CLIMATOLOGY

Climate change stimulated agricultural innovation and exchange across Asia

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Ancient farmers experienced climate change at the local level through variations in the yields of their staple crops. However, archaeologists have had difficulty in determining where, when, and how changes in climate affected ancient farmers. We model how several key transitions in temperature affected the productivity of six grain crops across Eurasia. Cooling events between 3750 and 3000 cal. BP lead humans in parts of the Tibetan Plateau and in Central Asia to diversify their crops. A second event at 2000 cal. BP leads farmers in central China to also diversify their cropping systems and to develop systems that allowed transport of grains from southern to northern China. In other areas where crop returns fared even worse, humans reduced their risk by increasing investment in nomadic pastoralism and developing long-distance networks of trade. By translating changes in climatic variables into factors that mattered to ancient farmers, we situate the adaptive strategies they developed to deal with variance in crop returns in the context of environmental and climatic changes.

INTRODUCTION

Projected estimates for global warming are expected to pose serious challenges for existing systems of grain production around the globe, with some regions having predicted decreases in production as high as 70% (1). Understanding how farmers coped with past changes in the mean state of climate may be crucial for understanding how we must adapt to a rapidly changing world. Humans are able to tolerate varying levels of failure in their agricultural systems. But exactly how many years of a bad harvest were humans able to cope with before they modified their farming strategies? What type of strategies did they use when returns got bad?

Between 5000 and 1500 years ago, economic systems across Eurasia experienced major shifts as farming spread into areas far outside of its original centers of domestication. Throughout this period, humans also dealt with notable episodes of climatic change that affected agricultural returns. During this period of time, broomcorn and foxtail millet made their way from China to Central Asia, and wheat and barley moved from Central Asia to the Far East. Who spread these crops across Asia—when, how, and by what routes—has been a topic of increasing debate (2, 3), as have the social and economic motivations behind their adoption (4–8). There is an increasing interest in how changes in precipitation and temperature may (or may not) have affected agricultural production in past societies (9–12). Where understanding the impact of climate in East Asian history has gained popularity (9, 13–15), these approaches often simply correlate paleoclimate proxies with archaeological data—and often fail to reveal the adaptive strategies used by humans when faced with variation in agricultural returns (16, 17).

We use a high spatial and temporal resolution model of the changing thermal crop niche for six grain crops across Central, South, and East Asia (Fig. 1) combined with a large (1187-entry) database that charts both the appearance and timing of use of broomcorn, foxtail millet, wheat, barley, buckwheat, and rice (see Materials and

methods for details about the model and database). We use this niche model to examine the impact that changing temperatures had on human's ability to subsist on these crops and to reveal the strategies they used to cope with these potential challenges. This model covers a wider geographic scope and temporal depth and more crop varieties than previously published thermal niche models (8), allowing us to make several general observations about the nature of grain crop farming across early-mid Holocene Eurasia.

RESULTS

Barley, wheat, foxtail, broomcorn, and buckwheat millet (Fig. 2 and movies S1 to S4) remain completely within the thermal niche across Central Asia during the early years of the transmission of these crops across Eurasia. Following the domestication of wheat and barley in the Fertile Crescent beginning c. 10,000 cal. BP (calibrated years before the present), they move into pre-Indus sites, such as Mehrgarh, as early as 9000 cal. BP (18, 19). Wheat and barley move deeper into Central Asia between 5450 and 4700 cal. BP (20–22). From this point, these crops move eastward between 4000 and 3600 cal. BP (23) and are rapidly adopted across the eastern Himalayas by 4000 cal. BP (8).

Following domestication c. 8500 cal. BP (24), millet farmers began a westward expansion that resulted in the spread of millet products to the eastern margins of the Tibetan Plateau between 5400 and 4400 cal. BP (movies S3 and S4) (25). Broomcorn millet (and potentially foxtail millet) begins to appear at sites throughout Central Asia following 4000 cal. BP (7).

These crops may have been exchanged along several different routes. A number of sites line up with a route that is consistent with the Inner Asian Mountain Corridor (2, 21, 26–28). Finds of wheat and barley cluster along this route, as do finds of broomcorn millet. For wheat and barley, a large and almost simultaneous cluster of sites across northern India makes a route to the south of the Himalayas route equally plausible—one that has been suggested by previous researchers as playing an important role (movies S1 and S2) (29). This route, however, is truncated by a lack of archaeobotanical research in Assam, Bangladesh, and Myanmar. A third route for these crops' transmission has been proposed—a route to the north of the Inner Asian Mountain Corridor. While this area remained within the thermal niche during the early years of these crops' transmission, there is no

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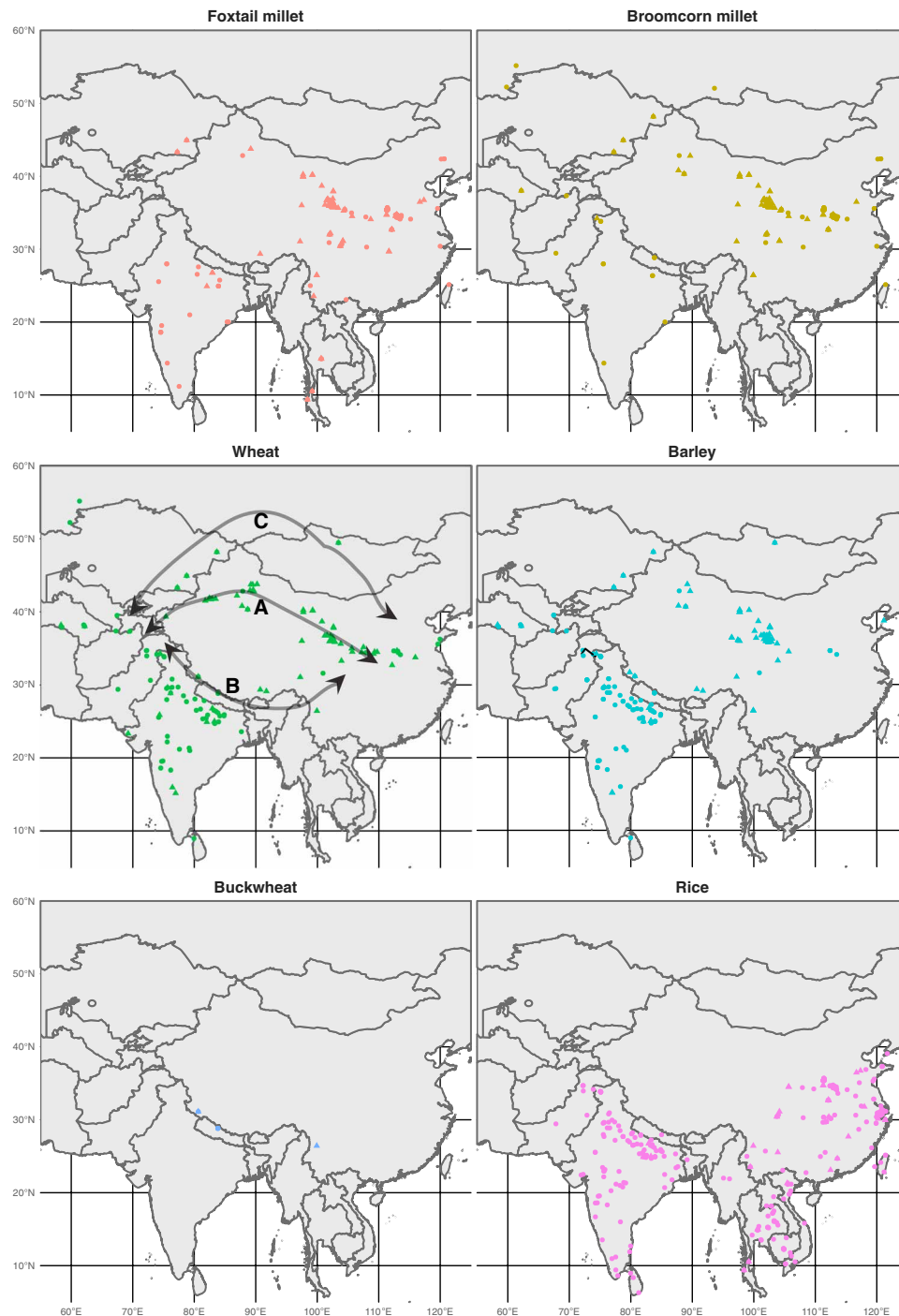
Fig. 1. Sites discussed in the text and routes of the proposed spread of millets, wheat, and barley. The routes are indicated by arrows in the wheat panel. (A) Pathway of the Inner Asian Mountain Corridor (*27*). (B) Southern Himalayan route (*29*). (C) Northern Asia route (*2*). The ages of sites represented by triangles are estimated from summed radiocarbon dates including those on grains; the ages of sites represented by circles are as reported in the literature. See data file S1 and table S2 for chronometric data and estimated site occupation spans.

archaeological evidence in our database to support crops moving along this route. It is worth noting that this route is also not supported by genetic evidence on barley landraces (*26*).

Between 6000 and 4000 cal. BP, the probability of being in the thermal niche ranges between 100 and 90% for sites with millet and barley, suggesting that temperature did not form an impediment to

their spread. During the early years of cultivation of all these crops, farmers exploited them conservatively and cultivated these crops in areas that had a high or, in most cases, almost certain probability of success (Fig. 3). This high probability of success is mirrored in the storage data from central China during this period of time. Individuals stored roughly half a year of grain crops—a quantity that a family
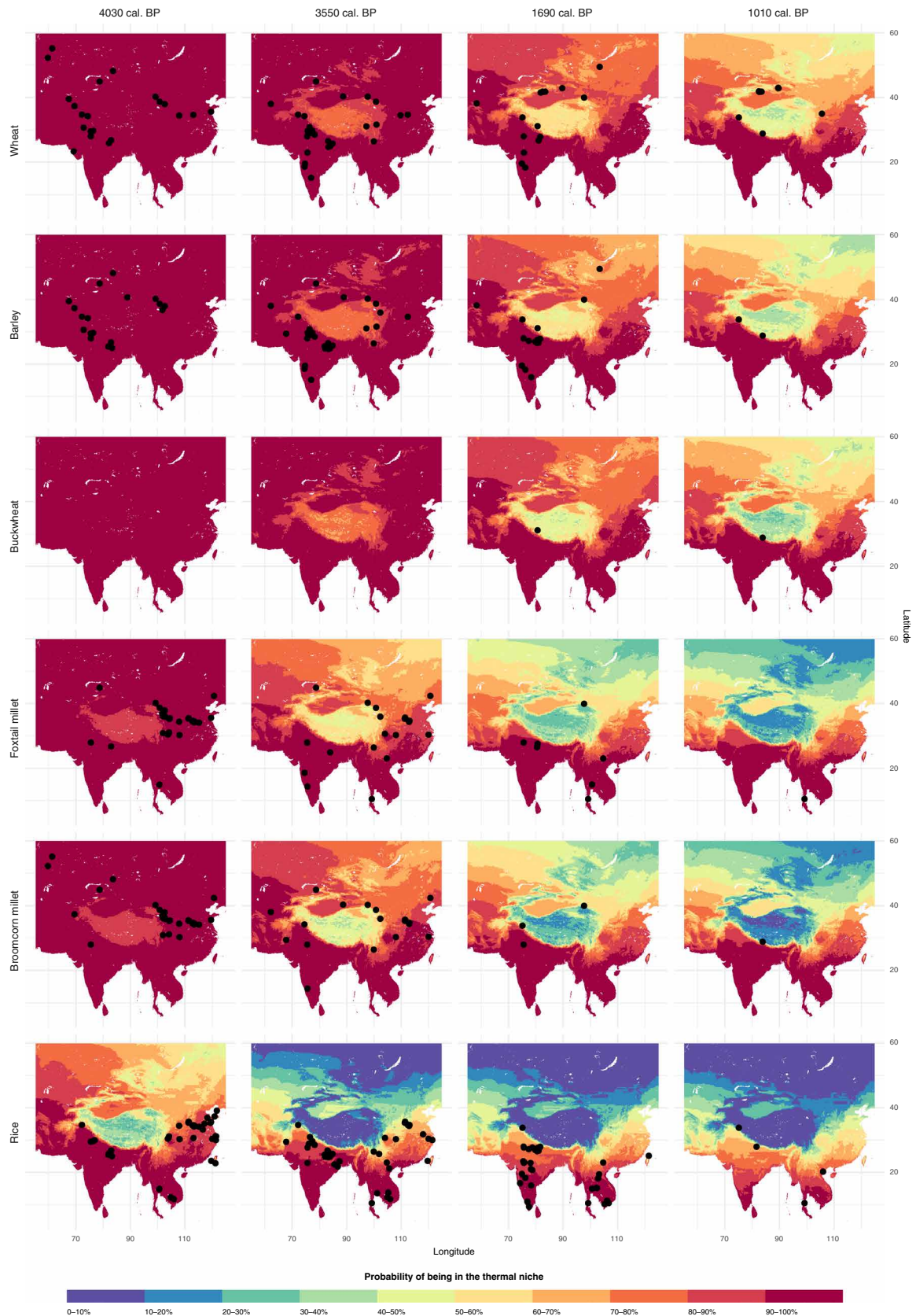
Fig. 2. The spread of wheat, barley, buckwheat, foxtail millet, broomcorn, and rice across Asia at the end of the Holocene Climatic Optimum (4030 cal. BP), 3550 cal. BP, 1690 cal. BP, and 1010 cal. BP. Sites that have evidence of a crop at a particular year are shown as black dots. See movies S1 to S6 for the full animations.

Fig. 3. Calibrated radiocarbon ranges for each site in our database (*x* axis) and the probability of each of these sites being in the niche during that same phase of occupation (*y* axis). An interactive version of this figure that labels each of the cross-plots and enables zooming is available as data file S2.

(that was also reliant on foraging) might have consumed over the course of a year, reserving some seeds for planting for the following years (see Materials and methods).

A decline in the thermal niche of both broomcorn and foxtail millet takes place around 3800 cal. BP, particularly in the higher-altitude areas of the Tibetan Plateau, Tianshan and Altai mountains, and Inner Mongolia (Fig. 3). How did millet farmers cope with this high probability of failure following 4000 cal. BP? In the Liao River Basin, the numbers of millet remains present in archaeological sites decrease following 3000 BP and major changes in settlement distri-

bution are seen during the Upper Xiajiadian period (*30*). On the southeastern Tibetan Plateau (SETP), the impacts of this cooling episode appear to have been catastrophic: Many sites in the region appear to have been abandoned during this period of time. However, in equally affected parts of the northeastern Tibetan Plateau (NETP), at one site in Central Tibet and two sites in Central Asia (Tasbas and Tuzusai), finds of millets persist despite being at only a 60 to 70% probability of being in the thermal niche (Fig. 3). What explains the continued presence of millets on the NETP and at select sites in Central Asia?
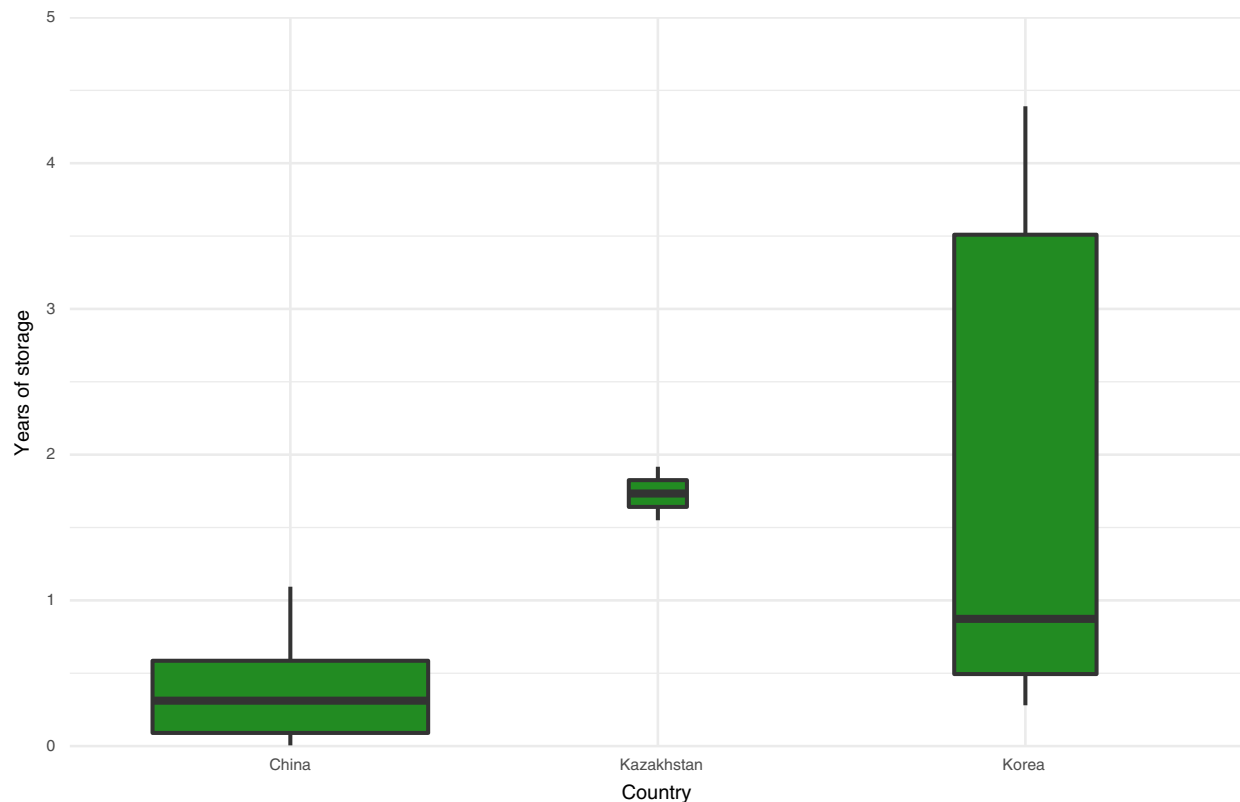
Fig. 4. Storage estimates for sites in three countries in Asia.

Wheat and barley appear on the SETP several hundred years after millet-producing sites had already been abandoned—not giving farmers an opportunity to integrate these new grains into the diet (8). On the NETP, however, wheat and barley arrived before the 4000 cal. BP cool down. Following 4000 cal. BP, millets begin to form a much smaller percentage of total grains found at a given site and are largely replaced by wheat and barley. We argue that faced with cooling climatic conditions, farmers on the NETP used a risk reduction strategy based on grain crop diversification to include cold-tolerant wheat and barley. Given the high probability of millet's failure and the lack of available warm days for temporal diversification throughout the year, we argue that it is likely that farmers used a spatial diversification strategy—planting wheat and barley on cooler slopes and millets in warmer basins. This strategy allowed farmers to continue to cultivate millets on a small-scale basis even as their probability of failure rose sometimes to 30% (Fig. 3).

Researchers in Central Asia have pointed out that at Tuzusai and Tasbas (two Central Asian sites situated at about 70% probability of being in the thermal niche for millet), inhabitants of the sites grew millets, wheat, and barley as an attempt at diversifying crops to reduce risk (31–33). Households in this part of Central Asia also appear to have invested more in storage than those in early Holocene central China: Here, they appear to have stored a year and a half of crops (see Materials and methods), closely mirroring the probability of success of wheat and barley.

Millets could also have arrived at low probability sites via exchange with individuals occupying lower and warmer elevations. Archaeologists have often assumed that seeds found on an archaeological site were grown in the immediate vicinity of the site. It has been difficult

for archaeologists to determine whether plant remains found on archaeological sites were locally grown because of a lack of understanding where the limits of their cultivation lay or how these limits changed with changing climates. When crops are locally cultivated, they are often found in association with crop-processing debris. In many societies, crop processing takes place on a daily basis, which results in the distribution of crop-processing waste across the site (34). A lack of systematic archaeobotany in China and reporting on crop-processing remains makes it impossible to comment on this issue for most sites located within China. However, at Tuzusai in Kazakhstan (2360 to 2100 cal. BP), where such data have been reported, no crop-processing debris was found at the site for wheat and barley. Spengler et al. (31) interprets this lack of chaff as being due to crop processing taking place off site; however, it is also possible that this indicates that the inhabitants may have derived their crops through increasing networks of trade and exchange that had begun to develop in the area. Crop-processing remains of millet can only be documented through the microbotanical record, and more work on this front is necessary to determine whether these crops were locally grown or rather traded into the area.

The fact that these earlier sites lie within or close to the borders of being in the thermal niche makes both crop diversification and exchange viable strategies for explaining the presence of these grains on archaeological sites. Systematic application of strontium isotopes and microbotanical analysis should be used to confirm or refute this explanation.

An event at c. 2000 cal. BP is the point when the largest changes take place in the crop niche for all six crops. For wheat and barley, large parts of the Tibetan Plateau become very cold and fall out of
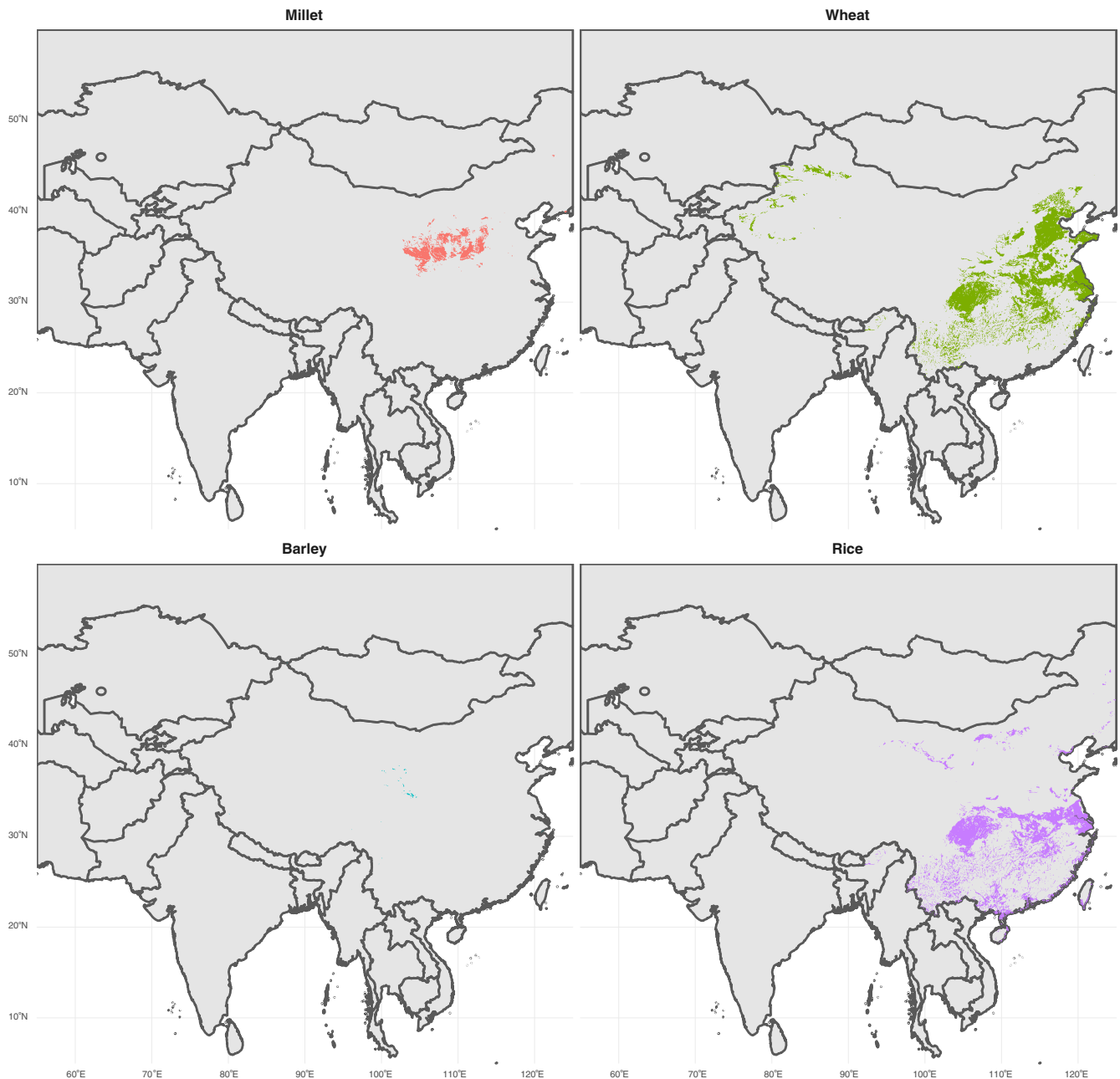
Fig. 5. The historic distribution of millet, wheat, barley, and rice cultivation, as recorded in the China Vegetation Atlas (57).

the thermal niche, as do the Tian Shan and Altai mountains (Fig. 2). When temperatures reach their lowest point, at about 1690 cal. BP (260 CE), almost the entire area corresponding to Mongolia falls outside of the thermal niche. Wheat and barley also experience difficulties in northern China. By 1670 cal. BP, broomcorn and foxtail millet completely lose their niche not only on the Tibetan Plateau but also across much of northwestern China (Outer and Inner Mongolia, Qinghai, Ningxia, Gansu, Heilongjiang, Liaoning, and North Korea); even parts of central China fall within the area that corresponds to the lower confidence interval (Fig. 2). Likewise for rice, the entire area north of the Yangtze River falls below the 70% probability of being in the niche (Fig. 2).

Systematic archaeobotany has not been carried out at large numbers of sites dating to the historic period; however, textual records show that this period also corresponds to a substantial retreat of the Han dynasty out of Central Asia. Between 1660 and 1633 BP (290 to 317 CE), a massive southward migration began after the Jin dynasty became too weak to resist the constant incursions of "barbarians" ("Hu") along their northern margins (35). By 1633 BP (317 CE), the dynasty abandoned Chang'an and established itself in Nanjing (Jiankang) in Jiangsu—an area, while at the border of our lower confidence interval, that still fell within the niche not only for millets but also for wheat and barley. Xianbei pastoralists capture the north entirely by 1564 BP (386 CE) and rename themselves the
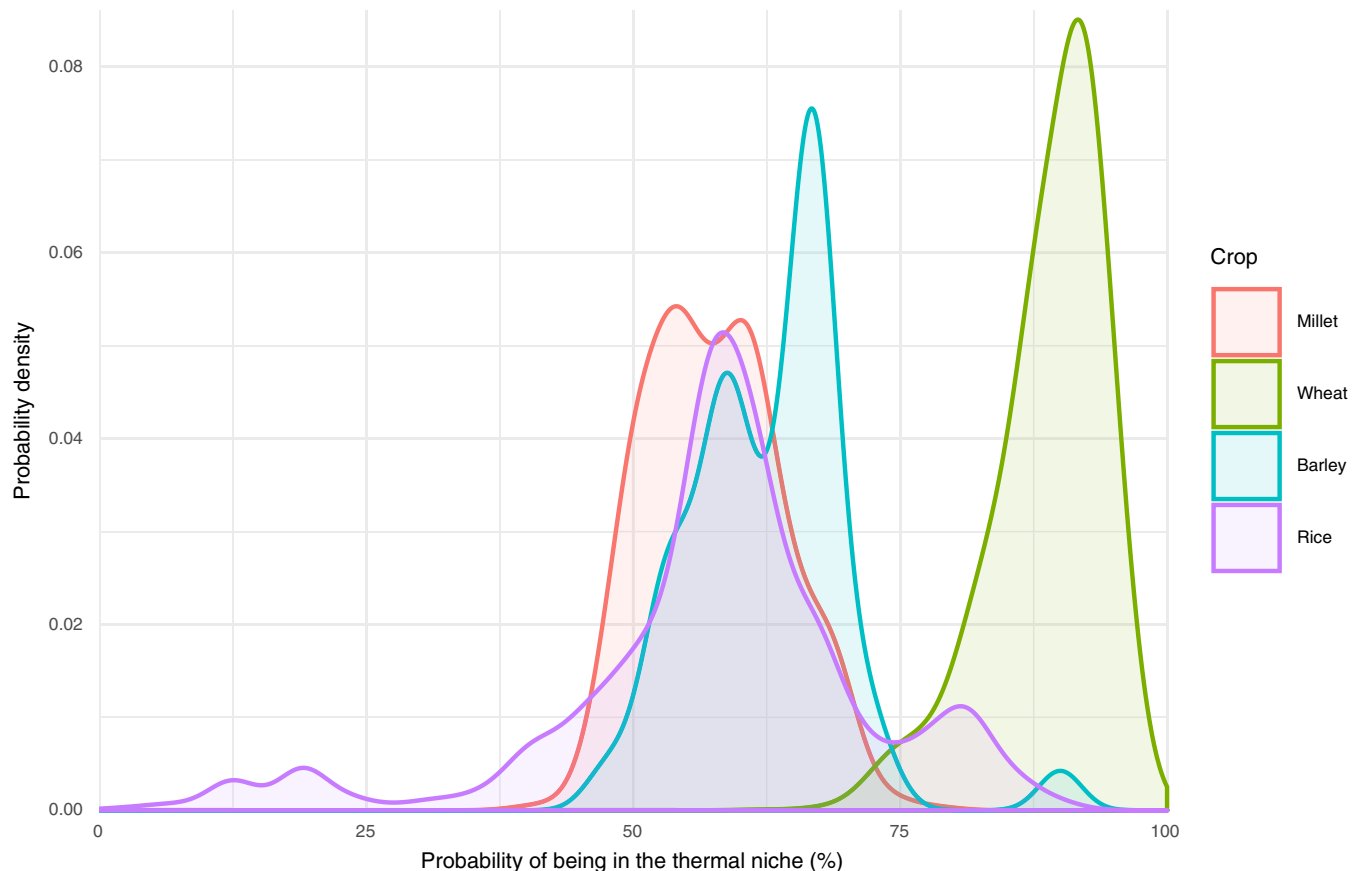
Fig. 6. Kernel density estimates of the niche probability data for the historic distribution of millet, wheat, barley, and rice cultivation.

northern Wei dynasty (*36*). An estimated one in eight farmers from northern China moved to southern China during this period of time. While warfare undoubtedly contributed to this movement, the changes in crop returns may have played a major role in convincing farmers (and the Chinese Jin court) to leave (*37*). It is precisely between 1659 and 1590 BP (291 to 360 CE) that historical records report several decades of particularly catastrophic harvests (*37*). The more variable returns experienced in crops after this date may have encouraged the migration of China's core agricultural zone away from the Yellow River valley and toward the south. The creation of the Grand Canal during the Sui dynasty (1369 to 1332 BP or 581 to 618 CE) served the purpose of transporting grain produced in southern China from Hangzhou in south central China to Luoyang, Chang'an, and to the northern border near Beijing—an ingenious technological development for providing reliable access to food in areas marginal for grain production.

Despite these crops already falling out of their climatic niches in China's higher-altitude margins after 4000 cal. BP, farmers in the warmer low-lying north-central China continued to rely heavily on millets. Wheat and barley remained minor components of the diet of north-central China up until 200 CE (*4*). However, following 200 CE, wheat and barley move from being minor crops to food staples in northern China. Rotary querns are also introduced to northern China during this period of time, suggesting that similar ways of processing wheat and barley also began to make their way over from China's peripheries (*4*, *38*). We argue not only that this shift in dietary strategies in northern China took place as a result of a gradual

change in culinary preference (*4*) but also that increasingly higher risk associated with growing millet led farmers in northern China to experiment with the multicropping strategies and pastoralism that were already used on their margins. This shift was likely facilitated by contact with groups more heavily invested in pastoralism such as the Xianbei, who moved into this area and who may have already been engaged in low-level cultivation of these crops on China's margins.

Our model demonstrates that after 2000 cal. BP is the first time that grains begin to appear at a number of sites (such as Mebrak, Kyung-Lung Mesa, Huang Niangniangtai, and several grottoes along the Silk Road), where probabilities of a successful harvest are less than 50% (Fig. 3). It is unlikely that the inhabitants of these sites attempted to grow crops in these areas, making trade and exchange a plausible solution for explaining the appearance of grain at these sites. This possibility is not surprising, particularly for several key sites on the Tibetan Plateau, like Kyung-lung Mesa and Ding-dun, where we know that nomadic pastoralism formed an important component of the economy (*25*). This represents another form of spatial diversification (exchange in items like salt, fur, hide, meat, and milk for grain with individuals situated in areas of lower altitude) that grew in importance in high-altitude and high-latitude Eurasia throughout time. In the ethnographic present, Tibetan pastoralists engage in networks of trade that bring products produced hundreds of kilometers away into their settlements (*39*). Following their arrival in East Asia during the fourth millennium BP, the mobility and economic diversification afforded by the exploitation of pastoral animals aided humans in further cementing their resilience.

We know that following 2000 cal. BP, China engaged in substantial trade and exchange with groups engaged in pastoralism along its borderlands (*36, 40, 41*). For instance, a Wei court document dating to 1430 BP (520 CE) writes that one group received "one thousand bushels of newly cooked rice, eighty bushels of parched wheat, fifty bushels of roasted nuts… and two hundred thousand bushels of grain" (*36*).

DISCUSSION

Humans have a variety of different mechanisms that can allow them to increase their resilience in times of less than desirable agricultural production. Long-term social memory can allow humans to return to, or exploit with renewed intensity, foraged resources (*42*). Humans can use strategies based on diversification such as growing additional crops, developing fields in new environments, or using combined agropastoral systems that allow humans to exploit a variety of different niches (*43*). Humans can also combat risk by intensifying their agricultural production—producing surplus or by investing in landesque capital such as irrigation systems that can aid in buffering against one aspect of fluctuating climate and changing rainfall (*43*). Last, humans can also increase their resilience by specializing and by engaging in increasing networks of exchange such as those that developed during the early Silk Road or through state-sponsored technological innovations such as the Grand Canal.

Our analysis shows that, for most sites in our database, farmers tolerated extremely low levels of risk, particularly before 4000 cal. BP; 88.4% of sites have median probabilities of a successful harvest greater than 0.75. The trans-Eurasian exchange in crops took place during a period of time where thermal conditions were favorable to the cultivation of these crops. Following an initial climatic downturn c. 4000 to 3750 cal. BP, millet farmers in high-latitude and high-altitude Asia, who faced challenges with dwindling returns, began to innovate with systems of crop diversification following the introduction of wheat and barley. Trade may also have played an important role during this period of time. An even colder interval c. 1690 cal. BP, which began to make millet farming challenging in even central China, leads farmers to diversify their holdings and to finally shift toward consuming larger amounts of wheat and barley. Our crop niche models demonstrate that following 2000 cal. BP, the development of deeper trade networks fueled by pastoralist groups leads to the movement of grains well outside of areas where they could be cultivated. It is following this date that the exchanges across Central and high-altitude Asia coalesced to form the Silk Road—an adaptive network of exchange that included domesticated crops and that allowed humans to occupy areas well outside of the niche of any grain crop on a more permanent basis.

Throughout time, our models demonstrate that humans across Asia increased their resilience to growing levels of crop failure throughout the late Holocene not only through crop diversification, increased storage, and redistribution but also through economic specialization and extensive strategies such as pastoralism. Trade and mechanisms, such as the development of the Grand Canal that moved crops from areas more suitable for production to areas where the probability of failure was high, also increased during this period of time. Our models demonstrate that changes in temperature throughout the Holocene did not affect all areas of Asia equally. Humans experienced changes in climate locally through variance in their staple crop returns and changes in the landscape surrounding them. Crop niche models allow us to move beyond hemispheric estimates of climatic impacts to scales that mattered to ancient farmers and can thus help archaeologists situate the culturally resilient strategies they developed in the climatic context in which they took place.

MATERIALS AND METHODS

To examine how changing temperatures could have affected the ability of farmers to grow each crop, we used a global record of Holocene temperatures (*44*) to reconstruct available growing degree-days (GDDs) following the methods of d'Alpoim Guedes *et al.* (*8*). We derived daily modern temperatures from Global Historical Climatology Network weather stations across East, South, and Central Asia (*45*). To account for spatial heterogeneity in how stations at different altitudes respond to climatic change, we used variance matching and modulated maximum and minimum mean weather station climatology by SDs derived from Marcott *et al.* (*44*). We established crop niches by thresholding annual GDDs, a measure of the accumulated units of heat required by plants to complete their life cycle, for a variety of crops (table S1). We then used indicator kriging to spatially interpolate these niches across the ETOPO5 5 arc min (c. 10 km) resolution elevation model (*8, 46*). Indicator kriging uses binary observations at discrete locations (such as whether a measurement exceeds a given threshold, as here) to interpolate the probability that the given threshold will be met or exceeded across a grid.

A research compendium (*47*) containing all code and data to reproduce the analysis, as well the specification of the computing environment, is available as data file S3, in a publicly available GitHub repository (https://github.com/bocinsky/guedesbocinsky2018), and archived with Zenodo at http://doi.org/10.5281/zenodo.1239106. See the README.md file in data file S3 for details on reproducing the analysis. This code is written in R—a free and open source software environment for statistical computing.

We used temperature to examine how the crop niche changed over time for several reasons. (i) It is a primary limiting variable: This means that the extent of the crop niche cannot be increased by adding water. Our reconstructions should thus be interpreted as the maximum niche that might have been occupied by these crops—a niche that could be further reduced by limiting water. (ii) It is challenging to model how precipitation changed in the past as there are no accurate and high spatial resolution models for Asia that extend over this period of the Holocene.

We assembled chronometric data from 423 sites for the presence of different crops across our study area with a total of 1187 entries over 485 distinct occupations. Finds of crops were derived from site reports, publications on archaeobotanical remains, or compilations of radiocarbon dates (*15, 48*). Where available, we collected associated or direct radiocarbon dates on crop remains from each site—our database currently includes 908 radiocarbon dates covering 190 sites. For sites lacking radiocarbon dates, we used established age range estimates for agricultural occupation periods reported in the literature. In cases where we had both radiocarbon dates and age estimates, we used the radiocarbon dates to reestimate occupation ranges (see below). We also excluded records for which we could not find accurate site location data (see data file S3 for details). The chronometric dataset used in our analysis is presented in table S2, with associated references. Because of the sensitive nature of archaeological site locations, table S2 does not include locational data; the entire dataset—including data excluded from the present analysis

because they were from sites outside of our study area, or crops not discussed here—is archived in the Digital Archaeological Record (ID: 428089) at https://doi.org/10.6067/XCV8MK6G05.

All C-14 dates were calibrated using the IntCal13 calibration curve and the BchronCalibrate function available from the Bchron package version 4.2.6 in R (49). Calibrated probability density curves for all dates from each site/component were then summed and normalized to one to generate estimated occupations for each site (this is congruent to the Oxcal SUM command). Sites that only had estimated date ranges were assigned a flat distribution (also normalized to one). We established site occupation spans as the 95% confidence interval of the date distribution; estimated site occupation spans for all site occupations are presented in table S2.

Assessing archaeological storage capacity

Accumulating and storing grain from a given year's harvest is another key way in which farmers can deal with the uncertainty in returns that farming entails. Portions of this grain can be used for consumption throughout the rest of the year and for replanting the following year. When available, additional stored grain can be used to buffer against uncertainty in crop returns or against years of "failed crops."

Defining how many years of storage a given society has accumulated is thus crucial to understanding when changes in the crop niche reached thresholds that were critical for early farming societies. Looking at the number of years of storage farmers customarily accumulated can help us understand where these thresholds lie. Archaeologists have noted that societies around the world produce normal surpluses—an excess amount of crop products produced in good years that buffer against the risks of future crop failure (50).

In small-scale societies, storage is often carried out at the household level; however, as complexity, specialization, and interdependence increase, elites are able to extract and control surplus grains (50). Presumably, these grains are redistributed to farmers that contribute them in times of famine; however, this is not always the case. In societies based around household structure, subterranean storage associated with the house is often used to avoid freeloading (51).

Some examples of household-level storage pits exist in the archaeological record of Asia; however, collating a record of the levels of storage used by individuals across Asia has been complicated for several reasons. Only a few archaeological publications contain sufficient detail on the households (and hence number of persons) with which these storage units are associated. We review the evidence for household-level storage from three datasets: (i) data from the early agricultural site of Jiangzhai (7000 to 6000 cal. BP) in the Yellow River valley of China (52), (ii) data from two Iron Age settlements in Kazakhstan (Tuzusai and Taldy Balak) excavated by Chang (53), and (iii) a very complete record of Korean household-level storage in pits assembled by Bale (54) for sites ranging across the Mumum period (2900 to 2450 cal. BP). These datasets range widely both across regions and time periods.

To calculate the total number of years of storage, we first needed to calculate the numbers of inhabitants per house. Different estimates of residential density exist in the ethnographic literature. For the early China and Korean data, we followed Peterson and Shelach (52) in using a value of 4 m^2. In Kazakhstan, at sites inhabited by humans who had a substantial pastoral component to their diet, we used a value of 5.5 persons/m^2 following Brown (55) who based their sample

on a cross-cultural sample of societies with mixed mobility and subsistence patterns. Following Peterson and Shelach (52), we calculated a daily caloric requirement of 1500 calories (a value lower than current U.S. Department of Agriculture standards, but consistent with values for traditional societies) per resident, although we acknowledge that this requirement likely fluctuated according to the age and sex structure of each household.

Where data on individual pits associated with houses were available (Jiangzhai dataset), we calculated calories stored per household (see table S3). In other instances, we calculated surface areas of several houses per phase across sites and total numbers and caloric storage values of storage pits (Korean and Kazakh datasets). Data from these sites showed a range of less than half a year of storage at Jiangzhai, to approximately a year and a half in Kazakhstan, to a range of 0.5 to 4 years in the Korean dataset (Fig. 4). Several key outliers exist, however, in the Korean dataset, with some sites containing up to 25 years of storage.

Storage of half a year of millet likely corresponds to what a family at Jiangzhai would have consumed over the course of a year, reserving some seeds for planting at the end of the season, but only if their diet was also supplemented by other resources. We know that hunting continued to form an important strategy during the early Yangshao period, as did gathering of wild resources (52). Aside from a few households, a substantial investment in storing additional grain to buffer against failed harvests does not appear to have been a key strategy at the site. For a site that was located at a near 100% probability of being in its thermal niche, this seems like a reasonable strategy.

The amount of storage carried out at these different sites mirrors somewhat the challenges they faced in returns. At Tuzusai and Taldy Balak in Kazakhstan, individual households appear to have stored roughly a year and a half of crops: Compared to Jiangzhai, we see a more substantial investment in buffering against risk. They stored slightly more crops than would have been necessary to survive on over the course of a year. We know that individuals at both sites also heavily supplemented their diet through resources derived from pastoralism, meaning that these resources lasted them even longer (31, 53). For wheat and barley, Tuzusai is located at an 85 to 96% probability of being in the niche, whereas millets were between 64 and 75%. The year and half of available storage closely mirrors the probability of success of wheat and barley. The inhabitants of the site likely further increased their resilience to variable returns not only by either trading in or farming a riskier crop such as millet but also through buffering by reliance on pastoral products.

In the Korean dataset, the median number of years of storage was 1.8 years; however, a wider variability existed, with a number of sites having over 20 years of storage, such as Majeon-ri (c. 2750 to 2350 cal. BP). Korean sites appear to have been largely within the niche for these dryland crops during the Mumum period (89 to 91%); however, for rice, a crop that was also cultivated at these sites, the probability of success was far lower. Their ability to withstand variability in crop returns via reliance on storage was higher than both early Yangshao and Kazakh sites, and this may have been a function of the higher variability in returns derived from rice. While they practiced crop diversification to buffer against risk, inhabitants of these Korean sites do not appear to have relied on pastoral resources. Storage likely became an increasingly important way of dealing with risk.

It is worth noting, however, that while stored grain for food consumption can last several years, seed viability for replanting decreases

rapidly, with some species having averages of only 2 to 3 years. Multi-year crop failures may still have been devastating for communities despite investment in storage.

Although systematically derived archaeological data for storage are lacking in later periods in China, we know through textual sources that early states played an increasingly important role in extracting grain through taxation and redistributing this grain in times of hunger. A source describing agricultural strategies in Anhui, north-central China, that was composed c. 2000 BP states: "On average the state should be able to save a year's surplus from every three years crop… so that despite natural disasters the people will not suffer misery or destruction. A state that does not have [at least] nine years stored is said to have insufficient food, one which does not have six years is said to be in peril and one which does not have three years is said to be in desperate straits" (56).

Over time, we can thus see that an increasing preoccupation with storage was at the forefront of state concerns. While sociopolitical reasons for increasing storage undoubtedly played an important role in this process, the highly variable returns that began to characterize agriculture in central and northern China following 2000 cal. BP may have begun to make this a necessity.

We set the threshold between probabilities considered in the niche and out of the niche at 75% for illustration purposes; however, we recognize that wide variability existed in how much failure past societies could tolerate. We have seen that, at Jiangzhai, they were able to tolerate relatively little failure; however, at sites in Kazakhstan and Korea, the ability to deal with crop failure (not only through storage but also through crop diversification and investment in trade and other economic strategies like pastoralism) was different throughout Asia.

What we have is a provocative suggestion of how much risk people were willing to endure; however, this requires much further research and systematic recording of storage features in the archaeological record of Asia to elucidate the relationship between storage and agricultural returns.

Assessing the relationship between GDDs and contemporary crop extents

The instrumental record may provide data that allow us to outline the limits of where humans have grown crops in the present day. However, not all areas of the world have high-resolution spatial data on where crops are grown, nor do these records often distinguish between the type of crop grown. One such useful dataset exists for the People's Republic of China—the China Vegetation Atlas, a 1:1,000,000 scale vegetation distribution map of China of data collected between the 1950s and 1980s (57). Niche probability data were generated for the 1960–1990 calibration period using the same data for traditional cultivars we used in the rest of our analysis (Figs. 5 and 6). Because of the difficulty of accessing the China Vegetation Atlas in the United States, we have archived it in the Digital Archaeological Record (ID: 442484) at https://doi.org/10.6067/XCV85B05BG.

In the instrumental record, wheat grows in areas of niche probability of between 75 and 100%—a value consistent with the storage averages discussed in this article. Barley, millet, and rice range between 50 and 75% probability of being in the niche. Only a tiny proportion of cells in the raster fell into areas predicted as lying below 50% (Fig. 6).

The period between 1950 and 1980 spans that of a series of major transformations in Chinese agriculture. This include changes in the types of crops grown, increases in the area under cultivation, and the introduction of dwarf and hybrid varieties of some crops that have extended their range.

For instance, the once large area occupied by the Chinese northern staple millets lost ground to wheat (Fig. 5), reflecting a desire to switch to grains that are reportedly higher in production and have widely recognized international trade value.

The area where rice is grown in China expanded by 6.2 million hectares between 1949 and 1958 alone (58). Between roughly 1960 and 1970, the introduction of dwarf varieties followed by hybrid rice further extended the area in which rice was cultivated. With the exception of a few cells, the distribution of rice is confined to the area south of the Yangtze River valley. Some low probability cells in Xinjiang, Inner Mongolia, and Heilongjiang represent expansions of the area under cultivation during the Great Leap Forward and following the introduction of new types of rice. Our analysis uses GDD values for nonhybrid and nondwarf varieties of rice. The extended range that post-1970 varieties are able to occupy may partially explain why a small percentage of rice occupies an area that is in lower niche probabilities (Fig. 5).

It is worth noting that cells containing barley appear to be underreported in the database. This is likely a facet of recording methods used in this product. Agricultural cells reported on the Tibetan Plateau, for instance, were not coded for the type of grains grown and thus could not be included in this analysis (Fig. 5).

SUPPLEMENTARY MATERIALS

Data file S1. The chronometric data used in this analysis, radiocarbon laboratories, and associated references.
Data file S2. Calibrated radiocarbon ranges for each site in our database (x axis) and the probability of each of these sites being in the niche during that same phase of occupation (y axis).
Data file S3. An archived research compendium containing all R code and data to reproduce the analysis, as well as the specification of the computing environment.
Table S1. Common Eurasian crops and their thermal requirements.
Table S2. Estimated site occupation spans and niche probabilities over those occupations for all sites in this study.
Table S3. Storage estimates for sites in three countries in Asia.
Movie S1. The wheat niche.
Movie S2. The barley niche.
Movie S3. The broomcorn millet niche.
Movie S4. The foxtail millet niche.
Movie S5. The buckwheat niche.
Movie S6. The rice niches.

REFERENCES AND NOTES

1. C. C. Ummenhofer, H. Xu, T. E. Twine, E. H. Girvetz, H. R. McCarthy, N. Chhetri, K. A. Nicholas, How climate change affects extremes in maize and wheat yield in two cropping regions. *J. Clim.* **28**, 4653–4687 (2015).
2. L. Barton, C.-B. An, An evaluation of competing hypotheses for the early adoption of wheat in East Asia. *World Archaeol.* **46**, 775–798 (2014).
3. M. Jones, H. Hunt, E. Lightfoot, D. Lister, X. Liu, G. Motuzaite-Matuzeviciute, Food globalization in prehistory. *World Archaeol.* **43**, 665–675 (2011).
4. N. Boivin, D. Q. Fuller, A. Crowther, Old World globalization and the Columbian exchange: Comparison and contrast. *World Archaeol.* **44**, 452–469 (2012).
5. X. Liu, M. K. Jones, Food globalisation in prehistory: Top down or bottom up? *Antiquity* **88**, 956–963 (2014).
6. X. Liu, E. Lightfoot, T. C. O'Connell, H. Wang, S. Li, L. Zhou, Y. Hu, G. Motuzaite-Matuzeviciute, M. K. Jones, From necessity to choice: Dietary revolutions in west China in the second millennium BC. *World Archaeol.* **46**, 661–680 (2014).
7. N. F. Miller, R. N. Spengler, M. Frachetti, Millet cultivation across Eurasia: Origins, spread, and the influence of seasonal climate. *Holocene* **26**, 1566–1575 (2016).
8. J. d'Alpoim Guedes, S. W. Manning, R. K. Bocinsky, A 5,500-year model of changing crop niches on the Tibetan Plateau. *Curr. Anthropol.* **57**, 517–522 (2016).

9. U. Büntgen, V. S. Myglan, F. C. Ljungqvist, M. McCormick, N. D. Cosmo, M. Sigl, J. Jungclaus, S. Wagner, P. J. Krusic, J. Esper, J. O. Kaplan, M. A. C. de Vaan, J. Luterbacher, L. Wacker, W. Tegel, A. V. Kirdyanov, Cooling and societal change during the Late Antique Little Ice Age from 536 to around 660 AD. *Nat. Geosci.* **9**, 231–236 (2016).

10. B. M. Buckley, K. J. Anchukaitis, D. Penny, R. Fletcher, E. R. Cook, M. Sano, L. C. Nam, A. Wichienkeeo, T. T. Minh, T. M. Hong, Climate as a contributing factor in the demise of Angkor, Cambodia. *Proc. Natl. Acad. Sci. U.S.A.* **107**, 6748–6752 (2010).

11. E. R. Cook, K. J. Anchukaitis, B. M. Buckley, R. D. D'Arrigo, G. C. Jacoby, W. E. Wright, Asian monsoon failure and megadrought during the last millennium. *Science* **328**, 486–489 (2010).

12. S. Shennan, S. S. Downey, A. Timpson, K. Edinborough, S. Colledge, T. Kerig, K. Manning, M. G. Thomas, Regional population collapse followed initial agriculture booms in mid-Holocene Europe. *Nat. Commun.* **4**, 2486 (2013).

13. G. Dong, X. Jia, R. Elston, F. Chen, S. Li, L. Wang, L. Cai, C. An, Spatial and temporal variety of prehistoric human settlement and its influencing factors in the upper Yellow River valley, Qinghai Province, China. *J. Archaeol. Sci.* **40**, 2538–2546 (2013).

14. H. Li, C. An, W. Fan, W. Dong, Y. Zhao, H. Wang, Population history and its relationship with climate change on the Chinese Loess Plateau during the past 10,000 years. *Holocene* **25**, 1144–1152 (2015).

15. C. Wang, H. Lu, J. Zhang, Z. Gu, K. He, Prehistoric demographic fluctuations in China inferred from radiocarbon data and their linkage with climate change over the past 50,000 years. *Quat. Sci. Rev.* **98**, 45–59 (2014).

16. J. d'Alpoim Guedes, S. A. Crabtree, R. K. Bocinsky, T. A. Kohler, Twenty-first century approaches to ancient problems: Climate and society. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 14483–14491 (2016).

17. Z. Wei, A. M. Rosen, X. Fang, Y. Su, X. Zhang, Macro-economic cycles related to climate change in dynastic China. *Quat. Res.* **83**, 13–23 (2015).

18. L. Costantini, The beginning of agriculture in the Kachi plain: The evidence from Mehrgarh, in *South Asian Archaeology 1981: Proceedings of the Sixth International Conference of the Association of South Asian Archaeologists in Western Europe*, B. Allchin, Ed. (Cambridge Univ. Press, 1984), pp. 29–33.

19. L. Costantini, in *Prehistoric and Protohistoric Swāt, Pakistan (c. 3000-1400 BC):(c. 3000-1400 bC)*, G. Stacul, B. Compagnoni, L. Costantini, Eds. (IsMEO, 1987), pp. 155–165.

20. R. N. Spengler, G. Willcox, Archaeobotanical results from Sarazm, Tajikistan, an Early Bronze Age Settlement on the edge: Agriculture and exchange. *Environ. Archaeol.* **18**, 211–221 (2013).

21. R. Spengler, M. Frachetti, P. Doumani, L. Rouse, B. Cerasetti, E. Bullion, A. Mar'yashev, Early agriculture and crop transmission among Bronze Age mobile pastoralists of Central Eurasia. *Proc. Biol. Sci.* **281**, 20133382 (2014).

22. M. D. Frachetti, R. N. Spengler, G. J. Fritz, A. N. Mar'yashev, Earliest direct evidence for broomcorn millet and wheat in the central Eurasian steppe region. *Antiquity* **84**, 993–1010 (2010).

23. X. Li, J. Dodson, X. Zhou, H. Zhang, R. Masutomoto, Early cultivated wheat and broadening of agriculture in Neolithic China. *Holocene* **17**, 555–560 (2007).

24. R. L. Bettinger, L. Barton, C. Morgan, F. Chen, H. Wang, T. P. Guilderson, D. Ji, D. Zhang, The transition to agriculture at Dadiwan, People's Republic of China. *Curr. Anthropol.* **51**, 703–714 (2010).

25. J. d'Alpoim Guedes, H. Lu, Y. Li, R. N. Spengler, X. Wu, M. S. Aldenderfer, Moving agriculture onto the Tibetan plateau: The archaeobotanical evidence. *Archaeol. Anthropol. Sci.* **6**, 255–269 (2014).

26. H. Jones, D. L. Lister, D. Cai, C. J. Kneale, J. Cockram, L. Peña-Chocarro, M. K. Jones, The trans-Eurasian crop exchange in prehistory: Discerning pathways from barley phylogeography. *Quat. Int.* **426**, 26–32 (2016).

27. M. D. Frachetti, Multiregional emergence of mobile pastoralism and nonuniform institutional complexity across Eurasia. *Curr. Anthropol.* **53**, 2–38 (2012).

28. M. Frachetti, Bronze Age pastoralism and differentiated landscapes along the Inner Asian Mountain Corridor, in *Connections and Complexity: New Approaches to the Archaeology of South Asia* (Left Coast Press, 2013), pp. 279–298.

29. C. J. Stevens, C. Murphy, R. Roberts, L. Lucas, F. Silva, D. Q. Fuller, Between China and South Asia: A Middle Asian corridor of crop dispersal and agricultural innovation in the Bronze Age. *Holocene* **26**, 1541–1555 (2016).

30. X. Jia, Y. Sun, L. Wang, W. Sun, Z. Zhao, H. F. Lee, W. Huang, S. Wu, H. Lu, The transition of human subsistence strategies in relation to climate change during the Bronze Age in the West Liao River Basin, Northeast China. *Holocene* **26**, 781–789 (2016).

31. R. N. Spengler, C. Chang, P. A. Tourtellotte, Agricultural production in the Central Asian mountains: Tuzusai, Kazakhstan (410–150 B.C.). *J. Field Archaeol.* **38**, 68–85 (2013).

32. R. N. Spengler III, M. D. Frachetti, P. N. Doumani, Late Bronze Age agriculture at Tasbas in the Dzhungar Mountains of eastern Kazakhstan. *Quat. Int.* **348**, 147–157 (2014).

33. P. N. Doumani, M. D. Frachettia, R. Beardmore, T. M. Schmaus, R. N. Spengler III, A. N. Mar'yashev, Burial ritual, agriculture, and craft production among Bronze Age pastoralists at Tasbas (Kazakhstan). *Archaeol. Res. Asia* **1–2**, 17–32 (2015).

34. G. Hillman, Interpretation of archaeological plant remains: The application of ethnographic models from Turkey, in *Plants and Ancient Man: Studies in Palaeoethnobotany*, W. Van Zeist, W. A. Casparie, Eds. (A.A. Balkema, 1984), pp. 1–41.

35. J. Gernet, *A History of Chinese Civilization* (Cambridge Univ. Press, 1996).

36. S. Jagchid, V. J. Symons, *Peace, War, and Trade Along the Great Wall: Nomadic-Chinese Interaction Through Two Millennia* (Indiana Univ. Press, 1989).

37. Y. Su, X. Fang, J. Yin, Impact of climate change on fluctuations of grain harvests in China from the Western Han Dynasty to the Five Dynasties (206 BC-960 AD). *Sci. China Earth Sci.* **57**, 1701–1712 (2014).

38. E. N. Anderson, *Food and Environment in Early and Medieval China* (University of Pennsylvania Press, 2014).

39. K. M. Bauer, *High Frontiers: Dolpo and the Changing World of Himalayan Pastoralists* (Columbia Univ. Press, 2010).

40. T. J. Barfield, *The Perilous Frontier: Nomadic Empires and China, 221 BC to AD 1757* (Wiley, 1989), pp. 36–45.

41. O. Lattimore, The geographical factor in Mongol history. *Geogr. J.* **91**, 1–16 (1938).

42. A. M. Rosen, I. Rivera-Collazo, Climate change, adaptive cycles, and the persistence of foraging economies during the late Pleistocene/Holocene transition in the Levant. *Proc. Natl. Acad. Sci. U.S.A.* **109**, 3640–3645 (2012).

43. J. M. Marston, Archaeological markers of agricultural risk management. *J. Anthropol. Archaeol.* **30**, 190–205 (2011).

44. S. A. Marcott, J. D. Shakun, P. U. Clark, A. C. Mix, A reconstruction of regional and global temperature for the past 11,300 years. *Science* **339**, 1198–1201 (2013).

45. M. J. Menne, I. Durre, B. Korzeniewski, S. McNeal, K. Thomas, X. Yin, S. Anthony, R. Ray, R.S. Vose, B. E. Gleason, T. G. Houston, *Global Historical Climatology Network—Daily (GHCN-Daily), Version 3* (NOAA National Climatic Data Center, 2012); http://doi.org/10.7289/V5D21VHZ.

46. NOAA National Geophysical Data Center, *Data Announcement 88-MGG-02: Digital Relief of the Surface of the Earth* (NOAA National Geophysical Data Center, 1988); https://www.ngdc.noaa.gov/mgg/global/etopo5.HTML.

47. B. Marwick, Computational reproducibility in archaeological research: Basic principles and a case study of their implementation. *J. Archaeol. Method Theory* **24**, 424–450 (2017).

48. Institute of Archaeology and Chinese Academy of Social Sciences, *Radiocarbon Dates in Chinese Archaeology (1965-1991)* (Cultural Relics Press, 1991).

49. A. Parnell, M. A. Parnell, Package "Bchron" (2016); http://cran.biodisk.org/web/packages/Bchron/Bchron.pdf.

50. P. Halstead, The economy has a normal surplus: Economic stability and social change among early farming communities of Thessaly, Greece, in *Bad Year Economics: Cultural Responses to Risk and Uncertainty*, P. Halstead, J. M. O'Shea, Eds. (Cambridge Univ. Press, 1989), pp. 68–80.

51. A. Bogaard, M. Charles, K. C. Twiss, A. Fairbairn, N. Yalman, D. Filipović, G. A. Demirergi, F. Ertuğ, N. Russell, J. Henecke, Private pantries and celebrated surplus: Storing and sharing food at Neolithic Çatalhöyük, Central Anatolia. *Antiquity* **83**, 649–668 (2009).

52. C. E. Peterson, G. Shelach, Jiangzhai: Social and economic organization of a Middle Neolithic Chinese village. *J. Anthropol. Archaeol.* **31**, 265–301 (2012).

53. C. Chang, *Revisiting Central Asian Prehistory: Farmers, Shepherds, and Nomads* (Routledge Press, 2017).

54. M. T. Bale, An examination of surplus and storage in prehistoric complex societies using two settlements of the Korean peninsula. *World Archaeol.* **49**, 90–104 (2017).

55. B. M. Brown, Population estimation from floor area: A restudy of "Naroll's constant". *Behav. Sci. Res.* **21**, 1–49 (1987).

56. J. S. Major, S. Queen, A. Meyer, H. D. Roth, *The Essential Huainanzi* (Columbia Univ. Press, 2012).

57. Cold and Arid Regions Science Data Center, *China Vegetation Atlas 1:1,000,000 Scale* (Cold and Arid Regions Science Data Center, 2001); http://westdc.westgis.ac.cn/data/3f20ef3a-1be8-414d-a214-54e1a3639c80.

58. Z. He, A. Bonjean, *Cereals in China* (International Maize and Wheat Improvement Center, 2010).

http://doi.org/10.5281/zenodo.1239106. See the README.md file in data file S3 for details on reproducing the analysis. This code is written in R—a free and open source software environment for statistical computing. Because of the sensitive nature of archaeological site locations, table S2 does not include locational data; the entire dataset—including data excluded from the present analysis because they were from sites outside of our study area, or crops not discussed here—is archived in the Digital Archaeological Record (ID: 428089) at https://doi.org/10.6067/XCV8MK6G05. Because of the difficulty of accessing the China Vegetation Atlas (*57*) in the United States, we have archived it in the Digital Archaeological Record (ID: 442484) at https://doi.org/10.6067/XCV85B05BG.