): (1) the grain is drought-tolerant and can be grown along streams or near springs with low land and labor investment if fields are kept small; (2) they have a high yield per plant, so a 'nomad' can carry seed corn from one seasonal camp to the another; and (3) they have a short growing season, so a summer crop can be planted and harvested before having to move camp. Specifically, millet generally requires about half as much water as wheat (Shantz and Piemeisel, 1927). Its low water requirement is partly a function of its rapid maturation (Oelke et al., 1990), and it has a comparable-to-higher yield compared with wheat and barley (Purdue, 1996). It has also been suggested that the characteristically shallow roots of broomcorn millet, compared with other cereals, meant that plowing was unnecessary (Motuzaite-Matuzeviciute et al., 2012). Thus, few scheduling changes or labor adjustments are required when working millet into a mobile pastoral economy.

The archaeobotany of broomcorn and foxtail millet in Central and West Asia and the expansion of cultivation to the summer-dry regions

The earliest direct evidence, thus far, for broomcorn millet outside East Asia proper, comes from the northern Central Asian site of Begash (*c.* 2200 cal. BC; Frachetti et al., 2010; for a full discussion of the spread of millet into Central Asia, see Spengler, 2015; see also Lightfoot et al., 2013). Many scholars have argued that northern Central Asia is the pastoralist realm, and recent finds of

Table 1. Seasonal precipitation in millimeters and vegetation zone. Vegetation zones follow Djamali et al. (2012) categorization.

	Location	Summer	Winter	Vegetation
Summer precipitation >125 mm				
Kyzyl (Tuva)[a]	51.7 N, 94.4 E	343	115	
Aržan	52.1 N, 93.6 E			ES
Almaty[b]	43.2 N, 76.9 E	262	319	
Begash	44.9 N, 78.5 E			IT4
Tuzusai	45.5 N, 79.6 E			IT4
Tasbas	45.5 N, 79.6 E			IT4
Erzurum[c]	39.9 N, 43.2 E	251.6	208.9	
Sos Höyük	40.0 N, 41.5 E			IT2
Thessaloniki[d]	40.3 N, 23.4 E	193.5	246.4	
Kastanas	40.8 N, 22.6 E			M
Assiros Toumba	40.8 N, 23.0 E			M
Summer precipitation <125 mm				
Van[c]	38.5 N, 43.3 E	122	262	
Haftavan	38.2 N, 44.8 E			ES/IT2
Bastam	39.9 N, 45.0 E			ES/IT2
Panjakent[e]	39.5 N, 67.6 E	118.7	367.8	
Sarazm	39.5 N, 67.4 E			IT3/IT4
Polatlı[c]	39.6 N, 32.1 E	118.3	228.3	
Gordion	39.7 N, 32.0 E			IT2
Urmia[f]	37.6 N, 45.0 E	104	243	
Hasanlu	37.0 N, 45.5 E			IT2
Mersin[c]	36.8 N, 34.6 E	93.7	523.7	
Kilise	36.5 N, 33.8 E			M
Adıyaman[c]	37.8 N, 32.3 E	93.6	741.8	
Tille	37.7 N, 38.9 E			IT2
Aşvan Kale	38.8 N, 38.8 E			IT2
Ashkabat[g]	37.9 N, 58.4 E	55.6	175.8	
Ulugdepe	37.2 N, 60.0 E			IT3
Anau	37.9 N, 58.5 E			IT3
Shahroud[h]	36.4 N, 54.7 E	40	128	
Hissar	36.2 N, 54.4 E			IT2
Kunduz[i]	36.7 N, 68.9 E	38	285	
Shortugaï	37.3 N, 69.5 E			IT3/IT4
Mosul[j]	36.3 N, 43.1 E	31.4	354.7	
Nimrud	36.1 N, 43.3 E			IT1/IT2
Denau[k]	37.9 N, 67.6 E	28.9	269.6	
Kyzyltepa	38.1 N, 67.7 E			IT3/IT4
Urgench[l]	41.6 N, 60.6 E	20.2	71.1	
Kara-Tepe	41.9 N, 60.7 E			IT3
Irbid[m]	32.5 N, 35.8 E	18.1	91.8	
Deir 'Alla	32.2 N, 35.6 E			IT1
Bayramaly[l]	37.6 N, 62.1 E	16.8	138.2	
Ojakly	38.3 N, 62.2 E			IT3
Gonur	38.2 N, 62.0 E			IT3
Tahirbaj (Merv)	38.1 N, 62.1 E			IT3
Gyaur Kala (Merv)	37.7 N, 62.2 E			IT3
Erk Kala (Merv)	37.7 N, 62.2 E			IT3

Sources for precipitation data: [a]Kyzyl Tuva: http://en.climate-data.org/location/1807/; [b]Almaty: http://nsidc.org/data/G02174; [c]Erzurum, Van, Polatlı, Mersin, Adıyaman: *Meteoroloji Bülteni*, 1974; [d]Thessaloniki: http://www.thessaloniki.climatemps.com/precipitation.php; [e]Panjakent: https://en.wikipedia.org/wiki/Panjakent#Climate; [f]Urmia: http://www.orumieh.climatemps.com/precipitation.php; [g]Ashkabat: http://nsidc.org/data/G02174; [h]Shahroud: http://www.shahroud.climatemps.com/precipitation.php; [i]Kunduz: http://www.kunduz.climatemps.com/precipitation.php; [j]Mosul: http://www.worldweatheronline.com/Mosul-weather-averages/Ninawa/IQ.aspx; [k]Denau: http://nsidc.org/data/G02174 (J Böhner modeled Kyzyltepa annual precipitation as 231.54 mm) [l]Urgench, Bayramli: http://nsidc.org/data/G02174; [m]Irbid: http://www.worldweatheronline.com/irbid-weather-averages/irbid/JO.aspx.
ES: Euro-Siberian; IT: Indo-Turanian; M: Mediterranean.

domesticated crops call that into question – although low-investment forms of millet cultivation have traditionally accompanied pastoralism in Central Asia (Di Cosmo, 1994; Pashkevich, 1984; Vainshtein, 1980). The Begash grains were recovered in low abundance and ubiquity in late third millennium BC layers. In mid-second millennium BC layers at the site of Tasbas in the same region, unequivocal evidence has been recovered for local cultivation and some form of a mixed economy in the mountain foothills (*c*. 1400 cal. BC; Doumani et al., 2015; Spengler et al., 2014a). Broomcorn millet and, possibly, foxtail millet are a key part of this mixed productive economy at Tasbas. Contemporaneous sites, roughly 1000 km to the southwest, in southern Central Asia, have provided evidence that broomcorn millet was consumed at small-scale seasonal occupation sites across the Murghab region of Turkmenistan. Broomcorn millet was recovered from the sites of Ojakly (*c*. 1600 cal. BC; Spengler et al., 2014b), from the content and impressions on a vessel from the urban center of Gonur (*c*. 2500–1700 cal. BC; the grains were not directly dated; Bakkels, 2003).

The narrative of the spread of foxtail millet is even less clear than that of broomcorn millet. Nine fragments of what look like foxtail millet were recovered from *c*. 1400 cal. BC layers at the site of Tasbas (Spengler et al., 2014a), an identification supported by finds of *Setaria* phytoliths in the same contexts (see Doumani et al., 2015). Clear evidence for foxtail millet cultivation in the core of Central Asia does not appear until the mid-first millennium BC. Carbonized grains were recovered from the Iron Age site of Tuzusai in southeastern Kazakhstan, dating to 410–150 cal. BC (Spengler et al., 2013). The most clearly domesticated and best preserved evidence of mid-first millennium BC foxtail millet cultivation in Central Asia comes from the site of Kyzyl Tepa, a fortified Achaemenid site occupied from the 6th–4th centuries BC (Wu et al., 2015) (Figures 2 and 3).

Table 2 shows the sites considered for this paper and the presence or absence of millet in relation to the recorded precipitation of nearby modern centers, which is generally lower than the modeled precipitation data shown in Figure 1a. Most of the millet finds are consistent with the model proposed here: Prior to the first millennium, millet appears on sites where summer precipitation is more than 125 mm. In this ecological zone, millet cultivation would reduce agricultural risk. Sites without millet in the summer-dry region also fit the model; those that do have millet in this zone are dated to the first millennium BC and later, when empires and states across Eurasia initiated large-scale irrigation projects that would have brought water from perennial streams and qanats to fields. By the medieval period, summer-irrigated crops of many kinds were well established across Asia (cf. Watson, 1983). There are, however, a few sites that have yielded millet despite not fitting the climate-chronology pattern proposed here.

Seasonality of temperature and precipitation are the key factors for millet cultivation. The simplified model presented in the previous paragraph is based on readily available seasonal precipitation data, identifying a 'warm' season of May to October and a 'cold' season of November to April across Eurasia. The coarse geographical and temporal scale makes it necessary to explain apparent anomalies. With regard to Central Asia, there are only a few sites from the desert-steppe zone with millet remains dating to the second millennium BC: Ojakly, 1211, Gonur, and Shortugaï. The westernmost of the sites in Anatolia, Greater Mesopotamia, and Iran lies very close to moister millet-growing regions of Europe, northern Anatolia, and Iran (Haftavan, Gordion, Kilise).

Across the Kopet Dag foothills, even winter wheat and barley cultivation require(d) irrigation, but cultivated broomcorn millet is conspicuously absent from the early agricultural centers such as

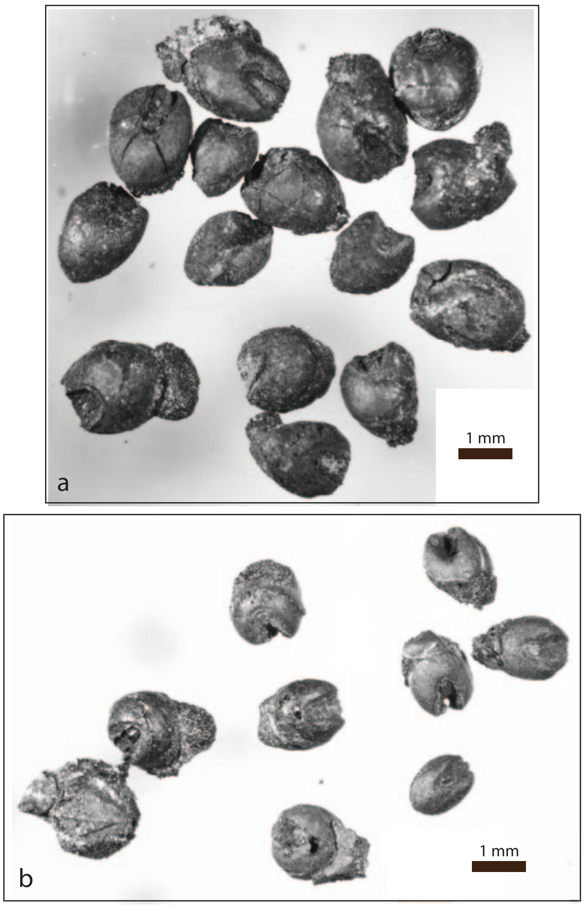

Figure 2. Millet from Kyzyltepa (Wu et al., 2015): (a) Broomcorn millet – *Panicum miliaceum* and (b) foxtail millet – *Setaria italic*.

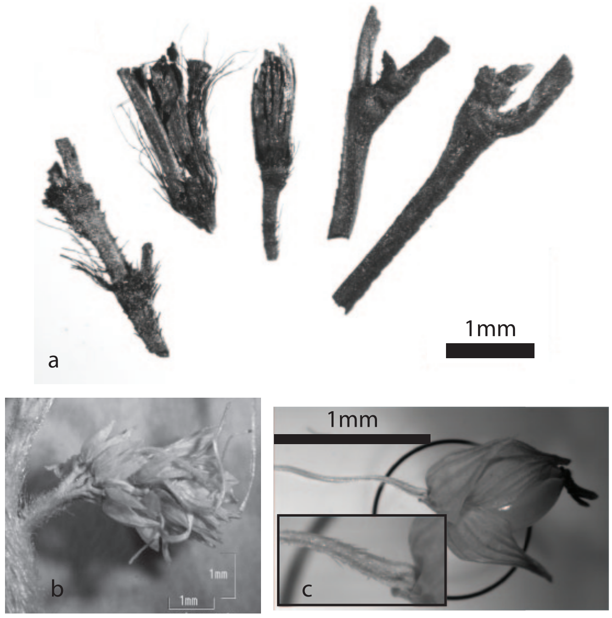

Figure 3. Millet rachis fragments. (a) Charred archaeological rachis fragments from Kyzyltepa (Wu et al., 2015). Three on left resemble *Setaria* and two on right resemble *Panicum*. (b) Modern wild *Setaria* (note hairs). (c) *Panicum miliaceum* (note few hairs).
Source: Photograph courtesy Xinyi Liu.

Anau, Djarkutan, or Sarazm (the latter is further northeast, in the Pamir Mountains (Spengler et al., 2014b)). In the Murghab delta, broomcorn millet was found in an early second millennium BC ritual context (Bakkels, 2003) at the agricultural settlement of Gonur. Millet was absent from large trash deposit excavated at that site by Fred Hiebert, but only one sample was floated (the rest were dry-sieved with 2 mm mesh (Miller, 1993; Moore et al., 1994). Although unexpected, two other sites nearby have millet – Ojakly and Site 1211, only 20 km from Gonur, also date to the first half of the second millennium. They are thought to be temporary campsites with ovens, but no permanent structures (Rouse and Cerasetti, 2014). There are no large irrigation works at this time, and the Ojakly and Site 1211 finds would fit the mobile pastoralist model presented above.

The broomcorn millet found at Shortugaï, Afghanistan, also comes from the second millennium BC (Level II, Period I; Willcox, 1991), but is not present in the earliest occupation layers. Willcox comments that the rain falls mostly in winter and early spring (Willcox, 1989), which would allow for an early unirrigated millet crop.

The presence of cultivated millet at Gordion, Haftavan, and Kilise, in regions with less than 125 mm of May–October precipitation, can be explained in several ways. First, the occasional early finds of millet identified as *Setaria italica* at Gordion in Central Anatolia may be associated with the migration of Early Iron Age peoples into Anatolia from southeastern Europe (Miller, 2010; Voigt, 2005: 29), where millet had already been cultivated for centuries. Large quantities of broomcorn millet grains from Haftavan, Iran (Nesbitt and Summers, 1988) date to *c*. 1900–1550 BC. At 122 mm of warm-season precipitation, the site is close enough to the model's 125 mm cut-off to fit the range of normal variation. Finally, at Kilise (Bending and Colledge, 2007), like at Shortugaï, millet could have been cultivated as a spring crop.

Risk reduction versus intensification

By the second millennium BC, broomcorn millet grains are present in several archaeobotanical assemblages from the open woodland regions of northern Anatolia, including Iran. With few exceptions, it is not until the first millennium BC that domesticated millets appear in archaeobotanical assemblages in the steppe and desert-steppe from Central Anatolia to Central Asia. We propose that natural and cultural factors – seasonal climate and large-scale water management practices – can explain this lag in the adoption of millet cultivation. Furthermore, the expansion of millet cultivation into a region manifestly unsuited to it was not motivated by risk reduction, but rather as a way to increase agricultural production through intensification and maximization of the return on land, labor, and capital investment.

First millennium BC sites in Central and West Asia exemplify these developments. For example, at Tahirbaj Tepe (Turkmenistan), dating to the Yaz II period (*c*. 650–500 BC, Diakonoff, 1985: 129), Mark Nesbitt (1994) identified a substantial number of broomcorn seeds (Herrmann and Kurbansakhatov, 1994). The roughly contemporary site of Kyzyl Tepa is located in the Surkhandarya region of Uzbekistan. Archaeological surveys there show that the regional population grew during the mid-first millennium BC (Stride, 2005). There were no pure samples of millet at Kyzyl Tepa, but two samples mixed with wood charcoal, barley, and seeds of a variety of wild and weedy plants also had substantial numbers of broomcorn ($n \geqslant 2000$) and foxtail ($n \geqslant 1500$) seeds; even the very delicate rachis fragments were preserved (Wu et al., 2015; Figures 2 and 3). In West Asia, millet is reported from Neo-Assyrian levels at several sites: Nimrud (Ziggurrat Terrace) and Fort Shalmaneser, Iraq (second half of the 7th century BC; Helbaek, 1966), Deir 'Alla, Jordan Phase VI (650 BC; Neef, 1989; for dating, see Groot and Dik, 2008). Large caches of foxtail millet, about 15 L in total, were found at Tille Hoyuk, southeastern Turkey, dating sometime after 708 BC (Nesbitt and Summers, 1988: 86).

Central Asians had the technology for growing summer-irrigated crops long before the first millennium BC, and the lines of communication and trade would certainly have permitted the adoption of millet cultivation. In summer moist areas, cultivating warm-season C_4 millets can reduce agricultural risk. In regions

Table 2. Presence or absence of *Panicum miliaceum* (P: broomcorn) and *Setaria italica* (S: foxtail millet) on sites with 3rd millennium BC and more recent occupations in regions with May–October precipitation greater than or less than 125 mm (–: archaeobotanical report does not mention millet).

	3rd Millennium BC	2nd Millennium BC	1st Millennium BC	AD	Source
Summer wet					
Aržan			P		Neef (2010)
Begash	P		P, S		Frachetti et al. (2010), Spengler et al. (2014c)
Tuzusai			P, S		Spengler et al. (2013)
Tasbas		P, S?			Spengler et al. (2014a)
Sos Höyük	–	–	S		Longford et al. (2009)
Kastanas		P	P		Nesbitt and Summers (1988)
Assiros Toumba		P			Nesbitt and Summers (1988)
Summer dry					
Haftavan		P			Nesbitt and Summers (1988)
Bastam			P or S		Hopf (1989)
Sarazm	–				Spengler and Willcox (2013)
Gordion		S	P, S	P, S	Marston (2010); Miller (2010)
Hasanlu			P		Costantini (n.d.)
Kilise		P	P		Bending and Colledge (2007)
Tille			S		Nesbitt and Summers (1988)
Aşvan Kale			P		Nesbitt and Summers (1988)
Ulugdepe	–	–	–		Mission Archéologique Franco-Turkmène (MAFTUR) (2012)
Anau	–	–			Harrison (1995); Miller (2003)
Hissar	–	–			Costantini and Dyson (1990)
Shortugaï		P			Willcox (1989, 1991)
Kyzyltepa			P, S		Wu et al. (2015)
Deir ʻAlla		–	P or S		Neef (1989)
Ojakly, 1211/1219		P			Rouse and Cerasetti (2014)
Gonur		P or S			Bakkels (2003)
Tahirbaj (Merv)			P		Nesbitt (1994)
Gyaur Kala (Merv)			P		Boardman (1995, 1997, 1999)
Erk Kala (Merv)				P	Boardman (1995, 1997, 1999); Nesbitt (1994)
Kara-Tepe				P, S	Brite and Marston (2012)
Nimrud			P		Nesbitt and Summers (1988)

with virtually no summer rainfall, however, it may reflect other changes in agricultural practice, namely, the state-sponsored expansion and intensification of water management systems. Ester Boserup (1965) observed that many technologies are known to people before they are adopted wholeheartedly out of usefulness or necessity. That observation would seem to apply in this case.

In the summer-dry region of Central Asia, the introduction of millet cultivation has several corollaries: first, in regions where the primary grains are fall-sown wheat and barley, summer-grown millet increases the total amount of carbohydrate-rich food. Second, irrigation would have expanded agricultural activities into the summer months – increasing productivity. Third, this would make the ordinarily slow summer season one of labor – spreading out the need for labor inputs. Planting, water management, and harvest would have kept people at home, whereas, previously, they might have moved to cool summer pastures with their flocks (see Miller, 2011). Fourth, the growing of summer crops would help justify the cost of the heavy capital investment in the expanded irrigation infrastructure (see Kirkby, 1977).

Conclusion

Over the past four millennia, people carried plants across the deserts and mountain valleys of Central Eurasia, along routes of communication and trade, a process of dispersal that is most evident with the historically documented Silk Road. One of the earliest crops to move through these mountain corridors was broomcorn millet, an East Asian domesticate that played a major role in the diet and culture of peoples across Europe and Asia by the first millennium BC. The adoption of broomcorn millet, as with most crops that farmers choose to grow, was influenced by climate, irrigation technology, and the social context of agricultural production. We have attempted to discern the decision-making process of prehistoric farmers in Eurasia and, in so doing, recognize two phases in the spread of the millets. The initial expansion of broomcorn millet cultivation beyond its East Asian homeland may have aimed at economic diversification – mobile pastoralists and small-scale farmers in Central Eurasia reduced (and still do today) risks associated with specialized economies by diversifying their subsistence base. Broomcorn millet, when it was first introduced to Central Asia (starting in the later third millennium BC), was only cultivated in the mountain foothills in regions where summer rainfall allowed for easy cultivation of the drought-tolerant crop without a need for irrigation. The fact that its cultivation remained mostly restricted to this ecologically rich zone until the latter half of the first millennium BC was likely because of its role in economy, as a low-investment catch crop providing a fallback in famine years.

By the second half of the first millennium BC, however, the crops had spread across the arid zones of Central Asia, onto the Iranian Plateau, southwest Asia, and across Europe, where it became an important crop in the Mediterranean during the 1st century AD In addition, foxtail millet appears to become more widespread at this time. We argue that this second wave of expansion was because of a change in the economic role of the crop; it was now taken up as a summer rotation crop in complex crop rotation systems that maximized productivity of land. The expansion of large-scale irrigation systems in the winter-wet, summer-dry zone is characteristic of the first millennium BC, preceding the major waterworks of the Sasanians. It is associated with imperial systems of West Asia from the Neo-Assyrians to the Achaemenids. Irrigation systems for winter-cropping wheat and barley were already in place; the introduction of the millets allowed for a novel economic system, incorporating for the first time summer-cropping in hot, arid-summer regions. A Neo-Assyrian rock inscription even associates canal expansion with sesame, which is a summer crop (Wilkinson and Rayne, 2010). Those empires could have drawn millets from the established crop repertoires of eastern or western Asia. Millet cultivation in the summer-dry region provided a way to extract more food from the same amount of land, unlike in other regions, where millet was grown to reduce agricultural risk.

In short, while the earliest spread of broomcorn millet out of East Asia was restricted to a specific ecological belt in Central Asia during the second millennium BC, its widespread distribution across Europe and West Asia by the end of the first millennium BC appears to be a response to changes in cultivation practices, technology, and society.

Acknowledgements

Dr Morteza Djamali provided an updated vegetation map, used as the base for Figure 1b. For this research, Professor Dr Jürgen Böhner (University of Hamburg) provided modeled precipitation data for Kyzyltepa.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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