Early evidence for the use of wheat and barley as staple crops on the margins of the Tibetan Plateau

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Edited by Ofer Bar-Yosef, Harvard University, Cambridge, MA, and approved March 27, 2015 (received for review December 13, 2014)

We report directly dated evidence from circa 1400 calibrated years (cal) B.C. for the early use of wheat, barley, and flax as staple crops on the borders of the Tibetan Plateau. During recent years, an increasing amount of data from the Tibetan Plateau and its margins shows that a transition from millets to wheat and barley agriculture took place during the second millennium B.C. Using thermal niche modeling, we refute previous assertions that the ecological characteristics of wheat and barley delayed their spread into East Asia. Rather, we demonstrate that the ability of these crops to tolerate frost and their low growing degree-day requirements facilitated their spread into the high-altitude margins of western China. Following their introduction to this region, these crops rapidly replaced Chinese millets and became the staple crops that still characterize agriculture in this area today.

modeling | wheat | barley | staple crops | Tibet

In recent years, there has been much debate as to the timing of the arrival of Western Eurasian domesticates in East Asia and their modes of adoption (1). Initially it was argued that wheat and barley agriculture were able to move into East Asia and become staple crops only after a long delay because of their short growing seasons (2). Others have focused on cultural factors and argued that resistance in food-preparation techniques delayed the incorporation of wheat and barley as staples in subsistence strategies (3). We have argued that it is not sufficient to consider growing season length; rather, it is crucial to examine other agronomic characteristics such as growing-degree days (GDD) (4, 5). To this end, we have created crop niche models that are capable of predicting the changing niches of crops over time (4, 5). These models formed a basis for the argument in a recent paper that tests this hypothesis on the northeastern Tibetan Plateau (NETP) (6). Using these models and data from the southeastern Tibetan Plateau, we demonstrate that wheat and barley were crucial in allowing agriculture to become established in highland China following the end of the Holocene climatic optimum (3, 4, 6). We argue that risk reduction may have been a key factor in the translocation of these crops across highland southwest China, particularly after the end of the Holocene climatic optimum. We present archaeobotanical evidence from the Ashaonao site situated in high-altitude Eastern Tibet of the early use of wheat and barley as staple crops (Fig. 1). We argue that in highland eastern Tibet these crops became an important facet of economic subsistence shortly after their introduction and that this region may have played a crucial role in the establishment of these crops as staples across the vast region of East Asia.

Background: The Archaeology of Highland Western Sichuan

Until recently, relatively little was known about the prehistory of highland southwest China. Archaeological research in this area has developed at an increasing pace and has revealed that farmers who practiced millet agriculture and pig husbandry first settled in this region circa 3500 calibrated years (cal) B.C. (7–12). These sites share a number of commonalities with the Majiayao culture of northern China, and scholars argue that the appearance of this cultural phenomenon in western Sichuan corresponds to a southward migration of farmers from northwestern China (7, 8). However, local adoption of domesticates by groups of hunter–gatherers remains a possibility that still needs to be explored for this region. Increasing evidence, such as that from the recent excavations at the Liujiazhai site, indicate that local foragers in this region may have selectively traded or grown domesticates while continuing to forage and that complex interactions may have been at play as agriculture spread into highland southwest China. Initial results of archaeobotanical analysis at low-elevation sites, Yingpanshan and Haxiu, suggest that broomcorn and foxtail millet (both crops that were domesticated in northern China) were exploited by at least some of the inhabitants of highland southwest China (13). At about the same time, millet agriculture also appears to have spread to the Karuo site on the Southeastern Plateau (6). A gap in both known settlements and radiocarbon dates seems to occur in this region circa 2000–1700 cal B.C. This gap may be correlated with climatic changes.

A new cultural facies that is substantially different from the previous period both in terms of site location and material remains appears in the area circa 1500 B.C. (14). This new behavioral pattern/facies appears to have been long-lived, lasting at least until the first centuries A.D. To date, virtually no evidence of habitation sites has been unearthed that relates to this set of material. Most known evidence from this period comes from stone-cist graves. This burial tradition is widespread and covers sites ranging from western Sichuan (15–23) to northwest Yunnan (Fig. 1) (24–27). Ceramic vessels, metal weapons, and ornaments from these graves show clear connections with objects from Gansu, Ningxia, Inner Mongolia, and the Ordos region (28–31).

Significance

Adapting agricultural systems to the high-altitude environment of the Tibetan Plateau has long been considered a major challenge for farmers. It has been asserted previously that the ecological characteristics of wheat and barley delayed their spread into East Asia. We argue instead that the ability of these crops to tolerate frost and their low heat requirements facilitated their spread into the high-altitude margins of western China. Following their introduction to this region, these crops rapidly replaced Chinese millets that could not adapt to the cooler temperatures of post-Holocene climatic optimum East Asia. We present data from the eastern Tibetan Plateau demonstrating that wheat and barley rapidly became staple crops shortly after their introduction.

Author contributions: J.A.d.G. and H.L. designed research; J.A.d.G., H.L., and A.H.S. performed research; J.A.d.G. and A.H.S. analyzed data; and J.A.d.G., H.L., A.M.H., and A.H.S. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1423708112/-/DCSupplemental.

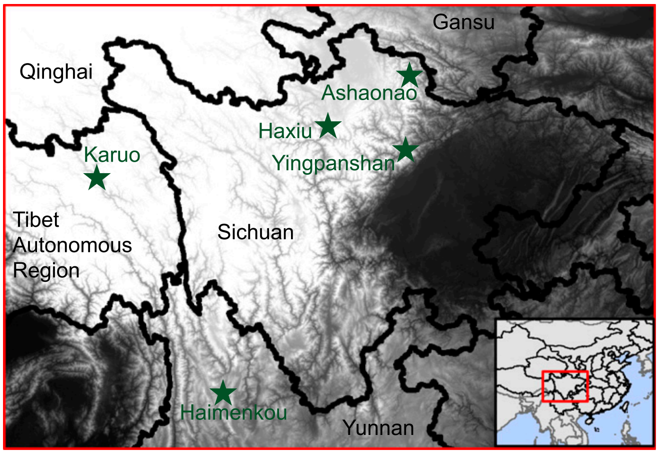

Fig. 1. Location of the Ashaonao site.

The contents of the stone cist burials show close relationships to sites in northwest China where sheep bones have been found (32), suggesting that the individuals buried in these graves may have practiced some form of pastoralism. However, the current lack of zooarchaeological analysis in this region makes it difficult to say exactly how this transition took place and what form of pastoralism the inhabitants of this region practiced. At the sites of Laolongtou and Maojiaba in Yanyuan (33) and at Jililong close to the Tibet border in Ganzi county (34), interred horse bones, harnesses, and heads suggest that the practice of horse mounting had reached this region by that time. Finds of large numbers of wheat and barley seeds from stone-cist graves at the site of Yan'erlong (15) suggest that in this region subsistence practices may have changed radically during the mid-second millennium B.C.

The Ashaonao Site

Situated in the Jiuzhaigou National Park, Sichuan Province, Ashaonao is, to our knowledge, the first site that has been excavated that contains evidence for the lifestyle of the builders of the stone-cist graves of Northwest Sichuan (Fig. 1). Excavations were carried out at the Ashaonao site in 2008, with a sampling season in 2010 by Sichuan University and the University of Washington (35–37). Eight stratigraphic layers were visible at the site. During excavations, a wattle and daub Han Dynasty house was identified, the foundations of which dug into earlier occupation layers (Fig. S1). This house covered more than 60% of the area of the excavation, and it was not possible in the constrained space to reveal features related to the earlier layers. However radiocarbon dating of visible deposits revealed archaeobotanical remains dating back to 1400 cal B.C.

This house, which had been partially destroyed by terrace collapse, contained two separate rooms. A hearth was found in the western room, which also held iron instruments used for agricultural activities and large amounts of pottery. The eastern room contained deer jaw bones and carbonized plant material. Other finds include a well-preserved basket and wooden building elements. The ceramics found inside the housing unit are characteristic of the Han dynasty (202 B.C.–220 A.D.) (Fig. S2). One piece of pottery that shared similarities with object types of the previous Majiayao-culture remains also was uncovered in layer 8 (Fig. S2), suggesting that earlier layers not targeted by our initial excavations exist at the site. In addition, a few pieces of low-fired red sandy-inclusion pottery that is typical of the stone-cist grave period were found in fill layers of the site, suggesting that the site had several earlier phases of occupation. Zooarchaeological work at the Ashaonao site is currently under way, and preliminary results suggest use of pastoral animals such as sheep (38).

Results

During the second season, in 2010, we collected archaeobotanical samples from several areas of the site. Inside the house these areas included (*i*) an ash pit (feature H2) that contained a large number of deer mandibles (Figs. S1 and S3*E*); (*ii*) the baulk wall that appears to have been part of a destruction layer (east wall Shineiduiji) (Figs. S1 and S3*D*); and (*iii*) a column sample from another baulk wall (Figs. S1 and S3*A*). Outside the excavated area, additional samples were collected systematically from two pits visible in the section of the terrace: LT4E H1 (Figs. S1 and S3*B*) and LT4E H2 (Figs. S1 and S3*C*).

The site was dated by optically stimulated luminescence and radiocarbon dates on charcoal and seeds (35–37). Unfortunately, no material for radiocarbon dating was retrieved from layers 9 and 8 where the early pottery was recovered. Radiocarbon dates on seeds show that some units (L7 and L6C) were occupied as early as 1400 cal B.C. with an occupation that extended until roughly 1000 cal B.C. The period between 700–500 cal B.C. is represented by a single date, suggesting a potential period of abandonment, after which the site was reoccupied with more intensity between 400 and 1 cal B.C. (Fig. S4). Inside the house, unit H2 dates to roughly from 800–1 B.C. Other parts of the site, including the deposit that accumulated at the east wall and layers 6A and 5, were dated to considerably later, from 400–200 B.C. (Fig. S4). It is likely that this house was occupied sometime between 800 and 400 cal B.C. and was filled in by destruction layers that date to roughly 400 cal B.C.–1 A.D. This house appears to have cut into earlier layers at the site that date between 1400 and 1000 cal B.C. The two pits outside the excavation area also date to the Han dynasty.

Throughout the occupation of the Ashaonao site, subsistence appears to have been based on wheat and barley (Dataset S1). Much like other finds in East Asia, the wheat present at Ashaonao appears to have been of a compact form (Fig. 2*A*). A total of 12 rachis bases revealed that the type of wheat cultivated at Ashaonao was a hexaploid bread wheat (Fig. 2*B*). The morphology of the barley caryopses conforms to a naked type, and the presence of twisted asymmetrical caryopses suggests that it was as a six-rowed form (Fig. 2*C*). A series of plants that could have been consumed as fruits also were found, including elderberry (*Sambucus* sp.), *Rubus* sp., and either *Potentilla* or *Fragaria*. *Malva* sp., which is eaten as a leafy green in the region today, also was unearthed at the

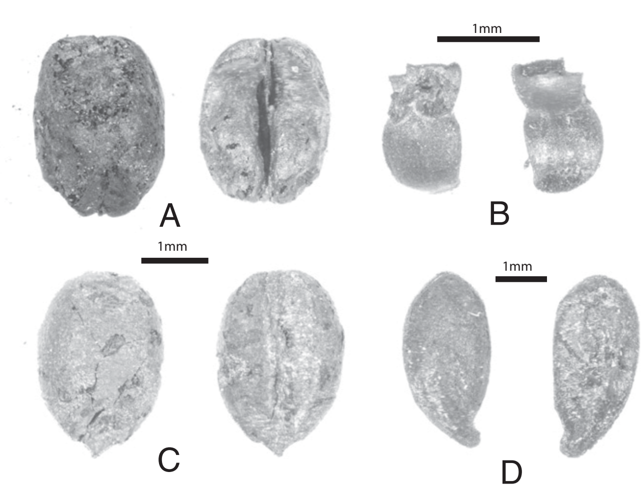

Fig. 2. Crops unearthed at the Ashaonao site. (*A*) Hexaploid bread wheat caryopsis (*Triticum aestivum*). (*B*) Hexaploid bread wheat rachis base (*Triticum aestivum*). (*C*) Barley (*Hordeum vulgare*). (*D*) Flax (*Linum* sp.).

site but may represent disturbance taxa. Other wild foods include a small pulse (*Vicia* sp.) that has been documented from other sites in the region (Fig. S5*B*), seabuckthorn (*Hippophae rhamnoides*) (Fig. S5*A*), and *Prunus* sp. (Fig. S5*C*). In addition to wheat and barley, the Ashaonao site also contains the earliest known evidence for the use of flax (*Linum* sp.) in East Asia (Fig. 2*D* and Figs. S2 and S6).

Discussion

An increasing body of directly dated evidence demonstrates that wheat appeared in China sometime during the second millennium B.C. (1–6, 39–48). Most of these early finds have come from Northwestern China, namely the provinces of Xinjiang (42), Gansu (41, 43–46), and Qinghai (6, 42), although some finds also are known from eastern China (47, 48). To date, little is known about the spread of western Eurasian domesticates to the peripheries of the eastern Tibetan Plateau; however, they are present on the northeastern and western Tibetan Plateau borders and in Nepal between the early second and first millennium B.C. (6, 49–52). On the eastern borders of the Plateau the remains of both wheat and barley have been found at the site of Haimenkou in western Yunnan province in contexts dating to roughly 1600–1400 cal B.C. (4, 53); however, these finds have not yet been fully published.

How western Eurasian domesticates eventually came to be part of East Asian agricultural systems has been increasingly debated. Some scholars have focused on ecological considerations and argue that wheat's growing requirements slowed its movement into East Asia (2). Only a single aspect of crop growth patterns was considered in these arguments: length of the growing season. They argue that individuals would have preferentially adopted millets across highland Eurasia because of their short growing season and ability to grow in the cold and high latitudes of northern Asia. The longer growing season of wheat and barley, on the other hand, is regarded as a factor that would have slowed the spread of these crops (2). Others also invoked ecological constraints on the spread of wheat agriculture across China and suggested that parts of China were unsuitable for wheat production (42).

Boivin et al. (3) focused on the role that these crops played in emulation, negotiation, performance, and competition. In particular, they argue that if increasing production levels was the goal of their introduction, then they should have been assimilated into the diet rapidly. However, they argue that in most of China, there is a delay of roughly two millennia before wheat and barley became an important part of subsistence practices because of cultural resistance to the uptake of new food technologies and preparation methods (3). Others suggest that this process may have taken even longer and that wheat remained a minor crop until the Tang dynasty (39, 42). In particular, Boivin et al. (3) suggest that wheat changed from being an exotic in the Bronze Age to a risk-buffering crop during the early Han and became a staple only during the late Han dynasty. They argue that baking bread and milling flour are not originally in line with Chinese cooking traditions, and as a result wheat and barley agriculture took hold in central China only after 200 B.C., following the development of rotary querns. Risk reduction, they argue, was only rarely a goal as humans moved crops across Eurasia.

Similar to positions we present in refs. 4 and 5, we argue that none of the positions cited above (2, 3, 42) are entirely correct, particularly with regards to the highlands of western Sichuan.

First, contrary to the original assertions made by Jones et al. (2), a careful evaluation of the agronomic literature reveals that wheat and barley are much better adapted than millets to areas of higher latitude and altitude.

Jones et al. (2) originally considered only one factor in plant growth: the length of the growing season. However, growing season length is only one of the measures used by plant biologists

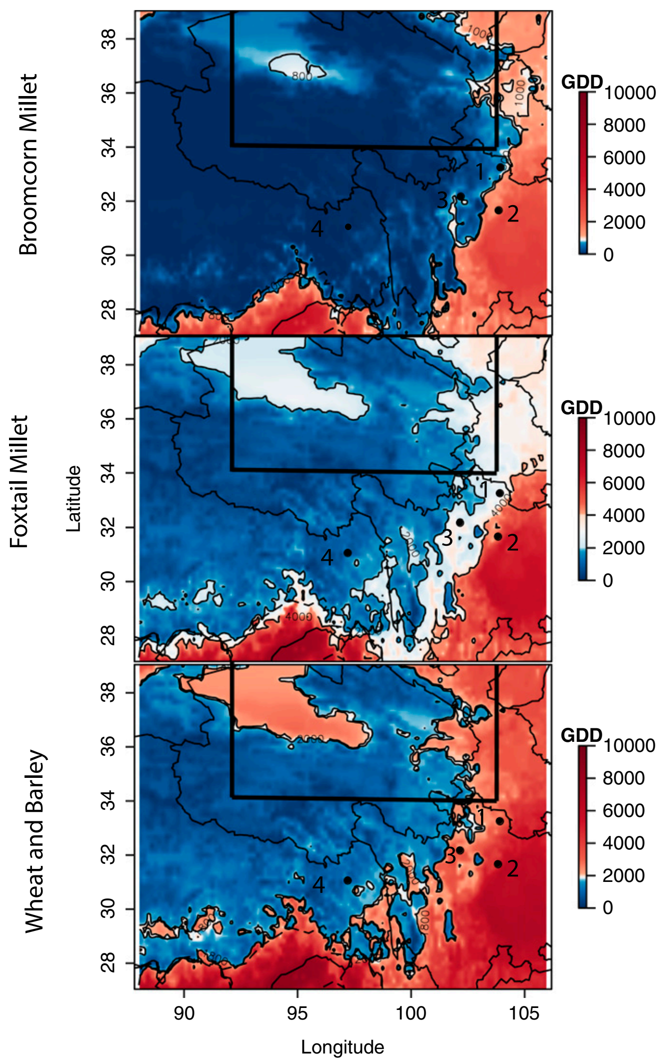

Fig. 3. The growing niche of broomcorn millet, foxtail millet, and wheat and barley in the region of study using GDD as a measure at modern temperatures. The areas where each crop can be cultivated successfully are shown in red. The border zone for cultivable viability is shown in white. It may be possible to cultivate some varieties in this area. The crop represented cannot be cultivated in the area shown in blue. The black-bordered box represents the NETP. Black dots represent archaeological sites discussed in the text: 1, Ashaonao; 2, Yingpanshan; 3, Haxiu; and 4, Karuo.

and ecologists to predict plant growth. Although the length of the growing season can be an adaptive feature, it does not predict where crops ultimately can be grown. In high-altitude and high-latitude environments, having sufficient available units of heat is a key factor in determining the distribution of plant species. In agronomy, heat traditionally is measured as GDD, the cumulative heat requirements of a plant (54, 55). In these environments, GDD is more useful than length of the growing season for determining the distribution of food crops. Although in some areas estimates of frost-free days or of growing-season length may provide similar estimates, GDD is a more accurate measure for calculating where crops can complete their life cycle for several reasons. Many plants require not only the presence of frost-free days (in other words, an adequate growing season length) to complete their lifecycle but also units of heat that may be well in excess of temperatures above 0 °C. For instance, although broomcorn millet requires between 45 and 100 frost-free days (Dataset S2), it cannot grow to maturity unless sufficient units of heat are available within those 45–100 days. Dataset S2 summarizes the GDD requirements of crops.

Wheat and barley share a key trait that makes them better adapted than broomcorn or foxtail millet to high-altitude environments: frost resistance (4, 5, 7). This trait often has allowed barley crops to extend the limits of cultivation (56). Both wheat and barley can sustain substantial frosts and can initiate growth at temperatures well below those required by foxtail and broomcorn millet (Dataset S2). Indeed, as we have pointed out elsewhere (4, 5, 7), winter varieties of these crops require cooler temperatures to meet their vernalization requirements. It is worth noting that Jones et al. recently have taken into account our work on thermal niche models (4, 5) and have revised their hypothesis in a recent paper (6) that shows support for our argument using data from the NETP.

A map comparing the growing niche of wheat and barley with that of millets was prepared in "R" using the methods described in refs. 4 and 57. This map reveals that wheat and barley would have been crucial crops for allowing the establishment of agriculture in high-altitude areas such as the Tibetan Plateau (Fig. 3).

In particular, the area around Ashaonao is not amenable to broomcorn millet cultivation and was on the very marginal production area for foxtail millet cultivation. The niche occupied by wheat and barley is visibly larger (Fig. 3). Contrary to what was originally implied by Jones et al. (2), millet agriculture is less adapted to areas of high altitude and latitude than wheat and barley. Rather it appears that the presence of western Eurasian domesticates was crucial to allowing humans to expand into these areas (3, 4, 7). Our maps reveal that in most of highland western China and Tibet, millets could be grown only in select river valleys and likely were a highly risky option even in these areas (Fig. 3). Millets can be grown in the area around Ashaonao only at temperatures 2–3 °C above those at present (Fig. S7), i.e., at approximately the temperatures that characterized the Holocene climatic optimum in this area (58–64). During the climatic optimum, temperatures in the area around Yingpanshan and in a small river valley near the Haxiu site were sufficient for the growth of broomcorn millet; however, this niche began to shrink with the cooling toward modern temperatures (Fig. 3). Foxtail millet may have been able to occupy a wider area; however, this area also shrank substantially following the end of the climatic optimum (Fig. S7). At the Karuo site in Eastern Tibet, it was possible to grow foxtail millet only at temperatures 3 °C higher than those of today, an observation that may mean that the inhabitants of this site were less involved in agricultural production than previously thought (5). Interestingly, all these sites appear to have been abandoned rapidly following the second millennium cal B.C. (5). An abandonment of millet-producing sites around the second millennium cal B.C. also has been noted for sites on the NETP (6). Shortly thereafter wheat and barley were adopted

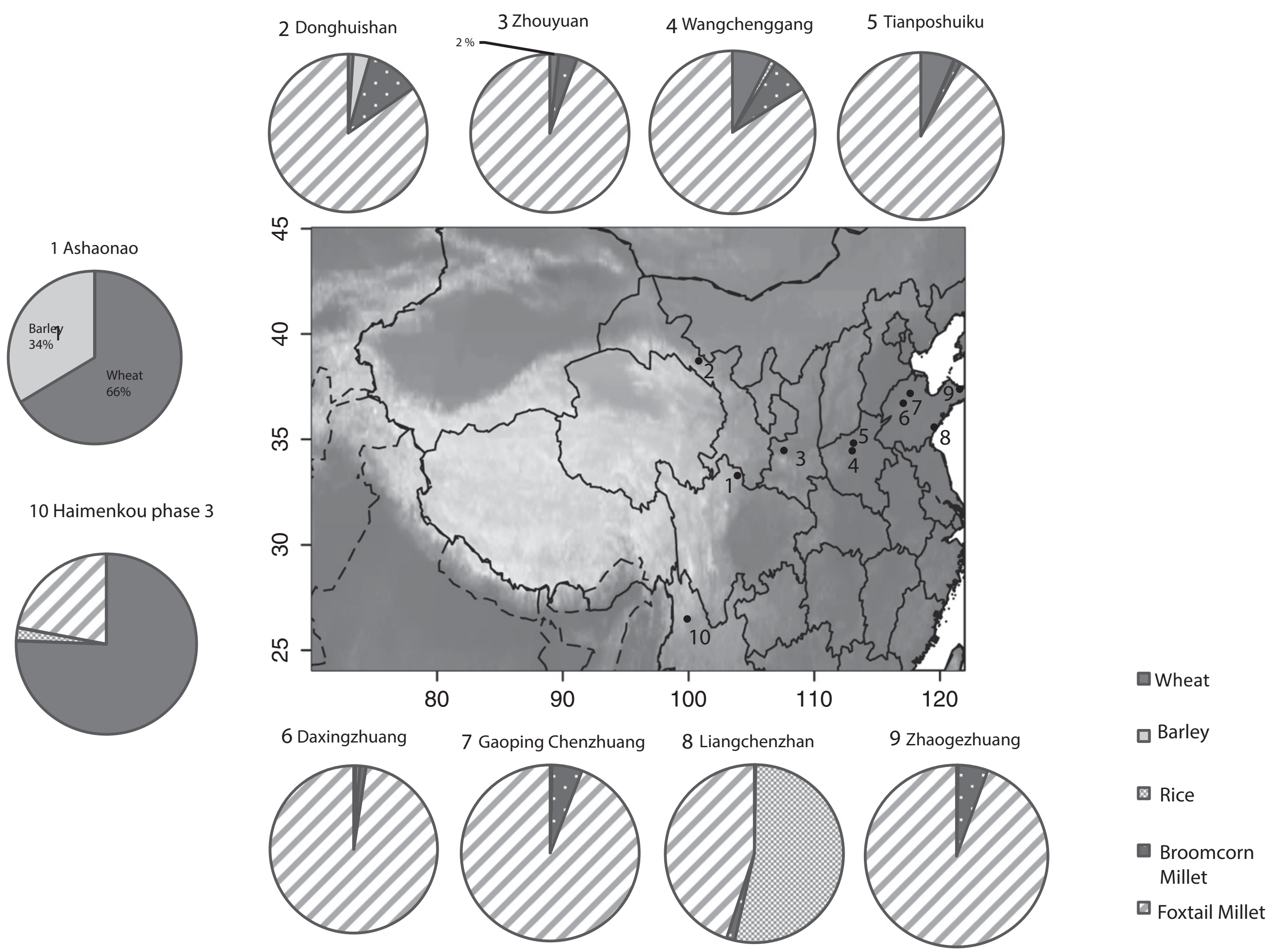

Fig. 4. Proportions of different crops at sites containing wheat and barley in pre-Han China. The proportions of wheat and barley are notably higher at the Ashaonao and Haimenkou sites than at other sites.

rapidly as central components of the diet (4, 5). The adoption of these crops appears to have facilitated the movement of humans into areas of cooler temperatures than those occupied in the Majiayao period, such as the area around Ashaonao (4, 5). Similar data from the NETP supports this hypothesis (6). It is possible that during this later period a switch in agricultural systems to one reliant on wheat and barley may have facilitated the movement of humans into these higher-altitude areas.

The end of the Holocene climatic optimum and the cooler temperatures that characterized the first and second millennia B.C. likely contributed to making the uptake of these crops a necessity in the highlands of western China, and these crops rapidly became a central focus of local subsistence practices after their introduction. We have suggested that this pattern may have led to wheat and barley replacing systems of rice and millet at the Haimenkou site in Yunnan. (See ref. 4 for a complete discussion of the data from this site.)

Second, although we agree with Boivin et al. (3) and An et al. (39) that in many areas of China the integration of wheat and barley into the subsistence regime took many millennia because of cultural barriers, the opposite was true on the margins of the Tibetan Plateau. At sites in northern and central China that have been the object of systematic archaeobotanical analysis, wheat forms no more than 10% of the total assemblage that otherwise is dominated by millets. At the Ashaonao site, however, wheat and barley completely dominate the archaeobotanical assemblage, and other staple crops are not present (Fig. 4). Similar trends in the data are seen at other sites in high-altitude areas, such as Haimenkou (Fig. 4), where, after their introduction, wheat and barley are adopted rapidly and soon form a key part of the assemblage (4). More recently this predominance of wheat and barley also has been demonstrated for the NETP (6).

Unlike highland western China, cultural resistance in the lower-lying plains of central China, where traditional crops like millets and rice could be grown easily, delayed the incorporation of wheat and barley as staples for several millennia (3). Individuals in farming societies with a successful established repertoire of crops may have had little motivation to experiment with the uptake of new crops on large scales, particularly when the properties of the new crops were still unknown.

In Eastern Tibet, different social, ecological, and climatic forces appear to have intersected to promote the full-scale uptake of these domesticates. Rather than crop globalization, it appears that selective incorporation by local communities facilitated the spread of cultural items from areas that eventually coalesced into the Silk Road (65). In highland western China, the intersection of changing climate, the highly vertical ecology, marginality for growing crops, and increasing networks of interregional contact appear to have come together to make the inhabitants of this region more likely to be amenable to a rapid transformation in agricultural strategies (5, 7, 66).

As discussed above, it is clear that during the first and second millennium B.C. the inhabitants of highland Eastern Tibet maintained close relationships with mobile pastoralist groups of central Asia. Although further modeling needs to take place to demonstrate that the mobile pastoralists of central Asia actually cultivated these crops, Spengler et al. (67) already have argued that pastoralists were important agents in the spread of these domesticates across Eurasia. These domesticates' ecological suitability to regions of high latitude and altitude may have made them uniquely adapted to being transported as occasional crops across the Eurasian steppes. When cooler temperatures characterized world climates after the end of the Holocene climatic optimum, conditions coalesced to make the adoption of wheat and barley as staples in highland western East Asia inevitable.

Conclusion

In sum, when discussing the spread of domesticates across East Asia, it is important to consider the role played by peoples that occupied China's peripheries. On the borders of the Tibetan Plateau, local groups maintained close ties to mobile pastoralist communities of central Asia. Partially out of necessity in the post-climatic optimum world, these peoples were open to adopting new economic systems and integrated new crops into their repertoire with considerable speed and flexibility. However, they modified these systems to suit the local requirements of the area and—rather than becoming highly mobile—appear to have integrated western Eurasian plants and animals into an agropastoral system that is still characteristic of this area today. Although the presence of other ecologically suitable crops may have enhanced cultural resistance to their uptake in the central plains of China, in highland western Sichuan both ecology and cultural links to the steppe promoted the uptake of these domesticates on a broad scale.

ACKNOWLEDGMENTS. We thank the Aba County Archaeology team and the Jiuzhaigou National Park for allowing us to carry out this research. This project was supported by the National Social Science Fund of China (Grant 14BKG005) and Sichuan University (SKJC201002) and by a Henry Luce Foundation Program in China Studies Postdoctoral Fellowship from the American Council of Learned Societies (to J.A.d.G.) with additional funding from the National Endowment for the Humanities.

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