

Rethinking the spread of agriculture to the Tibetan Plateau

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Abstract

New data from the Tibetan Plateau allow us to understand how populations dealt with the challenges of moving crops into altitudinally constrained environments. Despite the interest in explaining the timing and the mechanisms via which agricultural products spread to the roof of the world, current models for the spread of agriculture to this region have been simplistic and the presence of crop domesticates is often straightforwardly interpreted as indicating the existence of an agricultural system at the site. This is largely due to a fundamental lack of understanding of where crops could be grown in prehistory on the Plateau. Although it has generally been assumed that moving agriculture into this area was challenging, little work has specifically addressed the constraints imposed on humans as they moved crops into this area. Employing an agro-ecological niche model, I formally model the constraints that were faced by humans as they moved a series of crops into the Tibetan Plateau between the 4th and 1st millennium cal. BC. Based on the results of this analysis, I argue that the end of the climatic optimum meant that millet agriculture was no longer a viable strategy in many parts of the Eastern Himalayas. The arrival of frost tolerant crops in the 2nd millennium BC provided new opportunities in the cooler post climatic optimum world. These models further reveal that sites that have been previously considered as engaged directly in agricultural production may have been more distantly connected to an agricultural lifestyle than previously thought.

Keywords

agriculture, barley, ecological niche modeling, growing degree days, millet, pastoralism, Tibetan Plateau, wheat

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Introduction

The Tibetan Plateau is one of the least hospitable environments for agriculture on the planet. Consequently, it has been argued that full-scale occupation of the Plateau did not take place until the establishment of pastoralist societies (Madsen et al., 2006). However, we still understand very little about the nature of the challenges involved in permanently occupying the Plateau. The introduction of archaeobotanical research to the Tibetan Plateau has allowed us to begin to understand what kinds of plant foods the inhabitants of the Plateau exploited in the past (d'Alpoim Guedes et al., 2013). Hypotheses about the spread of domesticates across Central Asia have hinted at the role played by the biology of crops in hindering or facilitating this spread (Jones et al., 2011); however, no formal modeling has been applied to this issue. Fluctuations in ancient climate have become increasingly implicated in changes in subsistence practices in other areas of China (An et al., 2004, 2005; Liu and Feng, 2012); however, substantial uncertainty remains as to how these changes impacted the agricultural practices of ancient humans. Until now, archaeological research has not been able to quantify the kinds of challenges met trying to adapt agriculture to this high altitude environment. Similarly, it has not been able to disentangle if a crop's presence at a site means it was locally grown or arrived at site via trade or networks of exchange. This is a result of a fundamental lack of information regarding the boundaries of different ecological niches where farmers could exploit crops on the Plateau. Employing a thermal model to delimit different crops' agricultural niches, this paper describes the challenges encountered when moving agriculture onto the Tibetan Plateau. Modeling crop niches can help

identify the limits of the expansion of agriculture and allows us to hypothesize about the nature of the interaction between different groups in prehistory (d'Alpoim Guedes and Butler, 2014). I use this analysis to answer two specific questions: what areas of the Plateau were suitable for the production of different types of crops? What kind of circumstances led hunter-gatherers inhabiting the Plateau to incorporate domesticated plant products into their repertoire?

Using this analysis, I additionally explore the role played by foragers in the spread of agricultural products to the Plateau. To date, their role has only rarely been directly addressed (Aldenderfer, 2007; Aldenderfer and Zhang, 2004), and explanations based on migration have been a popular explanation for the spread of agriculture to the Eastern Tibetan Plateau (Su et al., 2000; Van Driem, 1998, 2002). Where adoption of a crop package by local groups of foragers has been implied, the extent to which these individuals were engaged in crop cultivation, and their motivation for adopting new practices has not previously been considered. My analysis of the niche occupied by two species of millet found at the Changdu Karuo site in Eastern Tibet reveals that despite previous arguments that their short growing season facilitated

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their movement through challenging environments (Jones et al., 2011), these crops would have suffered from substantial risk of failed seasons. I argue that populations of local foragers may have only become involved in small-scale cultivation of one of these millets and derived at least part of their subsistence package from trade. Finally, I argue that the end of the Holocene Climatic Optimum at around 2000 cal. BC made cultivating these millets impossible on the Plateau. This experiment with cultivation was thus abandoned. Agricultural systems could only become fully implanted in select niches on the Plateau following the introduction of cold adapted crops such as wheat and barley.

Geography and traditional subsistence

In contrast to flatter areas of the world, where thousands of kilometers might be traversed before one passes from one ecological zone to another, the Tibetan Plateau and Himalayan foothills are highly variable across short distances because of altitudinal clines. Much like other high altitude environments such as the Andes (Aldenderfer, 1998), this landscape can be envisioned as a set of steps or tiers, each of which contains specific sets of resources that can be exploited by humans.

The Tibetan Plateau covers an area of over 1.2 million square miles, most of which is over 4000 m a.s.l. (Chang, 1983). Temperature and rainfall gradients are important in defining ecological zones on the Plateau and have a profound effect on where crops can be grown. Southwest China and Tibet are governed by the southwest monsoon and most precipitation falls between May and September, while winter conditions are characterized by cool dry air (Flohn, 1981; He et al., 2004).

The Tibetan Plateau can be divided into four main economic geographic zones: (1) High Western Tibet, (2) the river valleys of Central Tibet, (3) the Changtang Plateau in Northern Tibet, and (4) Eastern Tibet. Ngari county in far Western Tibet is dominated by a shrubby desert, characterized by *Ceratoides latens*, and receives less than 50 mm of rain a year. The river valleys of Central Tibet (Tsang) are today the most agriculturally productive regions on the Plateau. These include the Yarlung Tsangpo River (Brahmaputra) valley, Nyang valley in Gyantse, the Yarlung valley, and the Lhasa valley. The majority of the modern population of the Plateau is concentrated in these river valleys. Mountains separate these valleys, and pastoralism is carried out in these areas of higher elevation. This has led to the development of an agro-pastoral economy (or 'samadrok' in Tibetan) in this area (Kapstein, 2006). In the north, the Changtang Plateau covers three-sevenths of the Plateau's total surface area. Characterized by a sparse shrubby desert, this area is virtually uninhabited, except for pastoralists who occupy it on a seasonal basis. The Eastern part of Tibet or Kham (in Sichuan, Yunnan, TAR, and parts of Gansu) contains rich pasture and forested lowlands. Wheat, barley, and other crops are grown in the river valleys, and in some areas of lower elevation maize is popular. Areas above 3000 m contain rich pasture and grasslands and are occupied by pastoralists. The sharp divides between ecological zones impact the distribution of modern crop niches on the Plateau, and must have in the past as well.

Methods

I propose that the thermal niche of different plant domesticates played an important role in constraining when and with what intensity the early inhabitants of the Tibetan Plateau were able to engage in agriculture practice.

Using methods described in d'Alpoim Guedes and Butler (2014), I outline the thermal growing niche of foxtail millet, broomcorn millet, wheat, and barley. Growing degree days (GDDs) were

used as a measure to calculate the available heat units in a given locale. GDDs can be calculated for each individual day using the following formula: $GDD = T_i - T_{base} > 0$, where >0 indicates that terms are counted only when positive. T_i is calculated as the average of daily T_{max} and T_{min} . These GDD values are then summed over the course of an entire calendar year to obtain a yearly GDD total.

GDDs is more commonly used by agronomists and plant biologists than measures familiar to archaeologists, such as length of the growing season (frost free days), to determine where plants can grow for several reasons. All plants require that a given locale contain a certain number of units of heat across the course of the growing season in order for them to be able to complete their lifecycle. For instance, broomcorn millet has an average growing season length of 45–100 days. If we calculate the length of the growing season as days that contain temperatures above freezing, we will overestimate the area in which broomcorn millet can be grown. This is because broomcorn millet not only requires that these days are above freezing, but it requires that over the span of its lifecycle, accumulated units of GDD are above 800–1000. Calculations of GDDs also have the advantage of employing a base temperature (T_{base}), a temperature beneath which it has been documented that an organism grows very slowly or growth halts. Different crops have different baseline temperatures and requirements of accumulated GDD in order to achieve maturity. For instance, while wheat, barley, and foxtail millet have a T_{base} of 0°C, broomcorn millet has a T_{base} of 10°C. These base temperatures have some variability within a crop and are less well documented for millets than for wheat and barley.

Estimates of the number of GDDs required by foxtail millet, broomcorn millet, wheat, and barley were obtained from a number of different sources (Cardenas, 1983; Cheng and Dong, 2010; Islam and Sikder, 2011; McMaster, 1997; McMaster et al., 2011; Stewart and Dwyer, 1987; Table S11, available online). I calculate the spatial distribution of GDDs by co-kriging (Fields Development Team, 2006) daily mean temperatures using great circle distances and altitude from 136 weather stations spread over China, India, and Central Asia obtained from the GHCN (Menne et al., 2012; Figure S11, available online). Resolution is at the 5-arc-min resolution ETOPO5 digital elevation map (NOAA, 1988).

In order to examine the effects of a changing climate following the end of the climatic optimum, I applied temperature perturbations to these data to explore how changes in mean temperature affected the distribution of crops. In the past, sensitivity and speed of response to climatic variations appeared to have differed widely across East Asia (He et al., 2004). Globally, there appears to be evidence for a Holocene climatic optimum from 8000 to 3000 BC where temperatures were on average warmer than those of today (Marcott et al., 2013). Following this date, temperatures appeared to have slowly cooled to reach modern levels. A review of the literature for climate change on the Tibetan Plateau indicates that in this region, the climatic optimum ended between 2000 and 700 cal. BC depending on the location. Temperature and precipitation then decline to modern levels. The climatic optimum is estimated to have been between 1°C and 3°C warmer than the present (see discussion in text S11 and Figure S11, available online).

Given the wide range of estimates for temperature during the climatic optimum presented in S11 (available online), I apply a series of perturbations of +1°C to +3°C to the temperature data in order to encompass the full range of uncertainty expressed by the pollen literature.

I acknowledge that other factors also influence the distribution of crops such as water availability and precipitation. However, precipitation is challenging to reconstruct on a spatial basis and requires high-resolution weather station data from across the Plateau, data that are currently not available for the region. In addition, although the data from speleothems and other sources discussed in

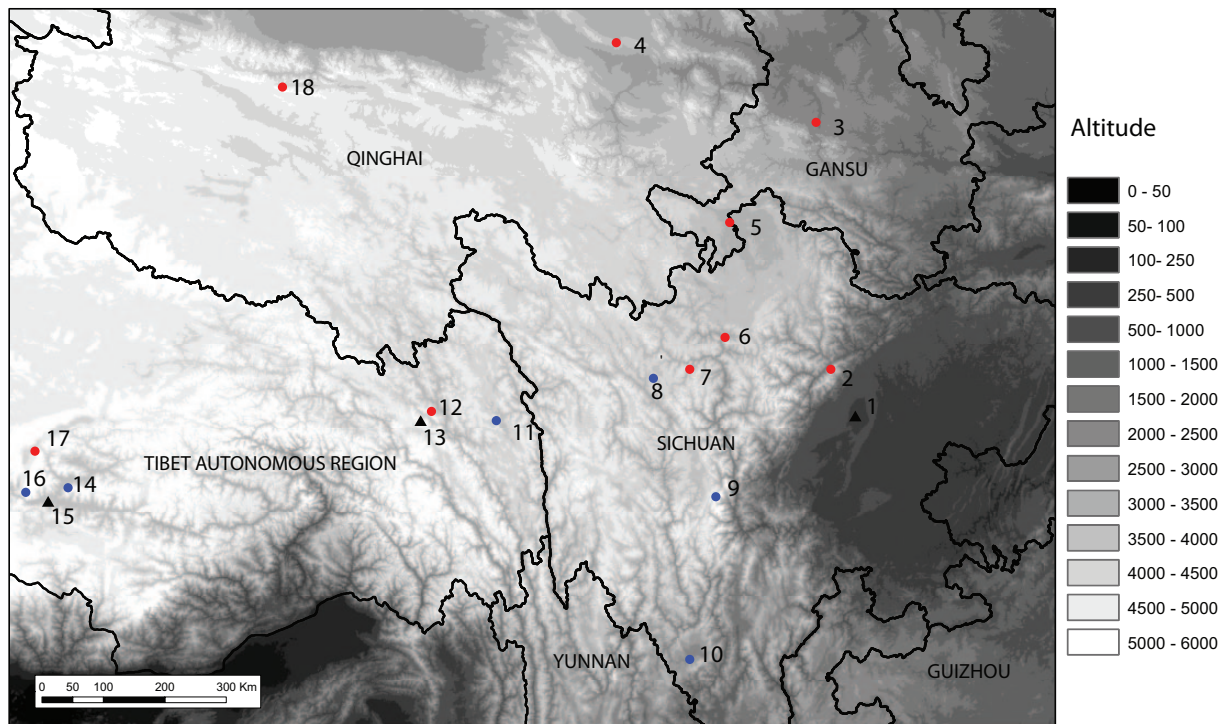


Figure 1. Distribution of sites mentioned in the text. Black triangles = modern cities; red circles = Majiyao Neolithic sites; blue circles = Bronze Age sites. Far left: (1) Chengdu, (2) Yingpanshan, (3) Majiyao, (4) Jiangxigou, (5) Xiemajian, (6) Haxiu, (7) Liujiazhai, (8) Yan'erlong and Benjiadi, (9) Jinjilong, (10) Yanyuan, (11) Xiangbei, (12) Karuo, (13) Changdu, (14) JQugong, (15) Lhasa, (16) Changuogou, (17) Jiaritang, and (18) Xidatan.

SI1 (available online) suggest that the climatic optimum generally had higher precipitation than the present day, there is much disagreement about how changing monsoonal patterns on the Tibetan Plateau affected rainfall. Furthermore, modern precipitation patterns provided an accurate analogy for past conditions as changes in monsoonal patterns could have significantly altered both the timing and location of rainfall. Once a higher resolution paleoclimatic record for monsoonal patterns across this region is available, attempting a reconstruction of precipitation patterns would be a crucial addition to this type of study. That said, a reconstruction of a thermal niche alone still has value: regardless of the abundance or absence of water, crops can still not be grown in areas that do not contain sufficient heat. My reconstructions of GDD thus constitute the maximal area that crops could occupy. The crop niche could be further constrained by variations in rainfall; however, it cannot not be extended beyond the boundaries I have modeled here by increasing rainfall.

Early agriculture on the Eastern Tibetan Plateau?

The nature of the earliest agriculture on the Tibetan plateau is still unclear; however, current consensus lists the Karuo site as providing the earliest evidence for an agricultural lifestyle on the Plateau. The Karuo site has been connected to an expansion of sedentary agriculturalists who moved into the Western Sichuan highlands from the provinces of Gansu and Qinghai (Su et al., 2000; Van Driem, 1998, 2002). These agriculturalists are associated with a cultural assemblage belonging to the Majiyao culture of Northwestern China. The earliest expressions of the related Yangshao culture (4800–4200 cal. BC) first appear in the Central Plains of China at settlements such as Banpo and Jiangzhai (Xi'an et al., 1988). During the Miaodigou phase (c. 4000–3500 cal. BC), Yangshao-style painted pottery begins to appear throughout Gansu and Eastern Henan, forming an important part of the local archaeological assemblage. Scholars have argued that the Majiyao phase (3500–2500 cal. BC) corresponds to a

further westward expansion of farmers who carried or traded high-quality painted ceramic vessels into the western provinces of Qinghai and Gansu (Hou et al., 2010; Li, 2009). This expansion has been suggested to correspond to a period of wetter and warmer weather that made the occupation of these highland areas possible (An et al., 2004, 2005, 2010; Dong, 2012; Dong et al., 2013; Hou et al., 2010).

Sites containing Majiyao-type pottery occur all throughout Western Sichuan, and to date, roughly 60 sites have been identified (Chen, 2007; Chen and He, 2007) (Figure 1). These settlements have been dated to roughly 3500–3300 cal. BC through limited radiocarbon dating. Similarity to Majiyao pottery varies between sites. While large portions of the pottery repertoire at many sites share extremely strong similarities to the Majiyao heartland (Jiang Zhanghua, personal communication, 2014), in others, such as Liujiazhai, a more local pottery repertoire is present (Chen Wei, personal communication, 2014). In particular, some high-quality painted ceramics that are visually similar to those from Northern China are present at these sites and seem to hint at long distance exchange. Recent petrographic analysis has revealed that these pots were sometimes manufactured in the Majiyao heartland (Cui et al., 2011; Hung, 2011), although others argue for their local manufacture (Ren et al., 2013). Other shared material such as characteristic 'half moon shaped' ground stone sickles or knives are also present across sites in Qinghai, Gansu, across Western Sichuan, and down into Northwest Yunnan. Microliths and bone needles (possibly used in the manufacture of clothing) also form an important part of the cultural repertoire at these sites.

Current archaeobotanical analysis indicates that the inhabitants of these sites practiced foxtail (*Setaria italica*) and broomcorn millet (*Panicum miliaceum*) agriculture. Gathered resources such as beefsteak plant (*Perilla* sp.), Chinese plum (*Prunus mume*), wild apricot (*Prunus armeniaca*), walnut (*Juglans* sp.), as well as possibly Sichuan peppercorn (*Zanthoxylum* sp.), *Chenopodium*, and seabuckthorn (*Hippophae* sp.) also appear to have supplemented the diet (Zhao and Chen, 2011). As archaeobotanical investigation

in this region has only just begun, it is unclear how much regional or temporal variability there is within this subsistence pattern as remains have come from poorly dated strata and sample sizes have, to date, been small.

Similarly, our understanding of animal exploitation by ancient humans in this area is patchy. However, initial evidence from two sites suggests that use of animal domesticates varied according to location and possibly cultural affiliation. For instance, evidence from the lower elevation site of Yingpanshan shows that, much like in the Majiayao heartland, domestic pig formed the most important component of the diet (He et al., 2009), whereas at Haxiu an initial analysis of the fauna suggests that hunting played a more dominant role (Chen and He, 2007). Although much more data are needed to examine this question, these differences in animal use suggest that, despite trade in some parts of material culture, full adoption of animal husbandry was not the norm everywhere.

The Karuo site

To date, the Karuo site contains the earliest evidence for the movement of certain aspects of this lifestyle in the high elevations of the Eastern Tibetan Plateau (Figure 1) (Aldenderfer, 2004; Li, 2007; Xizang Wenguanhui, 1985). In addition to foxtail and broomcorn millet, a few pieces in the pottery repertoire at Karuo, particularly some decorated wide bellied *hu* vessels, share similarities with the later phases of the Machang and Banshan phase (2600–2000 BC) pottery from Qinghai and Gansu provinces (Qinghai Sheng Wenwu Guanlichu Kaogudui and Zhongguo Shehui Kexue Yuan Kaogu Yanjiusuo, 1984). However, altogether the pottery assemblage at Karuo, both in terms of vessel type and decoration, appears sufficiently different that one could call it an independent development. Unlike the painted pottery in Western Sichuan that is visually indistinguishable from those in the Majiayao heartland, the pottery at Karuo imitates pottery from Northwestern China in appearance, but differs in the manner of both execution and production. Several aspects of the assemblage of cultural material at the site share similarities with material known from Western Sichuan. This includes ground axes and adzes, 'half moon shaped knives', bone needles, and awls that could have been used in the production of clothing and hide processing. Scrapers, choppers, burins, a few arrowheads, and a large number of microblades that were likely used as insets in more complex tools (Elston and Brantingham, 2002; Yi et al., 2013) characterize the lithic assemblage at the site. A few net weights were unearthed suggesting that the Karuo inhabitants supplemented their diet by fishing in the nearby river.

A total of 34 house foundations, many of which appear to have been rebuilt on top of each other, were uncovered at the site (Li, 2007; Zhongguo Shehui Kexueyuan Kaogu Yanjiusuo, 1991). Early houses at the site appear to be round semi-subterranean occupations with postholes that the excavators argue supported a tent like structure. During the later phases of the site, more permanent investments were built, such as rectangular and square subterranean constructions that are reinforced with stone, and stone reinforced wattle and daub double storied houses. The investment in this more permanent type of dwelling during this later phase of occupation suggests that the site was occupied on a full time basis. Other contemporaneous sites that show a similar array of cultural material such as Xiao'enda and Jiangqin have also been excavated on the Plateau (Xizang Wenguanhui Wenwu Puchadui, 1990), although no systematic analyses of the material from these sites have ever been published.

The Karuo site appears to have been abandoned suddenly at 1750 cal. BC, and there is no obvious successor for occupation in the region. Similar patterns appear to characterize the archaeological record from Western Sichuan, where following 2000 cal.

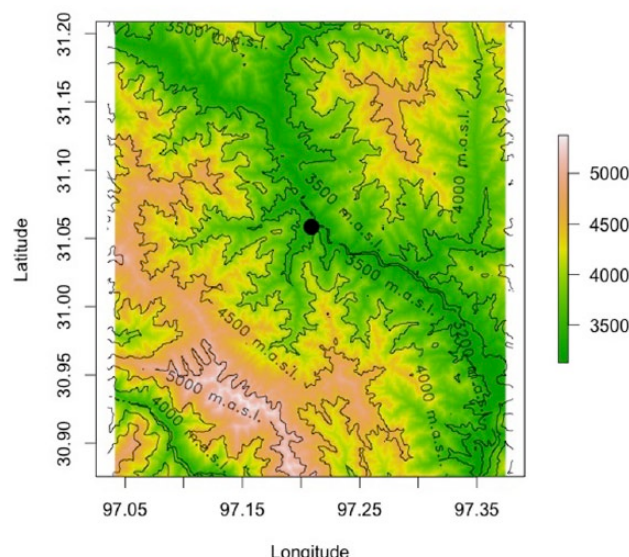


Figure 2. Area surrounding the Karuo site.

BC, there is a decrease in the numbers of published radiocarbon dates and sites dating to this interval. The reasons for this are, however, unclear.

Subsistence at Karuo

Overall, human–animal interactions at Karuo appear to have focused primarily on hunting a wide variety of different types of deer, gazelle and antelope, hare, marmot, and wild sheep (Aldenderfer and Zhang, 2004; Li, 2007; Xizang Wenguanhui, 1985). Pig and an unidentified species of bovid were unearthed during the first season of excavation at the site; however, each find was only represented by two teeth (Xizang Wenguanhui, 1985) and these finds have not since been duplicated (Li, 2007). Populations of wild boar are distributed across some of the lower lying areas of the Tibetan Plateau (Smith and Yan, 2008), making it possible that these teeth could have come from a wild specimen. It is also possible that these teeth could have been brought into the site from agricultural settlements further to the east or south. No MNI (minimum number of individual) counts are presented in the report; however, deer elements (particularly Chinese water deer (*Hydropotes inermis*)) dominate the assemblage (Lu, personal communication, 2014; Xizang Wenguanhui, 1985). Unlike sites in the lower elevations of Western Sichuan, human–animal interactions at Karuo were based on game hunting and not animal husbandry. According to Li (2007), animals hunted at the site cover a wide range of altitudinal zones, making it likely that its occupants engaged in at least some form of logistical mobility (Figure 2).

At Karuo, foxtail millet (*Setaria italica*), and to a lesser extent broomcorn millet (*Panicum miliaceum*), have been found in archaeobotanical assemblages from this site (D'Alpoim Guedes et al., 2013; Xizang Wenguanhui, 1985). The presence of products derived from millet agriculture along with permanent house structures was used to argue that the inhabitants of Karuo engaged in some form of agriculture (D'Alpoim Guedes et al., 2013). But just how involved in cultivation were the inhabitants of Karuo? In order to answer this question, we first need to establish whether or not millet agriculture at this site was possible.

Modeling early millet agriculture on the Tibetan Plateau

An analysis of the distribution of GDD required for millet cultivation across the Tibetan Plateau reveals the following patterns.

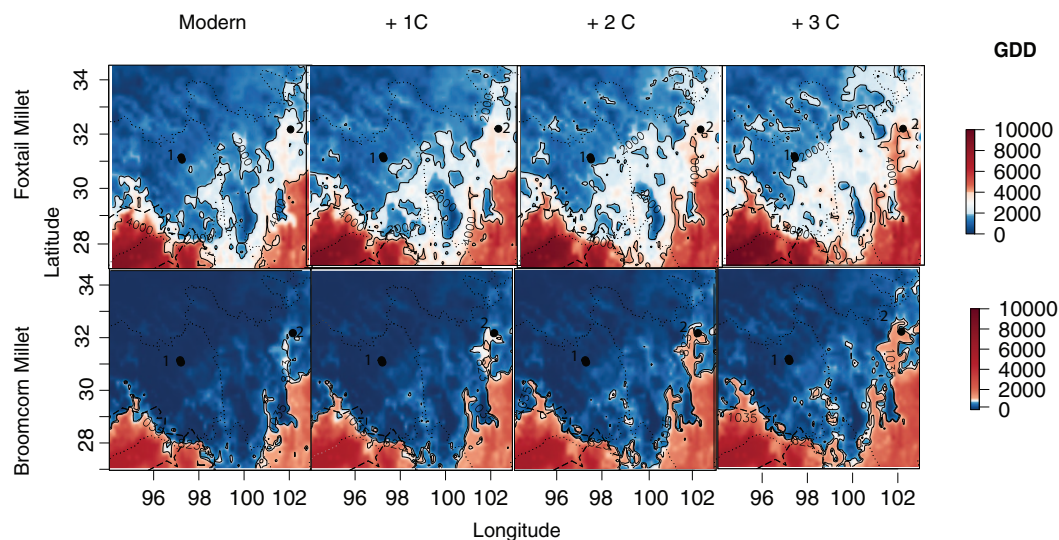


Figure 3. Distribution of foxtail millet and broomcorn millet at different temperature perturbations. Red areas represent the area where these millets can successfully be cultivated. White represents areas where foxtail millet may be able to be cultivated depending on the growth estimate used. Areas represented in blue cannot accommodate foxtail millet growth: (1) Karuo and (2) Haxiu.

Broomcorn and foxtail millet both have short growing seasons, and use water with high efficiency because of their C4 metabolic pathway and can flourish in relatively arid environments. There have only been very limited attempts to model the growth of these plants in the past or their relationship to water and temperature (Baltensperger, 1996, 2002; Cardenas, 1983; Saseendran et al., 2009), and there is much uncertainty about their phenological characteristics. In general, the phenology of broomcorn millet is better understood than foxtail millet, as more experimental studies have been carried out on this species, because of its more widespread use today.

Foxtail millet requires a minimum of 2000 GDD on a 0°C base, although it can require up to 4500 GDD to complete its growth cycle (Cheng and Dong, 2010).¹ Broomcorn millet has higher temperature requirements than foxtail millet and requires a base temperature of 10°C in order for plant growth to be initiated and sustained (Saseendran et al., 2009).

Foxtail millet (with a growing season of 60–120 days) has on average a longer growing season than broomcorn millet (45–100 days) but has lower heat requirements on a daily basis (Saseendran et al., 2009). For broomcorn and foxtail millet, variation in number of days required to achieve maturity is directly related to temperature at germination and temperature throughout early development (Saseendran et al., 2009). Lower temperatures at germination cause the plant to develop slowly, ultimately affecting its yield. In the author's experimental trials on broomcorn millet, under slightly cooler temperatures of only 25°C, the lifecycle of these millets was extended to between 150 and 170 days (D'Alpoim Guedes et al., in preparation). The cardinal temperatures required for successful germination are higher for broomcorn millet (30–40°C) than for foxtail millet (20–30°C) (Kamkar et al., 2006). Additionally, both broomcorn and foxtail millet have little to no frost tolerance (Cardenas, 1983; Kamkar et al., 2006; Saseendra et al., 2009).²

Our analysis of the GDD required for foxtail millet shows that at modern temperatures and temperatures below, modern foxtail millet could not be successfully grown anywhere in the vicinity of Karuo (Figure 2). Roughly 130 km away to the Southeast, some areas are open for cultivation in the Lancong river valley that runs along the border between the TAR and Sichuan. At temperatures 1°C higher than those of today, valleys where foxtail millet was viable begin to open in the vicinity of the site, and at temperatures 2°C higher than modern, the site becomes situated at the very

border for viability of millet cultivation. At 3°C higher, this range extends to Karuo, although the site is still situated on the border for cultivation viability (Figure 3). In contrast, the thermal growing niche of broomcorn millet is much more limited, and at all the temperature perturbations we have employed, it was not possible to grow broomcorn millet in the vicinity of the site (Figure 2). The data presented make it unlikely that broomcorn millet could have ever been locally cultivated at the site. That said, it is possible that our analysis was not able to resolve small valleys near the site that may have been amenable to millet cultivation.

Transformations during the 2nd to 1st millennium BC

Following the abandonment of Karuo and the end of the Majiayao cultural sites in Western Sichuan, a new cultural facies begins to appear in Eastern Tibet. Evidence of settlement sites for this period of time is scarce, and most known material from this period comes from characteristic stone-cist graves. This tradition is widespread and covers sites ranging from Western Sichuan to Northwest Yunnan (Figure 1).

These graves range widely in content and associated ritual practices (Chen, 1981; Chengdu Shi Wenwu Kaogu Yanjiusuo et al., 2002; Luo, 2012; Shen and Huang, 1985; Shen and Li, 1979; Song, 1983; Tong, 1978). The majority of tombs are constructed out of thin slabs of slate to create a narrow rectangular burial space in which the dead are placed. Recent direct C14 dates on human remains in stone-cist tombs from the sites of Yan'erlong, Benjiadi, Kasha lake, and Gazalong in Western Sichuan suggest that this tradition of burial began in c. 1700 cal. BC (Miyamoto, 2014). The presence of Han empire material in some of these graves indicates that this tradition was long lived (until the 2nd century AD). The most characteristic types of objects placed in these tombs are double-handled jars; some of the later varieties are decorated with a double-spiral motive that is interpreted as ram's-head decoration (Xie, 2005). Both ceramic vessels and metal objects (such as ring-pommel knives, daggers with fish-tail shaped handle, mirror ornaments, button-shaped clothing applications, and three-pronged short-swords with torqued handles) show clear connections with the bronze age Qijia, Xindian, Siwa, and Kayue cultures of Gansu and Qinghai, as well as cultural assemblages in Ningxia, Inner Mongolia, and the Ordos regions (Li, 2011; Luo, 2012; Miyamoto, 2014).

During this period, the people who occupied Western Sichuan also appear to have occupied, exploited, or at the very least buried their dead in areas of higher altitude (Figure 1). Although systematic zooarchaeological research is necessary to determine whether or not this was the case, their close relationship to sites of the Qijia, Kayue, and Xindian cultures, in which sheep bones have been found (Flad et al., 2007), suggests that individuals in this area may have also reared pastoral animals. At Yanyuan in Southwest highland Sichuan and at Jinlinlong close to the Tibet border in Ganzi county, the interment of horse bones, horse burials, and heads, as well as horse gear suggests that the practice of horse riding had already reached this region by the 2nd or 1st millennium BC (Hein, 2014; Sichuan Sheng Wenwu Guanli Weiyuanhui, 1986).

In Eastern Tibet, small numbers of horse teeth were unearthed alongside double-handled jars and a rudimentary bronze knife in a cist burial similar to those known from Western Sichuan at the site of Xiangbei in Gongjiao county (Aba Zangzu Qiangzu Zizhizhou Wenguansuo, 1987; Xizang Wenguanhui Wenwu Puchadui, 1989) and in a single burial from the Xiao'enda site (Xizang Wenguanhui Wenwu Puchadui, 1990). In Central Tibet, an entire horse skeleton has also been found in the later components of the Qugong site (c. 700 cal. BC) (Zhongguo Shehui Kexueyuan Kaogu Yanjiusuo, 1999). The presence of horse teeth and bones at these sites suggests that at least some pastoral animals had arrived on the Central and Eastern Plateau during the 1st millennium BC. These data fit well with what is already known from the Inner Asian mountain corridor, where use of pastoral animals appears to have been present as early as c. 2500 cal. BC (Frachetti, 2004, 2008), and in Southern Xinjiang, where recent evidence suggests that this lifestyle may have been present by the 1st millennium BC (Wagner et al., 2011).

Two settlements, Changuogou (1500–700 cal. BC) and Qugong (1750–1050 and 758–401 cal. BC) (Li and Zhao, 1999; Zhang and Geng, 1985; Zhongguo Shehui Kexueyuan Kaogu Yanjiusuo, 1999), contain important evidence for subsistence patterns on the Plateau during this period of time.

Small-scale excavations and surveys were carried out at the site of Changuogou in 1994; however, no proper maps of these excavations have ever been published (Li and Zhao, 1999). More extensive excavations were carried out at Qugong; however, no house features were visible in these excavation units, indicating that the inhabitants of this site may have employed mobile dwellings.

A well-developed pottery repertoire with round bottom shaped vessels, the design of which is substantially different from that of Karuo is present at Qugong (Shang, 1978; Wang, 1975). The lithic assemblage at this site appears to be consistent with one based on hunting, butchering, and processing hide. Microblades continue to be present at these sites along with core and flake tools including awls, burins, and various types of scraper. Grinding stones of various shapes and sizes were unearthed in ash pits. Both sites also contain a large number of denticulated flat ground stone tools that may have been used to process hide. A large number of bone tools were recovered from the site, many of which have been formed into burins and awls, and bone needles. Net weights also suggest that the inhabitants may have carried out some form of fishing.

Subsistence patterns in post-2nd millennium BC Tibet

Western Eurasian domesticates (wheat, barley, oats, rye, pea, lentil, and flax) begin to move into Central Asia between the late 7th and 2nd millennium BC (see summaries in Frachetti et al., 2010; Harris, 2010; Harris et al., 1996; Miller, 1993; Spengler and Willcox, 2013; Spengler et al., 2014). During the 2nd millennium BC, these crops also move into China (see summaries in An et al.,

2013; Betts et al., 2013; Chen et al., 2015; Crawford and Lee, 2003; Crawford et al., 2005; D'Alpoim Guedes et al., 2013; Dodson et al., 2013; Dong et al., 2013; Flad et al., 2010; Lee et al., 2007; Li et al., 2007; Zhao, 2009).

Wheat (along with barley, pea, lentil, flax, and domesticated grape) appears to have been present on the border of the Western Tibetan Plateau by as early as 2800 BC (Constantini, 1987; Lone et al., 1993; Meyer et al., 2009; Sharma, 2000). In Nepal, a similar suite of domesticates appears during the 1st millennium BC (Knörzer, 2000). Wheat and barley appear in sites in Western Sichuan and Northwest Yunnan during this period of time (Sichuan Sheng Wenwu Kaogu Yanjiusuo Kyushu University et al., 2012; Xue, 2010; Yunnan Sheng Wenwu Kaogu Yanjiusuo, 2009).

At Changuogou in Central Tibet, archaeobotanical remains were extracted from a large ash pit during excavations carried out in 1994 (Fu, 2001). A number of different Western Eurasian domesticates were found in these handpicked samples including a free-threshing variety of wheat (*Triticum* sp.), naked barley (*Hordeum vulgare*), foxtail millet (*Setaria italica*), a single pea (*Pisum* sp.), rye (*Secale* sp.), and naked oat (*Avena nuda*). In addition, a well-preserved tuber that Fu et al. (2000) identify as drolma (*Potentilla anserine*) was unearthed.

No systematic collection and analysis of animal remains was carried out at either Qugong or Changuogou; however, a few specimens from Qugong were sent to the Chinese Academy of Social Sciences for analysis (Zhongguo Shehui Kexueyuan Kaogu Yanjiusuo, 1999). The assemblage at this site is dominated by deer, but the horns, limb bones, and teeth identified as belonging to yak (*Bos grunniens*) were unearthed in ash pits that belonged to the early components of the site. Noting that the size of the teeth and horns is small, the excavators of the site conclude that it is possible that the yak had already undergone domestication by this point in time. The excavators also report finds of sheep (*Ovis* sp.) at the site; however, the status of these is unclear. The authors report that it is possible that these also belong to argali or Tibetan mountain sheep (*Ovis ammon*) as they report the bones as larger in size than known populations of domesticated sheep measured from the region. Teeth belonging to what is presumed to have been wild boar were also found in very small quantities, although again no systematic analysis of the material was carried out. As mentioned above, horse bones were also unearthed in the later components of the site. Further research is needed to determine the timing of the arrival of pastoral animals to the Central Tibetan Plateau.

The lack of obvious robust and immobile dwellings at Qugong suggests that whatever the subsistence strategy of the inhabitants of this site, they may have only occupied the site on a seasonal basis. The presence of Western Eurasian domesticates at sites of the same culture, such as Changuogou, thus seems somewhat perplexing. Were the inhabitants of these ephemerally occupied sites practicing agriculture? Were these seeds locally grown or traded?

Models for wheat and barley agriculture on the Plateau

Wheat and barley differ from millets in several key regards. First, both of these crops have frost resistance, a trait that allows them to adapt to the cool evenings and sudden swings in temperature that characterize the Tibetan Plateau. In particular, both can sustain substantial frosts during germination (Table S11, available online), although the crop becomes more sensitive to frost at the flowering stage (Synder and de Melo-Abreu, 2005). Before the introduction of wheat and barley onto the Tibetan Plateau (and most likely into East Asia), it is worth noting that both of these crops underwent a number of important changes. One of these is the development of a spring phenotype. Wild varieties of wheat

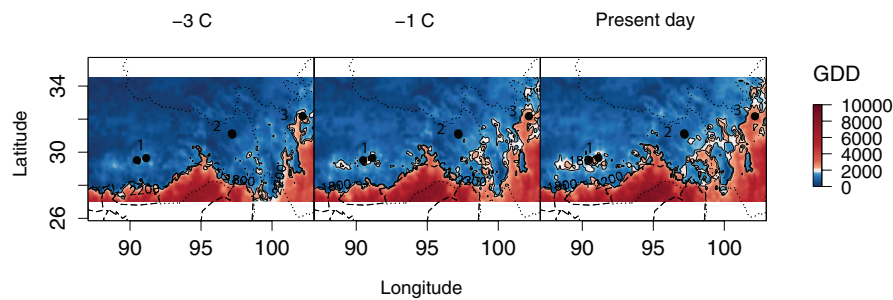


Figure 4. Distribution of wheat and barley on the Tibetan Plateau at different temperature perturbations. Red areas represent the area where wheat and barley can successfully be cultivated. White represents areas where these crops may be able to be cultivated depending on the growth estimate used. Areas represented in blue cannot accommodate their growth: (1) Qugong and Changguogou, (2) Karuo, and (3) Haxiu.

and barley have a winter habit (Takahashi et al., 1963, 1968). Varieties with a winter habit are sown in autumn and following a period of dormancy during which they must experience appropriately cold temperatures and can withstand substantial frost, they then flower in the spring once longer day length and warming temperatures initiate a photoperiod response. The earliest wheat and barley domesticated in Southwest Asia was of a winter variety. Winter varieties are adapted to areas with relatively warm winters that can sustain plant growth (Jones et al., 2008, 2011a; Von Bothmer et al., 2003). Although the factors that led to the development of this characteristic are unclear, barley and wheat with spring habits are believed to have developed later. These varieties are sown in the spring, and thus are more adapted to areas of higher latitude and altitude (Pourkheirandish and Komatsuda, 2007; Takahashi et al., 1963, 1968; Von Bothmer et al., 2003). It is argued that one of the prerequisites for the expansion of barley (and of wheat), particularly into the northern latitudes of Europe, was the development of a spring phenotype (Jones et al., 2008; Von Bothmer et al., 2003). It is likely that similar factors may have contributed to the delay in the spread of wheat and barley into the Central Eurasian Steppe and the Tibetan Plateau (d'Alpoim Guedes et al., 2013; Fuller and Zhang, 2007).

An analysis of the GDD required for wheat and barley cultivation reveals a very different pattern to that of millets. Following 2000 cal. BC, estimates suggest that temperatures on the Tibetan Plateau may have been similar to cooler than those of the modern period (1961–1990) (Herzschuh et al., 2009; Kramer et al., 2010; Marcott et al., 2013; Schlütz and Lehmkuhl, 2009; Shen et al., 2006, 2008; Shi et al., 1993; Tang et al., 2004; Yan et al., 1999, 2011).

At modern temperatures, sufficient GDDs are available to cultivate spring wheat and barley throughout the river valleys of Western Sichuan as well as in areas surrounding the sites of Changguogou and Qugong (Figure 4). At -1°C , these valleys retract around Karuo; however, in the area surrounding the modern city of Lhasa, wheat and barley agriculture still remains viable, although in a very limited area. These valleys only close at -3°C (Figure 4). At modern temperatures, these valleys expand substantially around Lhasa and the river valleys in Western Sichuan (Figure 4).

Discussion

Both hunters and pastoralists on the Plateau could have held complex relationships with neighboring farmers. Like ethnographic examples of foragers and pastoralists in marginal environments, they could have traded commodities like fur and salt for grain (Brosius, 1988; Headland and Reid, 1989; Hoffman, 1986; Kardulias, 1990; Phillips, 1961; Stiles, 1993). In similarly vertically constrained environments in other parts of the globe, such as the Andes, sharp altitudinal tiers can lead individuals to become specialized in the products of a given altitudinal niche and access those of other niches via exchange (Murra, 1975, 1985; Van

Buren, 1996). Presence of domesticates on the Tibetan Plateau should thus not necessarily be interpreted as evidence for local agriculture.

The analysis carried out above allows us to make several observations about the nature of early agricultural products on the Tibetan Plateau:

1. It appears that the warmer temperatures that characterized the Holocene climatic optimum were crucial for foxtail millet to be grown successfully on the Tibetan Plateau, particularly at Karuo.
2. Even during the warmer climatic optimum, it seems unlikely that broomcorn millet was cultivated at Karuo. It seems likely that this crop was not locally grown but rather was brought in from areas of lower altitude like other aspects of the material culture at the site.
3. Given the patterns seen in our analysis of GDD, the relatively sudden abandonment of Karuo at 1750 cal. BC date is not entirely surprising. Even minor climate fluctuations away from $+2^{\circ}\text{C}$ could have made cultivating millet at this site impossible. Our review of the paleoclimate literature suggests that an overall cooling trend was in place from the end of the Holocene climatic optimum to present day and it is likely that climate reached modern temperatures c. 2000–1500 BC (see SI1 and references therein, available online). Karuo's abandonment temporally overlaps with the end of the optimum, a period of time when it has been argued that cooling events had an effect on agricultural production in Northern China (Wu and Liu, 2004). It has been suggested that the abandonment of the site may be linked to this climatic event (Aldenderfer, 2007). Indeed, our analysis demonstrates that at Karuo, even slight cooling would have simply made millet agriculture impossible. Even prior to the 2nd millennium decrease in temperature, the Karuo site was located at the very border of foxtail millet's thermal niche. Yearly fluctuations in temperature could have increased its probability for failure.

Who then were the inhabitants of Karuo? The presence of millet at Karuo has often been described as being the result of migration of farmers from lower lying areas (Li, 2007; Xizang Wenguanhui, 1985). A closer examination of the material culture from this site reveals, however, some alternative explanations. Although some similarities are shared with lowland sites, many parts of the material culture at Karuo (most notably its pottery) are markedly different from anything known in the Western Sichuan highland or in areas further to the north and south. If Karuo were to be interpreted as a migration of agriculturalists onto the Plateau, one might expect to see a greater degree of cultural continuity between the site and the Majiayao cultural sites with which Karuo shares a similar date.

Sharp contrasts between Karuo and these lower altitude sites are also visible in meat acquisition patterns. Although hunting still formed an important part of the economy in Western Sichuan, domestic pig overwhelms the faunal assemblage at lower elevation sites (Chen and He, 2007; He et al., 2009). The evidence for pig husbandry at Karuo is tenuous at best. The presence of domesticated pig in Western Sichuan implies that the inhabitants of the site had sufficient feed with which to provision these animals. At Karuo, on the other hand, the risk associated with growing millet may mean that it was not a reliable source of agricultural surplus that could be used to fodder domesticated animals.

By continuing to rely on hunting (and potentially gathering) as a major source of calories, the inhabitants of Karuo may have been able to ensure a reliable food base. Successful hunting likely required at least some form of logistic mobility from at least a portion of the population. If cultivated on site, foxtail millet would have required that another portion of the population remained at the site for at least the 2 months that this crop was grown in the summer time. If the inhabitants of Karuo did cultivate foxtail millet, it is possible that this crop's short growing season and low labor investment requirements made it attractive to forager populations who needed to maintain a high degree of spring, autumn, and winter mobility. If grown by the inhabitants of the Tibetan Plateau, the growing niche of these millets would have tightly constrained the areas that groups seeking to cultivate them could occupy. We should thus not envision that agricultural societies were implanted across large areas of the eastern plateau during this period of time. Rather, it seems that they exploited select and tightly constrained niches. Foraging by and large would have continued to be the lifestyle of choice in the vast expanses where millet cultivation was impossible.

We can also not eliminate the possibility that at least a portion of the foxtail millet uncovered from Karuo was moved through a network of exchange or traded farmers that occupied areas of lower altitude. Our analysis demonstrates that broomcorn millet could not have been grown at the site, and hence we must develop alternative explanations for its presence. Deriving grain from lower elevation sources could have allowed the occupants of Karuo to remain sedentary for a portion of the year and to practice logistical mobility. An examination of housing structures at Karuo seems to reinforce this interpretation. In the earliest components of the site, lighter duty pit-houses may have been used by hunter-gatherers who practiced logistical mobility. The more permanent structures of the later phases of the site could suggest a year round occupation of the site. I hope that future work at these important sites can begin to gather the evidence that will allow us to distinguish between these alternative hypotheses.

4. Around the time of Karuo's abandonment, other subsistence technology began to arrive on the scene in East Asia and probably on the Tibetan Plateau, including animals that could be taken out to pasture and which did not require foddering and competition with human resources such as sheep, goat, and cattle. These animals may have been what was finally required to make animal husbandry an attractive proposal for populations of hunters/low level food producers who already employed animal tracking and mobility in their daily lifestyle.

Their ability to tolerate frost and cool temperatures meant that the introduction of Western Eurasian crops altered forever the parameters of the kind of life possible on the Plateau. Previous analyses have argued that millet's short growing season would have facilitated their spread across Eurasia, whereas the longer growing season of wheat and barley would have been an impediment to their movement (Jones et al., 2011b). However, my analysis of these crops' thermal niche reveals that millets

were a far riskier endeavor than Western Eurasian crops because of their high GDD requirements and inability to withstand frost. When wheat and barley were introduced to the highland areas of Western Sichuan and NW Yunnan, their ability to withstand frost made them a food of choice over millets and eventually led to them dominating archaeological assemblages in these areas (d'Alpoim Guedes et al., 2013).³ Higher caloric returns and average yield could also have contributed to people having a preference for these crops (Bray, 1984). Rather than being due to a long growing season, it is likely that the delay in the arrival of both of these crops to areas such as northern Europe and across the northern Eurasian steppe and Tibetan Plateau had more to do with the need to develop a nonphotosensitive spring phenotype. Compared with populations in other areas of China (Boivin et al., 2012), the inhabitants of the plateau appear to have rapidly adopted these colder-adapted alternatives.

Here too, however, it is worth asking if these products were in fact locally grown and what kind of mechanism was involved in the adoption of wheat and barley agriculture on the Tibetan Plateau. Increasing evidence shows that microblade producing hunter-gatherers were present on the Tibetan Plateau for several millennia. Assemblages of lithics that were initially thought to date to the late Pleistocene or early Holocene have been shown to be mid Holocene in date. Examples include those from the sites Xidatan and Jiangxigou (Brantingham et al., 2013; Madsen et al., 2006) and the recently discovered Xiemajian site in Western Sichuan (Lu Hongliang, personal communication, 2014). Recent evidence from the Jiaritang site found in the Qinghai–Tibet railway project shows that a hunter-gatherer lifestyle may have continued on the Tibetan Plateau well into the late Holocene (c. 1200–900 BC) (Xizang et al., 2005). Restrained by millet's growing niche, the experiments that took place at sites like Karuo likely did not spread onto areas of higher elevation and appear to have been regionally confined to the Eastern Tibetan Plateau. How then did these hunter-gatherers on the Central Plateau end up being engaged in the uptake of Western Eurasian agricultural products?

Although Qugong and Changuogou have been described as agricultural sites in the literature, we call into question this identification. Unlike Karuo, both contain little evidence for housing structures. The focus of production at both sites appears to have been on processing hide. Although the rather dubious nature of the faunal record at Qugong suggests that pastoral animals like sheep and horse may have already been introduced to the Plateau by this point in time, the primary goal of subsistence at this site appears to be focused on hunting deer. Further studies are needed to ascertain the status of the yak remains found at the site. Should the presence of domesticates at these sites lead us to understand these settlements as sedentary agriculturalist or agro-pastoralist occupations? Not necessarily. The ethnographic record shows that hunters can be involved in complex patterns of exchange with agriculturalists and pastoralists and can trade furs and other goods like salt for domestic grains and can sometimes assist with the herding of domestic animals (Wilmsen, 1973, 1994). In other situations, hunter-gatherer populations can also acquire domestic animals from farming communities and adopt a loose management strategy that allows them to continue their traditional lifestyle (Krause-Kyora et al., 2013). Animals could be acquired directly via trade, exchange, or stealing and indirectly through capturing escaped animals.

In China and much of Eurasia, the presence of objects associated with the steppe has been interpreted as evidence for the presence of a highly mobile nomadic pastoralist lifestyle, despite the fact that stylistic attributes of decorative items may not be very good markers of identity and they reveal very little about economic behavior (see critiques in Linduff, 2006; Shelach, 2006, 2009). Pastoralism, simply defined as the keeping of pastoral animals by humans (Meadow, 1992) can refer to a set of different

lifestyles that differ widely in annual mobility, supplementary resource exploitation (agriculture, trade, mining, and craft production) depending on ecological and sociopolitical pressures. If occupied by pastoralists who relied on mobility as an important way of accessing resources, we should not automatically assume that the presence of grain at these sites implies that they were locally cultivated. In particular, mobile pastoralists can obtain large amounts of grain through trade with agriculturalists (Shishlina and Hiebert, 1998). For instance, nomadic pastoralists in the northern plateau obtain as much as 50% of their caloric inputs from grains obtained through trade with farmers (Goldstein and Beall, 2002).

Although my analysis reveals that cultivation of wheat and barley in select valleys of Central Tibet was possible, careful excavation and analyses of the sites are necessary to determine if the inhabitants of Central Tibet engaged in the cultivation of these plants themselves during the 1st millennium BC.

Conclusion

I argue that by first outlining the limits of the possible for human behavior, models such as these can lend strength to social hypotheses for past change in food-ways. Humans are limited both by their environment in determining what they grow and also by cultural choice. It is precisely by outlining the former that we may be able to highlight instances where cultural choice played an important role in determining past subsistence strategies. In areas of the world where altitudinal clines produce sharp delineations, temperature can often be a primary limiting factor in agricultural strategies. In order for social models of crop choice to be strengthened, it is important that we build our models of human behavior from the ground up.

I have shown that on the Tibetan Plateau, ecological factors constrained where certain types of plant domesticates could be grown. Whether or not crops were locally grown or exchanged had profound implications for the nature of social interactions in highland East Asia in prehistory. Here, I have demonstrated that millets were tightly constrained by their biological requirements and only foxtail millet could be grown in a few select valleys in Eastern Tibet during the warmer temperatures of the climatic optimum. The timing of the abandonment of Karuo suggests that these crops and the lifestyle that became associated with them were no longer viable on the Plateau, not by social choice, but rather by ecological necessity. It is likely that these populations reverted back to hunting and gathering following this date.

The way in which the adoption of wheat and barley was linked to the development of pastoralism on the Plateau remains a topic for deeper exploration. However, it is likely that given pastoralism's association with a cultural package that spread across Eurasia during the 2nd millennium BC, these developments took place either simultaneously or within short time spans of each other. During the post-Holocene climatic optimum-cooling period that characterized their introduction, wheat and barley could only be grown in select valleys in the Southern Plateau. If a transition to an agro-pastoral lifestyle took hold in these areas first, we propose that hunters on the rest of the Plateau may have made the transition to exploiting pastoral animals without significantly investing in agriculture. Similar scenarios have been noted in parts of the Western Eurasian steppe (Frachetti, 2012). Whatever the social relations involved in their uptake, the introduction of Western Eurasian domesticates that could be grown in select valleys on the Plateau helped agriculture become implanted in an ecological situation that remained fundamental through the development of society on the Tibetan Plateau.

In the adoption of both of these systems, the role played by hunter-gatherers and the nature of their interaction with agriculturalists, agro-pastoralists, and pastoralist societies is important to

consider. Future and more systematic research on the Plateau will help identify what factors may have motivated hunter-gatherers to engage in either trade with agriculturalists or adopt their lifestyle. Until recently, hunter-gatherers have been relatively invisible in discourses on agricultural and pastoral origins in China. In Southwestern China and Tibet, there is a need not only to develop the tools to identify these individuals but also to view them as critical and active actors in the spread of agriculture and pastoralism throughout East Asia (Stein, 2002). More evidence, but also more complex narratives than simple migrationism, is necessary to explain the spread of agricultural practices and pastoral animals to the Tibetan Plateau.

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Notes

1. It is worth noting that foxtail millet is not currently extensively grown and has been the object of very few field trials. Studies of foxtail millet distribution across China use a 0°C base temperature (Cheng and Dong, 2010). Others have used a 10°C base temperature (McMaster et al., 2011). We compare both of these estimates in Figure SI3 (available online). Note that the areas where foxtail millet can be grown without risk remain the same between these two. Further field trials are necessary to elucidate at what temperature foxtail millet halts growth.
2. Despite its need for higher temperatures, broomcorn and foxtail millet's short growing season makes them particularly drought resistant (Arnon, 1972). According to experimental studies in Pakistan, foxtail millet performed better than other millets (including African millets) in terms of drought resistance (Seghatoleslami et al., 2008).
3. Since this article was submitted, this same group has now accepted our suggestions for this scenario in a recent publication: Chen FH, Dong GH, Zhang DJ, Liu XY, Jia X, An CB, Ma MM, Xie YW, Barton L, Ren XY, Zhao ZJ, Wu XH and Jones MK (2015) Agriculture facilitated permanent human occupation of the Tibetan Plateau after 3600 B.P. *Science* 349(6219): 248–250.

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