Agricultural origins and the isotopic identity of domestication in northern China

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Stable isotope biochemistry ($\delta^{13}C$ and $\delta^{15}N$) and radiocarbon dating of ancient human and animal bone document 2 distinct phases of plant and animal domestication at the Dadiwan site in northwest China. The first was brief and nonintensive: at various times between 7900 and 7200 calendar years before present (calBP) people harvested and stored enough broomcorn millet (*Panicum miliaceum*) to provision themselves and their hunting dogs (*Canis* sp.) throughout the year. The second, much more intensive phase was in place by 5900 calBP: during this time both broomcorn and foxtail (*Setaria viridis* spp. *italica*) millets were cultivated and made significant contributions to the diets of people, dogs, and pigs (*Sus* sp.). The systems represented in both phases developed elsewhere: the earlier, low-intensity domestic relationship emerged with hunter–gatherers in the arid north, while the more intensive, later one evolved further east and arrived at Dadiwan with the Yangshao Neolithic. The stable isotope methodology used here is probably the best means of detecting the symbiotic human–plant–animal linkages that develop during the very earliest phases of domestication and is thus applicable to the areas where these connections first emerged and are critical to explaining how and why agriculture began in East Asia.

East Asia | millet | Neolithic | origins of agriculture | stable isotope biochemistry

It is widely believed that East Asian agriculture evolved in isolation from early agricultural developments elsewhere around the globe, producing a developmentally distinct suite of domesticates including rice, broomcorn millet, foxtail millet, pigs, dogs, and chickens (1–11). Although the details of this East Asian agricultural revolution are cloudy, existing evidence points to 2 historically-independent evolutionary phenomena rooted in separate and ecologically distinct parts of mainland China: a rice-based system in the warm-humid south and a millet-based system in the cold-arid north (7, 8, 12, 13) (Fig. 1). There is some support for an alternative idea that the millet-based system is merely the "northern phenotype" of the southern rice-based system (14, 15), holding that as the southern rice-based system spread toward the more arid north, rice farmers already familiar with the drought-tolerant wild ancestor (*Setaria viridis*) of foxtail millet (*Setaria viridis* spp.*italica*) increasingly adopted it to compensate for lower rice productivity. In this view, agriculture everywhere in East Asia (excepting New Guinea) arrives via migration from the Yangzi River core in a Neolithic farming diaspora that explains the modern distribution of language families throughout the region (14, 16).

New data from locations well beyond the lower Yangzi (17–19) suggest the transition to agriculture was less unified and much more complex than suggested by this single-origin, or East Asian "Garden of Eden" model. Most notably, a second drought-tolerant annual grass, broomcorn millet (*Panicum miliaceum*) appears to have been cultivated as early as rice and foxtail millet in areas hundreds to thousands of kilometers beyond the southern, humid Yangzi River region, suggesting that East Asian agriculture evolved in many different places almost simultaneously, under different natural and social circumstances, and likely by different processes.

Unfortunately, we know very little about the domestication of broomcorn millet in northern China, only that it appears early and suddenly from an as-yet-unidentified wild progenitor and is gradually replaced by foxtail millet (20–22). Plant domesticates are typically identified by measuring the degree to which they have been modified from their wild type (*SI Text*), but these data are rare in the East Asian record. Few samples represent the earliest domesticated forms, fewer still have been dated directly. The problem, however, is not one of preservation but of method. The standard molecular and morphological indices of domestication are unlikely to catch the initial stages of domestication before the strength of human selection has had time to register (*SI Text*), nor do they speak directly to the importance of different domesticates in the diet. Stable isotope biochemistry makes both possible, and we use it here to document the initial establishment of domestic symbioses between people, millet, dogs, and pigs at the Neolithic site of Dadiwan in northwest China.

ANTHROPOLOGY

Dadiwan

Dadiwan is the westernmost expression of early agriculture in northern China (17, 22). The site produced China's earliest painted pottery and is the earliest and type site of the Laoguantai cultural tradition, which extends from Dadiwan south to the Qinling mountains and east down the Wei River (12). Although Laoguantai is considered an independent development (23), it shares basic similarities in pottery (cord marked), architecture (round houses), and site plan (scattered dwellings) with other "pre-Yangshao" Neolithic complexes of the Huang He drainage (Cishan, Peiligang, and Houli). All were eventually replaced by the distinctive Yangshao and other contemporary Neolithic traditions between 6800 and 6000 calendar years before present (calBP).

The Neolithic farming sequence at Dadiwan begins at 7900 calBP and can be divided into 2 distinct phases separated by ≈700 years: Phase 1 (pre-Yangshao/Middle Neolithic), from 7900 to 7200 calBP; and Phase 2 (Yangshao/Late Neolithic), from 6500 to 4900 calBP (*SI Text*). As in other early millet sites, carbonized broomcorn millet macrofossils are present at Dadiwan but rare in the older Phase 1 deposits (21, 22) and tell us almost nothing about the domestication, use, or importance of

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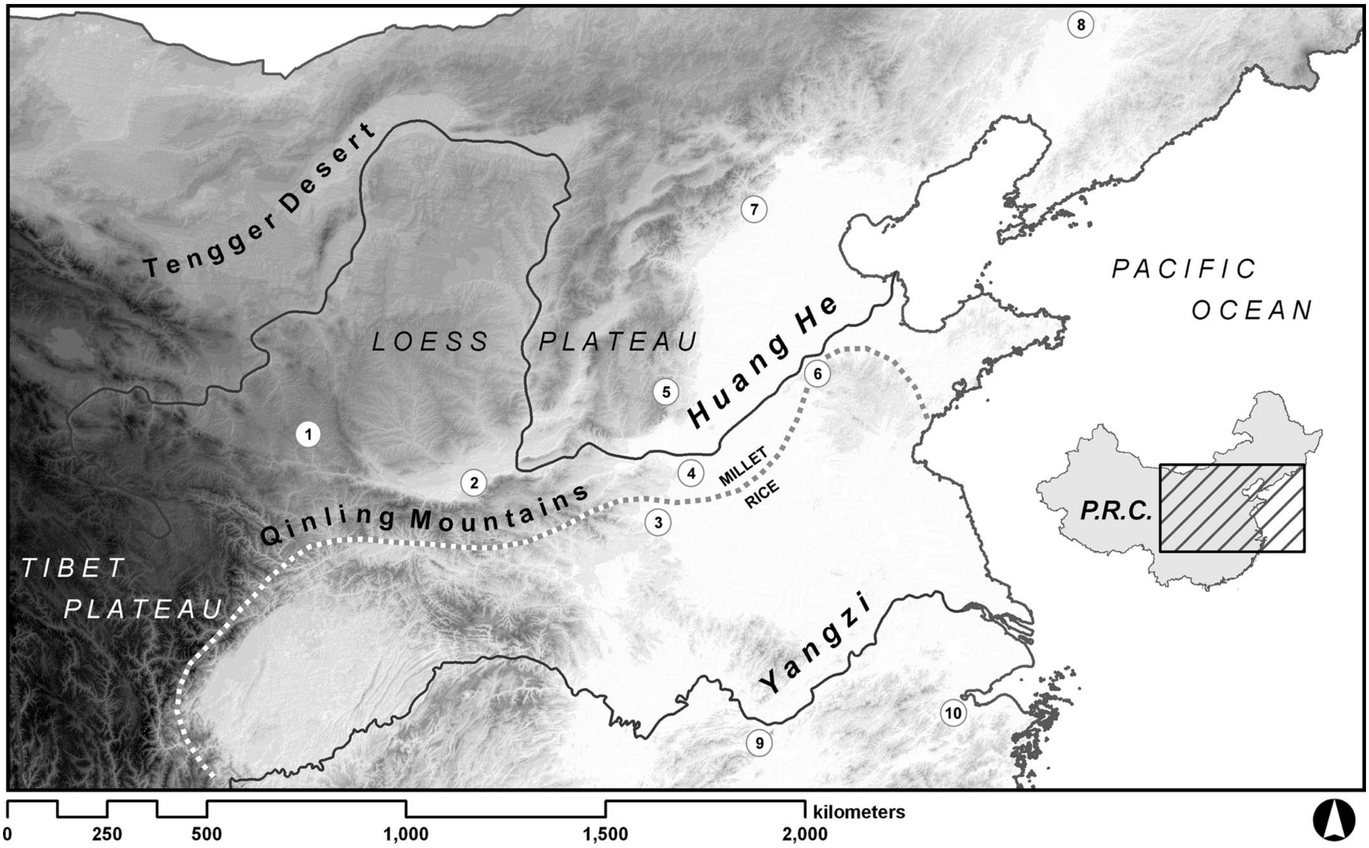

Fig. 1. Archaeological sites where early plant or animal domestication has been proposed. ① Dadiwan. ② Baijia. ③ Jiahu. ④ Peiligang. ⑤ Cishan. ⑥ Yuezhuang. ⑦ Nanzhuangtou. ⑧ Xinglongwa. ⑨ Diaotonghuan. ⑩ Kuahuqiao. The margin between rice and millet farming is approximate. P.R.C., People's Republic of China.

the species. Accordingly, we trace the evolution of broomcorn millet agriculture by observing the effect of its direct and indirect consumption, through stable isotopes, using carbon and nitrogen isotope values from Dadiwan Phase 1 and 2 human and animal bone samples selected from Gansu Museum and Lanzhou University collections on the basis of cultural affiliation, species, and bone preservation (Table S1). Seventy-four collagen samples were prepared and analyzed for their carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopic composition (see *Methods* and Table S1). Of these, 34% were dated directly by accelerator mass spectrometry to corroborate cultural and temporal affiliations assigned by the excavators (*SI Text*, Table S2, Fig. S1). Obviously, it would be nice to have samples from the late Pleistocene—early Holocene occupation of Dadiwan, but suitable plant, animal, and human remains from this era have not been found (17); indeed, we were unable to obtain any Phase 1 human bone. Despite these gaps, the Dadiwan isotopic data date back to the very beginnings of agriculture in northwest China, allowing us to follow and evaluate human diet and human–plant–animal mutualism as it unfolded in this very important independent agricultural center.

Domestication and Stable Isotope Biochemistry

To evaluate early domestication with stable isotope biochemistry, potential domesticates must differ isotopically from other wild taxa so that the consumers of the potential domesticates will also be isotopically distinct from consumers of other taxa. Because the millets of northern China are C_4 grasses, characterized by high $\delta^{13}C$ values, heavy millet consumers will stand out only if local vegetation was in the past dominated by C_3 plants characterized by relatively low $\delta^{13}C$ values. Although their productivity varies as a function of temperature and precipitation, C_4 plants are rare in northern latitudes (24–27), and north China is no exception: C_4 plant growth is largely confined to summer months (25), comprising <10% of perennial terrestrial vegetation (28). At Dadiwan, therefore, high $\delta^{13}C$ values in bone collagen would indicate heavy consumption of C_4 plants whose availability was extended by human planting, tending, storage, and related activities. Because bone collagen is replaced slowly throughout the life of an organism, isotopic values represent an average of dietary patterns over many years. Humans with high $\delta^{13}C$ values must have stored and consumed large quantities of C_4 grain or kept and consumed animals with $\delta^{13}C$ values elevated by year-round provisioning with the grain or hay of C_4 plants and/or the meat or waste of animals whose $\delta^{13}C$ values were elevated for the same reason. Any C_4 plant will elevate skeletal $\delta^{13}C$, but in northern China only millets attracted such attention. Certainly at Dadiwan, the archaeobotanical records from Phase 1 and Phase 2 are dominated by millets and contain very little else (21, 22). Alone, high $\delta^{13}C$ values in bone collagen do not confirm domestication or even cultivation of C_4 plants, but at Dadiwan they do reveal the intensive human selection on otherwise rare plant populations (most likely millet) that might generate the morphological and molecular attributes of the domestication syndrome (*SI Text*). The connection between millet use and elevated values of skeletal $\delta^{13}C$ is well established for the Phase 2 Yangshao millet farmers throughout the Huang He drainage. By ≈6000 calBP, human, dog, and pig remains from these late Neolithic sites display uniformly high $\delta^{13}C$ values (29–31), attesting to a millet-anchored symbiotic mutualism already entrenched enough to alter human settlement patterns profoundly and to produce important morphological change in the species involved.

What little data we have for the earliest food-producing systems of north China show the same connection between millet use and elevated $\delta^{13}C$ values. In far northeast China during the Xinglongwa period (≈8100–7200 calBP), for example, high $\delta^{13}C$ values in human skeletal elements go hand in hand with the carbonized remains of 2 types of millet (*Panicum* and *Setaria*) (18, 32). By contrast, south of the Huang He at Jiahu (≈9000–7800 calBP), low $\delta^{13}C$ values in human skeletal elements agree with an archaeobotanical record that includes rice and other C_3 species but not millet (33). In the lower Huang He drainage at Houli culture sites like Xiaojingshan and Yuezhuang, $\delta^{13}C$ values suggest that C_4 plants were a minor component of a diet dominated by C_3 plants (34), despite the presence of both rice and millets (35). Last, a few human samples from the middle Huang He site of Baijia (≈7500–6500 calBP) point to a very mixed C_3/C_4 diet (31) and at least occasional use of C_4 plants, almost certainly millet, although it is impossible to be sure because plant remains were not recovered from the site. Close to the northern margin of early rice farming, Baijia's mixed C_3/C_4 signal might reflect millet compensating for diminishing rice production, as predicted by the Garden of Eden single-origin dispersal hypothesis, but it might just as easily reflect a nonintensive phase of early millet cultivation. Either way, the connection between millet use and skeletal $\delta^{13}C$ in north China is clear.

$\delta^{15}N$ furnishes a second, quite different line of evidence regarding early millet farming systems. Because $\delta^{15}N$ values increase by ≈3‰ with each trophic step in a food web, the $\delta^{15}N$ value from an organism indexes its position in the food chain. For dogs and pigs, "ascending the early farming food chain" meant becoming more heavily dependent on domestic sources of protein (e.g., meat table scraps, offal, and miscellaneous domestic waste including human feces), thus elevating the $\delta^{15}N$ value of their tissues. Pigs and dogs whose diet was further augmented with millet grain as slop or table scraps, or that consumed meat scraps or domestic waste from animals fed with millet grain or hay, should have simultaneously elevated $\delta^{13}C$ values. Accordingly, the position of dogs and pigs in the web of early food production should be marked by an isotopic gradient from wild types with relatively low $\delta^{13}C$ and $\delta^{15}N$ values to domesticated types with high $\delta^{13}C$ and $\delta^{15}N$. This relationship should register as a positive correlation between $\delta^{13}C$ and $\delta^{15}N$ in archaeological samples of human and animal bone. Together, these 2 lines of evidence comprise the isotopic identity of domestication, which is useful for evaluating domestication where archaeological plant or animal remains are scarce or otherwise uninformative.

Results

As expected, relatively low $\delta^{13}C$ and $\delta^{15}N$ values characterize the wild prey at Dadiwan. Phase 1 and 2 ungulates, birds, and a single bear show that from ca. 7900–4900 calBP local vegetation was predominantly C_3 (Fig. 2*A*, Table S1, and Fig. S1). Likewise, 2 of the Phase 1 dogs and all 4 of the Phase 1 pigs display this C_3-based diet (Fig. 2*B*). Three of the Phase 1 dogs, however, display simultaneously high $\delta^{13}C$ and $\delta^{15}N$ values that clearly distinguish them from their wild counterparts. The bimodal distribution of isotopic values for Phase 1 Dadiwan dogs reveals 2 distinct groups: wild-foraging dogs captured, and perhaps eaten by human hunters; and dogs that lived with, hunted with, and were likely provisioned by humans. The latter camp-fed, behaviorally-domestic dogs consumed millet in quantities possible only through association with humans that selectively harvested and stored millet. Dogs provisioned with millet also consumed animal products in far greater quantities than did dogs living on wild forage. Consumption of human feces alone would not likely lead to such differences, and because there is no animal source to account for their elevated $\delta^{13}C$ levels during Phase 1, camp dogs appear to have been fed or were tolerated in such

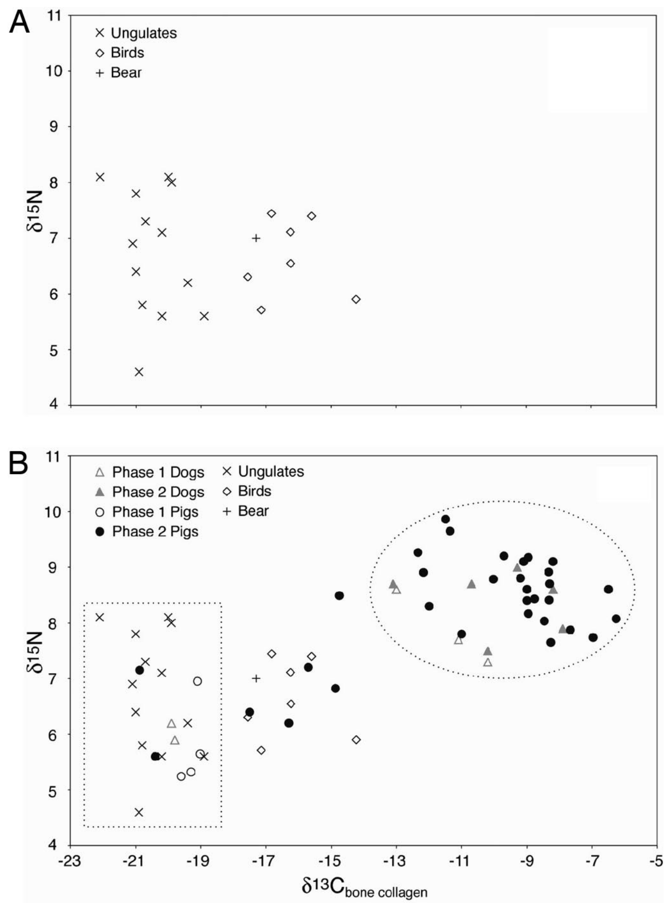

Fig. 2. The isotopic identity of domestication at Dadiwan. (*A*) Low $\delta^{13}C$ values in wild-foraging taxa establish the dominance of C_3 plants in the landscape. (*B*) Positive correlation between high $\delta^{13}C$ and high $\delta^{15}N$ illustrates life within the domestic sphere. Gradation between wild and domestic illustrates the plasticity of early farming systems. Phase 1 dogs (△) within the dotted oval are the earliest examples of domestication in northwest China. Ungulates include deer (*Cervus* sp. and *Moschus* sp.) and cattle (*Bos* sp.) but not pigs. Birds have been tentatively identified as *Gallus* sp., bear as *Ursus arctos* (22).

proximity to be able to scrounge a combination of millet, most likely grown by humans, and meat obtained in the wild by humans, likely with their aid. Whether the high $\delta^{13}C$ values in the Phase 1 dogs reflect intensive harvest of natural (wild) or managed (domestic) stands of millet is unclear, because the current study straddles the tentative divide between the two. What is clear is that the bimodal distribution of $\delta^{13}C$ values in dogs results from an exposure to millet that is impossible for animals living without human help. Here, the persistent and intensive human use of both dogs and millet reveals the circumstances expected of early experiments with plant and animal domestication.

Directly dated between 7560 and 7160 calBP (Table S2 and Fig. S1), these Phase 1 Dadiwan dog bones provide the earliest evidence for an integrated system of food production in northwest China (Fig. 2*B*).* These are the oldest samples we were able to analyze, so it is possible the food production system they

*Dogs may have been domesticated earlier. The numerous Phase 1 "wild" dogs were at minimum "camp followers" and certainly benefited from a close association with humans, who may have found them useful to have around, in the hunt, for example. Still, the Dadiwan data show that dogs moved closer to humans about the same time humans moved closer to millet.

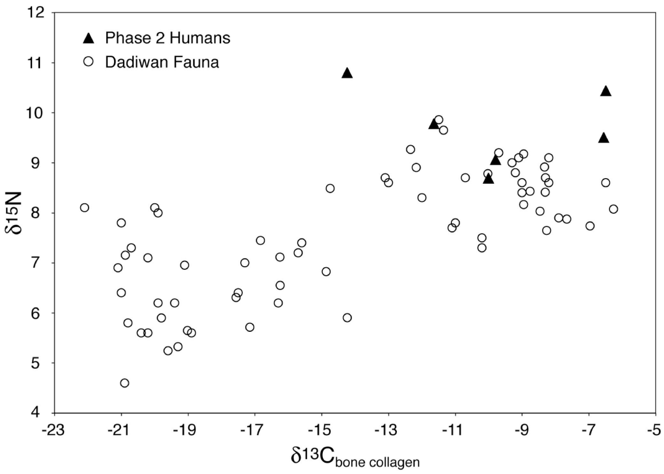

Fig. 3. Human diet during the Yangshao Neolithic at Dadiwan. As regular consumers of C_4 plants with regular access to animal products (likely including the flesh of animals that also eat C_4 plants), humans clearly reside within the domestic sphere.

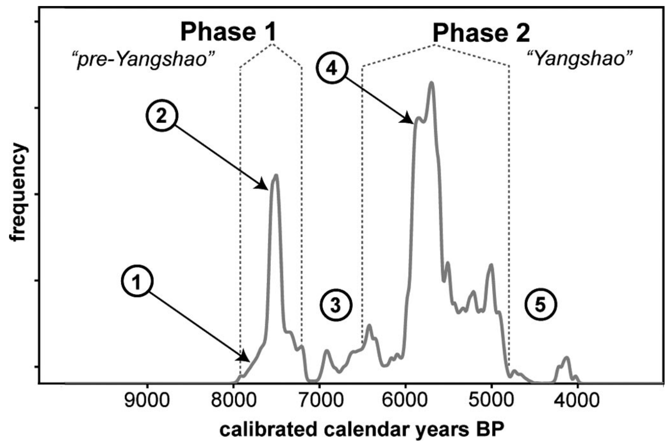

Fig. 4. A chronology of Holocene occupation and domestication at Dadiwan. This summed probability distribution of calibrated radiocarbon dates (Table S3) provides a rough proxy for occupation intensity at the site. ① Hunter–gatherers arrive at Dadiwan. ② The earliest evidence for domestication of dogs and broomcorn millet. ③ The site is largely abandoned. ④ Intensive agriculture involving dogs, pigs, broomcorn, and foxtail millet arrives with the Yangshao Neolithic. ⑤ The site is abandoned again.

document extends further back, to the very beginning of Phase 1. Either way, it was very short-lived: there is little evidence of human occupation at Dadiwan, or anywhere else in the western Loess Plateau, after 7200 calBP.

The much more intensive farming system that appears when Dadiwan was reoccupied in Phase 2 features both broomcorn and foxtail millet (21, 22), camp-fed dogs and, for the first time, pigs dependent on a camp diet of millet and extra meat (Fig. 2*B*). All Phase 2 dogs ($n = 6$) display the typical camp diet (high $\delta^{13}C$ and $\delta^{15}N$), suggesting dogs had been wholly drawn into the domestic farming sphere (Fig. 2*B*). Phase 2 pigs show a similar isotopic pattern, with high $\delta^{13}C$ and $\delta^{15}N$ values appearing for the first time ≈5800 calBP, suggesting their domestication sometime between 7200 and 5800 calBP. Some Phase 2 pigs ($n = 4$), however, have low $\delta^{15}N$ and $\delta^{13}C$ values, showing they foraged and were presumably taken in the wild (Fig. 2*B*). These and several individuals with intermediate $\delta^{13}C$ and $\delta^{15}N$ values representing either wild animals that raided millet fields or free-range animals occasionally provisioned with millet and meat demonstrate quite clearly that pigs had not as yet been as fully incorporated into the domestic farming sphere as dogs. As with most of the phase 2 pigs ($n = 25$) and all of the Phase 2 dogs ($n = 6$), Phase 2 humans ($n = 6$) also have high $\delta^{13}C$ and $\delta^{15}N$ values (Fig. 3) suggesting the same heavy reliance on millet and domestic animals seen elsewhere in the Yangshao Neolithic culture area (29–31). As a result, a $\delta^{13}C$ and $\delta^{15}N$ biplot for all specimens from both Dadiwan phases ($n = 74$) shows the expected trajectory of millet domestication and farming in northern China; humans, dogs, and pigs with high $\delta^{13}C$ also had higher $\delta^{15}N$ values, suggesting that when they ate more millet they also ate more meat (Figs. 2*B* and 3). Together, $\delta^{13}C$ and $\delta^{15}N$ illustrate the strength of the relationship between people, plants, and animals, providing a stand-alone index of domestication, against which the morphological and molecular attributes of plant or animal domestication can be compared. A summed probability distribution (36) of all known Holocene radiocarbon dates from the Dadiwan site (Table S3) provides a chronology of occupation and food production in the western Loess Plateau (Fig. 4).

Implications

That only dogs were provisioned with meat and millet in Phase 1, and pigs only later, in Phase 2, suggests that broomcorn millet was initially targeted in an economy that emphasized hunting. This idea is consistent with the Phase 1 archaeological record, notably the abundant remains of large wild animals (red deer, sika, musk deer, and pig), makeshift dwellings, impoverished middens, and sparse archaeological assemblages (22), suggesting intermittent occupation and a continuing need for regular moves between seasonal camps. Millet farming seems to have made a fairly small contribution to this economy. Apart from a few carbonized seeds (21, 22), dogs provide the only concrete evidence of its contribution, and the Phase 1 archaeological assemblage and its mixture of wild and camp-fed dogs indicates occasional, pragmatic, and opportunistic food production, resembling the "low-level" food production that so frequently characterizes agricultural origins in various independent centers around the world (37).

The early Holocene climate of northwest China was episodically harsh enough (38, 39) to encourage short-term use of low-return plants by hunter–gatherers living in north China's more marginal environments. Severe cold-dry intervals like the hemispheric climatic anomaly at 8,200 calBP (40) may have forced some living in the deserts on either side of the upper Huang He to move southward into the western Loess Plateau (17). Evidence for this is particularly compelling at Dadiwan. Phase 1 microblades and microblade cores made from exotic raw materials are entirely without precedent in local lithic technology, suggesting that the earliest food producers at Dadiwan were immigrant hunter–gatherers from the arid north where this microlithic technology is common (41, 42).

Given the long coassociation between humans and dogs in northern Eurasia (43), dogs were likely essential to the hunting system of these early millet farmers, and their experiments with quick-growing, storable plants were probably motivated by the need to provision their dogs as much as themselves whenever more traditional resources were scarce. Because *Panicum* grows faster and is more cold- and drought-tolerant than other candidate crops (44), it is an ideal crop for mobile hunter–gatherers attracted to flexible resources requiring minimal investments, and limited delays. We suggest this complementarity both enabled and promoted numerous independent experiments with *Panicum*-based food production across northern China and, perhaps more generally, throughout Eurasia (45, 46). Although climate in the deserts north of the Loess Plateau would have held millet productivity in check, it likely flourished when exploited in settings like the upper Huang He near Dadiwan, where summer monsoon rains were more reliable than in the desert north. That even these very modest experiments were relatively short-lived again suggests a connection with hunting; food production was too costly and inhibited mobility too much for hunters except during short periods of extreme hardship, a short-term solution to short-term deficits within a generally stable economy of hunting and gathering.

By contrast, the millet farming system that appears when Dadiwan is reoccupied in Phase 2 is full time, intensive, and attended by the classic Yangshao cultural package: hard-fired pottery, square houses, and moat-enclosed village plan (22). The remains of wild game (including pigs with low δ^{13}C and δ^{15}N values) show that hunting persists well into the late Neolithic, but Dadiwan's Phase 2 occupants were clearly farmers heavily dependent on millet and the animals provisioned with it, living a sedentary lifestyle that entailed stable annual cycles of field preparation, cultivation, harvest, processing, storage, and protection. This Phase 2 domestic agricultural system is clearly part of the Yangshao Neolithic of the Huang He drainage (2, 4, 29–31). Equally clear is that it does not originate at Dadiwan. Foxtail millet, the featured Yangshao species, was not a part of Dadiwan's Phase 1 system, and although it was the species of choice in other early millet farming locations (e.g., Peiligang and Cishan), Yangshao did not arise from any of these but from another, as-yet-unidentified, early farming complex.

In combination with those previously available, the Dadiwan data presented here illustrate adaptive programs that developed independently around 2 different plants, in what were almost certainly quite different subsistence-settlement systems across an area of $>$1 million km^2. All of the early millet farming systems so far documented, including Dadiwan, were short-lived and none is the source of the Yangshao Neolithic system that would in very short order replace all of the early, low-level millet farming systems of the Huang He drainage. This replacement was likely quick and easy because economies based on mobile hunting support only small populations with little ability to defend the large territories required to maintain them. When larger groups require less land to support themselves (as expected under agricultural food production) they invade easily and expend less to hold their ground.

The key to explaining the rapid diffusion of agriculture in East Asia is in identifying those places where larger groups capable of territorial maintenance emerge and in discussing why they expand. If agricultural food production is central to this expansion, methods for establishing the timing and intensity of the stable interactions between people, plants, and animals are essential for tracking it. The methodology illustrated here provides for this, and with it we can begin to evaluate the competing hypotheses for the origins of agriculture in East Asia.

Methods

For δ^{13}C and δ^{15}N analysis, a $\approx$100-mg sample of compact bone was removed from each specimen with a low-speed cutting tool. Bone fragments were cleaned of sediment and demineralized in 0.5 N hydrochloric acid (HCl) for $\approx$12–15 h at 5 °C. The resulting material was treated repeatedly with a chloroform/methanol (2:1) mixture to remove lipids and then lyophilized. Dried samples ($\approx$0.5 mg) were sealed in tin boats and analyzed with a Carlo-Erba elemental analyzer (NC 2500) interfaced with a Finnegan Delta Plus XL mass spectrometer (Carnegie Institution of Washington).

Isotopic results are expressed as δ values, δ^{13}C or $\delta^{15}n = 1{,}000 \times [(R_{\text{sample}}/R_{\text{standard}}) - 1]$, where R_{sample} and R_{standard} are the ^{13}C/^{12}C or ^{15}N/^{14}N ratios of the sample and standard, respectively. The standards are Vienna-Pee Dee Belemnite limestone for carbon and atmospheric N_2 for nitrogen. The units are expressed as parts per thousand or per mil (‰). The within-run standard deviation of an acetalinide standard was $\leq$0.2‰ for both δ^{13}C and δ^{15}N values. As a control for the quality of bone collagen, we measured the carbon-to-nitrogen ([C]/[N]) ratios of each sample to test the possibility that isotopic values were altered postmortem. The atomic C/N ratios of all bone collagen samples are 2.9–3.4 (Table S1), well within the range that characterizes unaltered collagen (47). Duplicate isotopic measurements were performed at the Center for Arid Environment and Paleoclimate Research at Lanzhou University on $\approx$90% of all unknown samples, yielding a mean absolute difference of 0.2‰ for δ^{13}C and δ^{15}N values.

Human and animal bone collagen samples were prepared for accelerator mass spectrometry radiocarbon analysis (48) at the Center for Accelerator Mass Spectrometry of Lawrence Livermore National Laboratory. Raw bone samples were crushed and demineralized in 0.5 N HCl at 5 °C for $\approx$12–16 h. The resulting organic matter was twice rinsed with deionized H_2O, and gelatinized in 0.01 N HCl at $\approx$60 °C for $\approx$16 h. These gelatinized samples were filtered with glass microfiber filters, then ultrafiltered with centrifugal filters to remove low molecular weight ($\approx$30 kDa) fragments, then vacuum-concentrated. Collagen was then combusted to CO_2 and graphitized for accelerator mass spectrometry. All dates reported are in calBP. All radiocarbon age estimates on bone are based on a 5,568 half-life, are δ^{13}C-corrected, include a background subtraction based on similarly and simultaneously-prepared ^{14}C-free bone, and have been calibrated to 2σ range by using OxCal 4.0 (49) and the INTCAL 04 calibration curve (50) (Table S2).

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Supporting Information

Barton et al. 10.1073/pnas.0809960106

SI Text

Domestication. Domestication is both a process and a resultant state (1). The process is one of adaptation to a novel environment defined by the interactions between people, plants, and/or animals. Construction of this relationship is the very beginning of agricultural origins, and the intensification of it is a hyperselective coevolutionary regime. The resultant state is the condition of numerous interacting organisms each with novel physical or behavioral attributes specific to their adaptive history. In plants it includes things like larger seeds or simultaneous ripening (2), facial neotony or docility in animals (3), and even a reduction in total size, stature, and bone structure in humans (4). The attributes comprise the "adaptive syndrome of domestication" used to distinguish domesticated plants or animals from their wild or feral relatives.

The lag between the development of the initial relationship and the appearance of these morphological or genetic features is variable (5, 6). Not all symbiotic relationships between humans and other taxa result in domestication, but when they do they can take thousands of years, or they can happen within 20–50 years (7–10). Furthermore, domestication is a continuum of change dictated by the strength of selection, the genetic architecture of change, and the environmental parameters of both (11, 12). Because no single attribute in any one taxon constitutes domestication, prehistoric domestication is difficult to identify, which makes it difficult to talk about origins. If domestication is a process, and that process entails the evolutionary ratchet of symbiotic interaction, our attention should be trained on identifying, measuring, and explaining these interactions.

The Archaeological Identity of Domestication. Domestication is often gauged by the degree to which plants or animals have been modified from their wild type. Presumably, these changes tell us about the strength of human selection on a resource population and about the importance of this resource to human survival.

Plant domestication is typically viewed through a combination of morphology and genetics. Efforts to determine the identity of charred or desiccated remains of plants from archaeological contexts depend largely on interpretation of the adaptive syndrome of domestication, and expectations for how the morphological attributes of plants should evolve under selection (2, 13). Grain size, for example has long been used to identify domesticated plants from archaeological sites (14). However, overlapping variation across the plastic continuum of wild types, feral weeds, and crop varieties in a single plant species makes early domestication difficult to identify using morphology alone. Furthermore, the symbioses of domestication may exist without morphological change, and some of the traits we attribute to it may also appear without domestication.

Molecular analysis tells us about population history, the regions of the chromosome that control attributes affected by domestication, and the effects of domestication on genomewide variation (15). Additionally, if we opt to define domestication as genetic change itself (10), then molecular analysis should help us to see it. But because the genetic marker is actually a result of the domestic relationship, on its own the marker adds little to our understanding of process, nor does it explain how the genetic change occurred. Furthermore, many of these molecular evaluations rely on a comparison between different populations of the same plant, including the wild type, the weed, and the crop. If the wild type is unknown (as it currently is in *Panicum miliaceum*, the plant under inspection in northern China) then the power of the analysis is low.

As with plants, animals can be studied with morphology and genetics, and the limitations of documenting the domestic relationship are similar (16). Animals have their own analog to the wild-weed–crop continuum, and the plasticity of both their physical attributes and their population structure makes the domestic relationship difficult to identify. Intentional burial of animals or coburial of animals with people (17, 18) also imply a domestic relationship, but these occurrences are relatively uncommon, and there is no reason to believe that people could not bury or be buried with totally wild animals. Quantitative age and sex profiles of archaeological fauna provide sound evidence for human harvesting, interference, and management of animal populations (19–21). These demographic patterns precede the phenotypic and genetic markers of domestication and track the early construction of the domestic niche. But this, too, has its limitations as it can be difficult to distinguish mutual benefit from intensive predation.

Last, mutual dependence can be established from dietary patterns, and stable isotope chemistry has been used to establish mutualisms between various combinations of people, plants, pigs, and dogs (22–28). Yet none of these studies evaluate the change in diet during the initial formation of the domestic niche.

The Evidence for Domestication in China. Humans in the Yangzi Drainage may have harvested wild rice (*Oryza* sp.) as early as 12,000 BP (29) but the earliest morphological evidence for its domestication varies in age from 10,000 to 6,000 BP (5, 29–32). The issue is unresolved, but we know far more about rice in the south than we do about millets in the north. The best data allude to domestic forms of broomcorn millet (*Panicum* sp.) and foxtail millet (*Setaria* sp.) by ≈7700 BP at Xinglonggou in the far northeast (33), broomcorn millet between 7900 and 7500 BP at Dadiwan on the western Loess Plateau (34–36), and both millets and rice at Yuezhuang along the lower reaches of the Yellow River by 8000 BP (37). The evidence for millet domestication in China is entirely based on the morphology of carbonized seeds.

Documenting domestication is also problematic for pigs (38, 39) and dogs (17, 40). Genetic data suggest pigs were domesticated independently in China (41) and a combination of morphological and demographic data suggest domestication by 8500–8000 BP at Cishan north of the Yellow River (42). Other early claims for pig domestication are unconfirmed but could represent multiple independent processes over a very large area (43, 44). The mere presence of *Canis* sp. bone suggests domestication at Nanzhuangtou between 12,000 and 10,700 BP (45), and at several sites throughout the Yellow River drainage, 8,000–7,000 BP (43, 46). Yet the strength of the relationship between humans and dogs has not been demonstrated for any of these places because it is difficult to infer from skeletal morphology alone. Although the deliberate burial of dogs in Siberia by ≈10,600 BP (17) suggests a long history of human–dog mutualism in northeast Asia, the earliest dog burials in northern China appear during the Yangshao Neolithic (34), well after agricultural expansion. During this time pig mandibles also become a common feature of human interments in northern China (47).

Explanation of Radiocarbon Dating at Dadiwan. The radiocarbon dates contributing to Fig. 4 and appearing in Table S3 are the product of several different research programs beginning with the earliest excavations at Dadiwan in 1978 (34, 48–51). Shortcomings in these original data include inconsistent reporting of dates from the early excavation, and incomplete information (such as laboratory numbers, dating material, etc). We view these shortcomings as inconsequential here, primarily because Fig. 4 is merely a succinct way to illustrate archaeological interpretations with radiocarbon data. The summed probability distribution of all calibrated radiocarbon dates reported from Dadiwan, compiled with the CalPal software package (52) and the INTCAL04 calibration curve (53) illustrates abundance and preservation of charcoal from different time periods, a method repeatedly used to infer occupation intensity (53, 54) and population change (55) through time. Although taphonomy and sampling surely compromise the efficacy of this method for reconstructing prehistoric demography (56), we suggest its use here is sound. The 81 Holocene radiocarbon dates presented here come from nearly 14,800 m^2 of excavation. If anything, the later portion of the phase 2 occupation of the site is underrepresented in this distribution of radiocarbon dates thereby reflecting a sampling strategy that biases the earlier, more cryptic occupation. Furthermore, local environmental proxies (57–59) provide no indication of Holocene depositional regimes that might favor preservation of one cultural horizon over another. The summed probability distribution is provided here as an illustration of occupation intensity and should not be misinterpreted as a rigorous presentation of population history.

Unique to the isotopic data reported here are the radiocarbon estimates on human and animal bone. Bone samples were selected from collections at the Gansu Museum (all excavations between 1978 and 1984) (34, 35, 60–62), and Lanzhou University (for excavations of 2004 and 2006) (50, 51), all of which had cultural affiliations assigned by the excavators. The vast majority of the original cultural affiliations were determined by stratigraphic position and/or association with pottery. In several cases, direct dates on bone from the present study point to errors in the original cultural assignments, implying stratigraphic mixing, interpretive error, or fundamental problems with the cultural sequence. For this study, direct radiocarbon dates on bone were used to assign samples to either phase 1 or phase 2. Where direct dates were not available, the original cultural affiliation was used.

Phase 1 and Phase 2 designations for this study should not be confused with the stratigraphic age sequence derived from the original excavations at Dadiwan (34, 35): Dadiwan I (Dadiwan, Laoguantai, or pre-Yangshao, 7800–7300 calBP), Dadiwan II (Late Banpo or Early Yangshao, 6500–5900 calBP), Dadiwan III (Miaodigou or Middle Yangshao, 5900–5500 calBP), Dadiwan IV (Late Yangshao, 5500–4900 calBP), and Dadiwan V (Lower Changshan 4900–4800 calBP). Although we did sample one pig (LM-104) dating to the Lower Changshan (assigned originally to Late Yangshao), our analysis does not address this period. Instead, our study compares samples from the phase 1 pre-Yangshao culture (which includes Dadiwan I), to those of the phase 2 Yangshao culture (which includes Dadiwan II, III, and IV). The purpose of this 2-part division was to evaluate change in subsistence systems during the time when agriculture is thought to evolve and spread. Because of the new, calibrated, direct dates on human and animal bone provided by this study, calendar ages for the 2 phases reported here differ slightly from the determinations published elsewhere (34, 35): including 2σ ranges, phase 1 now dates from 7950–7160 (ca. 7900–7200 calBP); phase 2 from 6470–4890 (ca. 6500–4900 calBP).

Several points emerge from the revised dating presented here. First, although we do find a single, isotopically domestic dog (LM-096) predating the earliest recorded Yangshao presence at Dadiwan (CAMS 134426, 6471–6315 calBP 2σ), very few radiocarbon dates from the site fall within this interval. This may represent an isolated, short-term occupation of the Dadiwan site by mobile hunter–gatherers, quite similar to those during phase 1. Second, although the excavators assigned many of the faunal remains tested here to the Late Banpo phase, most were in fact much younger. Together, these points suggest that the site was little occupied during the time of the Late Banpo florescence further east, but was instead occupied later as the bearers of this tradition moved west. It seems that the Late Banpo (or early Yangshao) tradition manifests later and persists longer at the Dadiwan site than it does in the east at sites like Beishouling, Jiangzhai, or Banpo itself. The full complement of direct dates on domesticated dog (LM-087, CAMS 134425), pig (LM-038, CAMS 134371) and millet (CAMS 128457) does not appear at Dadiwan until ≈5800 calBP. Although it is possible all of these domesticates were present at Dadiwan during the early years of phase 2, the radiocarbon distribution suggests otherwise.

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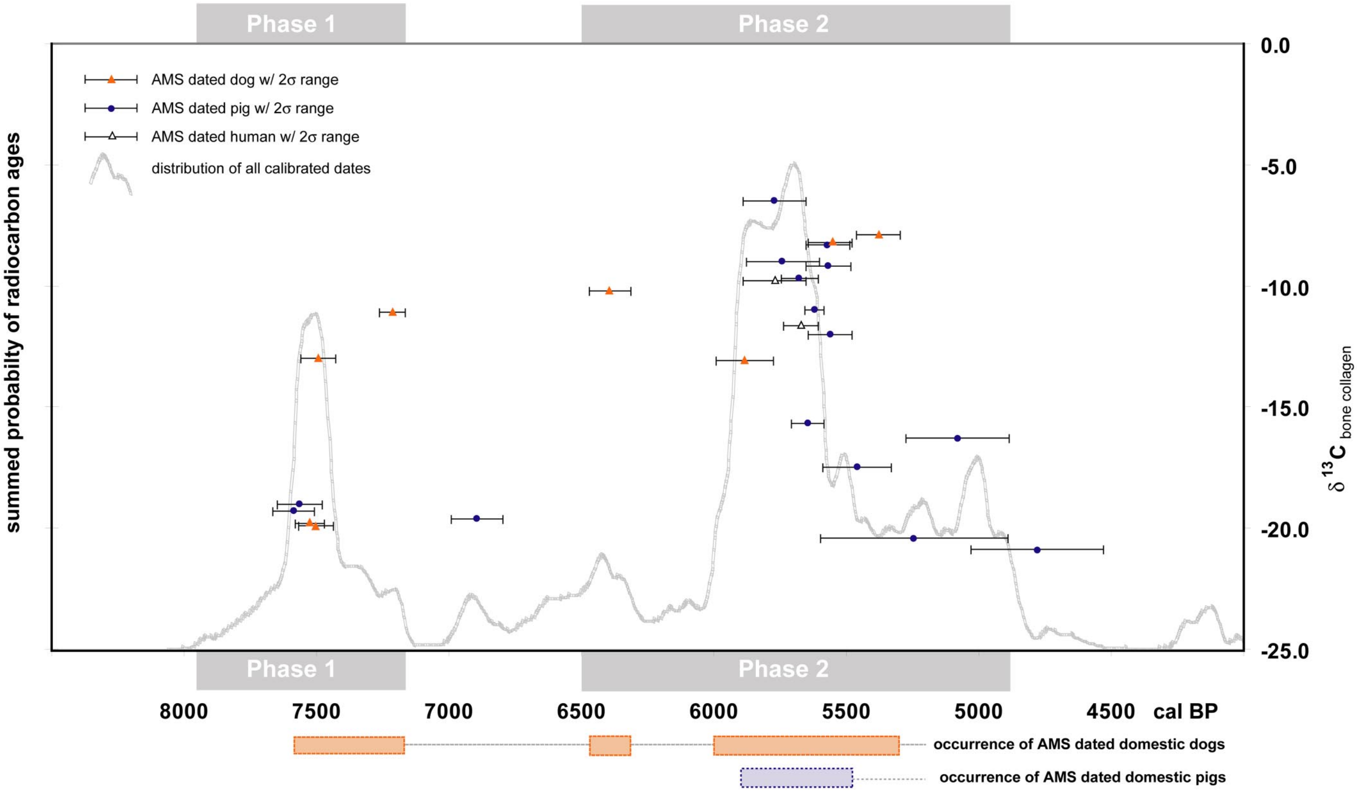

Fig. S1. A radicarbon chronology of domestication at the Dadiwan site. Here, dated samples and their 2σ calibrated ranges are plotted against their associated $\delta^{13}C$ values (right *y* axis), and superimposed on the summed probability distribution of all calibrated radiocarbon dates from the Dadiwan site (left *y* axis).

Table S1. Complete listing of samples (n = 74), taxonomic identifications, cultural affiliations and isotopic data

MS-ID	Taxon	prov	exPhase	^{14}C	anPhase	[C]	[N]	C/N	$\delta^{13}C_{col}$	$\delta^{15}N_{col}$
LM-003	Homo sapiens	M311	LYS		2	47.57	17.67	2.69	−6.6	9.5
LM-004	Homo sapiens	M701	LYS		2	46.02	17.25	2.67	−6.5	10.4
LM-005	Homo sapiens	M318	LYS		2	47.98	17.80	2.70	−14.2	10.8
LM-010	Homo sapiens	H5-A37	LBP		2	48.69	17.34	2.81	−10.0	8.7
LM-011	Homo sapiens	H235-A137	LBP	*	2	46.58	16.91	2.75	−9.8	9.1
LM-012	Homo sapiens	H235-A1	LBP	*	2	47.41	17.11	2.77	−11.6	9.8
LM-020	deer (Moschus)	F229–157	LBP		2	48.88	17.62	2.77	−20.8	5.8
LM-021	deer (Moschus)	F203	LBP		2	46.58	16.91	2.76	−20.9	4.6
LM-023	deer (Moschus)	F229–152	LBP		2	42.78	14.26	2.81	−21.1	6.9
LM-024	deer (Moschus)	F229–33	LBP		2	45.94	16.81	2.73	−20.2	5.6
LM-025	Canis	F361-A3	LBP	*	2	50.20	18.14	2.77	−7.9	7.9
LM-026	Canis	F219-A2	LBP	*	2	43.52	15.85	2.75	−8.2	8.6
LM-027	Canis	F337-A10	LBP		2	44.83	16.37	2.74	−10.7	8.7
LM-028	Sus	H205-A43	LBP		2	48.40	17.50	2.77	−8.5	8.0
LM-029	Sus	F347-A3	LBP	*	2	45.24	16.22	2.79	−15.7	7.2
LM-030	Sus	H325-A78	LBP		2	49.77	18.16	2.74	−8.3	8.4
LM-031	Sus	H345-A1	LBP		2	48.80	17.94	2.72	−14.7	8.5
LM-032	Sus	F223-A1	LBP	*	2	45.11	17.01	2.65	−17.5	6.4
LM-033	Sus	H259-A6	LBP		2	49.01	17.80	2.75	−7.0	7.7
LM-034	Sus	F347-A7	LBP	*	2	43.35	15.84	2.74	−9.7	9.2
LM-035	Sus	H211-A66	LBP		2	49.38	18.04	2.74	−9.0	9.2
LM-036	Sus	F361-A6	LBP		2	49.07	17.94	2.74	−10.0	8.8
LM-037	Sus	H73-A1	LBP		2	47.32	16.69	2.83	−6.3	8.1
LM-038	Sus	F250-A35	LBP	*	2	46.06	16.92	2.72	−6.5	8.6
LM-039	Sus	H211-A46	LBP		2	50.19	18.28	2.74	−8.8	8.4
LM-041	Sus	H211-A62	LBP		2	47.94	17.15	2.79	−11.5	9.9
LM-042	Sus	H211-A68	LBP		2	48.42	17.60	2.75	−12.2	8.9
LM-043	Sus	F246-A12	LBP		2	41.56	14.07	2.95	−9.1	9.1
LM-044	Sus	H211-A14	LBP		2	49.54	18.07	2.74	−11.4	9.6
LM-045	Sus	F361-A7	LBP	*	2	36.04	12.79	2.82	−9.2	8.8
LM-046	Sus	F218-A2	LBP		2	45.74	16.57	2.76	−8.2	9.1
LM-047	Sus	F222-A29	LBP	*	2	28.77	9.95	2.89	−8.3	8.7
LM-048	Sus	H211-A67	LBP		2	45.44	16.50	2.75	−14.9	6.8
LM-049	Sus	F250-A26	LBP		2	44.10	16.08	2.74	−9.0	8.4
LM-053	Bos	H398-A290	LBP		2	28.62	9.32	3.07	−19.9	8.0
LM-058	deer (Cervus)	F250-A34	LBP		2	45.08	16.85	2.68	−21.0	6.4
LM-060	deer (Cervus)	F250-A11	LBP		2	44.58	16.32	2.73	−21.0	7.8
LM-062	Bos	H3100-A10	LBP		2	45.61	16.90	2.70	−22.1	8.1
LM-063	Sus	F382-A28	LBP	*	2	44.30	16.11	2.75	−9.0	8.6
LM-064	Sus	H5-A27	LBP		2	50.16	18.17	2.76	−7.7	7.9
LM-065	Sus	H709-A8	LBP		2	45.94	16.35	2.81	−8.3	8.9
LM-066	Sus	T347-A4	LBP		2	47.39	17.12	2.77	−9.0	8.2
LM-067	Sus	F229–19	LBP	*	2	44.84	16.63	2.70	−11.0	7.8
LM-068	Sus	H253-A12	LBP		2	48.60	17.35	2.80	−12.3	9.3
LM-069	deer (Cervus)	H363-A3	DDW		1	41.88	14.90	2.81	−20.2	7.1
LM-070	deer (Cervus)	H254-A2	DDW		1	40.40	14.67	2.75	−19.4	6.2
LM-075	deer (Cervus)	F310-A3	LBP		2	46.39	16.87	2.75	−18.9	5.6
LM-076	deer (Cervus)	H3114-A10	DDW		1	42.76	15.68	2.73	−20.0	8.1
LM-078	deer (Cervus)	H363-A30	DDW		1	38.86	14.48	2.68	−20.7	7.3
LM-081	Canis	H398-A127	DDW	*	1	48.50	17.54	2.77	−19.9	6.2
LM-082	Canis	H398-A377	DDW	*	1	46.44	17.10	2.72	−19.8	5.9
LM-083	Canis	F103–17	LBP		2	39.25	14.17	2.77	−9.3	9.0
LM-084	Canis	H398-A271	DDW		1	43.58	16.25	2.68	−10.2	7.3
LM-085	Ursus	H398-A310	DDW		1	42.11	15.11	2.79	−17.3	7.0
LM-086	Canis	M224-A1	LBP	*	1	45.45	16.24	2.80	−13.0	8.6
LM-087	Canis	M224-A1	LBP	*	2	44.08	15.77	2.79	−13.1	8.7
LM-089	Bird (possibly Gallus)	H398-A115	DDW		1	43.37	15.90	2.73	−15.6	7.4
LM-090	Bird (possibly Gallus)	F371-A11	DDW		1	44.60	16.37	2.72	−16.8	7.4
LM-091	Bird (possibly Gallus)	H393-A93	LBP		2	44.73	16.27	2.75	−16.2	7.1
LM-092	Bird (possibly Gallus)	H227-A140	LBP		2	43.09	15.84	2.72	−17.6	6.3
LM-093	Bird (possibly Gallus)	H227-A52	LBP		2	41.65	15.18	2.75	−14.2	5.9
LM-094	Bird (possibly Gallus)	H227-A50	LBP		2	43.71	15.87	2.76	−17.2	5.7
LM-095	Bird (possibly Gallus)	H227-A53	LBP		2	43.88	15.71	2.79	−16.2	6.5
LM-096	Canis	H398-A273	DDW	*	2	44.38	16.14	2.75	−10.2	7.5

MS-ID	Taxon	prov	exPhase	^{14}C	anPhase	[C]	[N]	C/N	$\delta^{13}C_{col}$	$\delta^{15}N_{col}$
LM-097	Canis	H398-A275	DDW	*	1	41.88	15.36	2.73	−11.1	7.7
LM-099	Sus	H398-A4	DDW	*	2	45.51	16.46	2.77	−12.0	8.3
LM-101	Sus	H359-A1	DDW	*	2	40.82	14.26	2.86	−16.3	6.2
LM-103	Sus	H363-A66	DDW	*	2	44.74	15.73	2.84	−20.4	5.6
LM-104	Sus	H359-A12	DDW	*	2	42.88	14.72	2.91	−20.9	7.2
LM-106	Sus	uncertain	NA	*	1	43.76	15.39	2.84	−19.6	5.2
LM-107	Sus	H363-A43	DDW	*	1	46.16	16.37	2.82	−19.3	5.3
LM-108	Sus	H398-A215	DDW		1	44.06	15.95	2.76	−19.1	7.0
LM-109	Sus	H398-A147	DDW	*	1	44.05	15.71	2.80	−19.0	5.6
LM-117	Sus	DDW02 4.2B	LBP		2	48.54	17.45	2.78	−8.3	7.6

The archaeological provenience (prov) of each sample is recorded in curatorial lots from the Gansu Museum or Lanzhou University. Because the original excavators determined the cultural affiliation of each provenience (exPhase), each sample can be assigned to a cultural tradition, and therefore has an approximate age range. However the radiocarbon results (SI Table 2) occasionally required that these affiliations be changed. The phases used for the analysis and interpretations (anPhase) reflect these changes. Asterisks identify samples dated directly by radiocarbon accelerator mass spectrometry.

Table S2. New AMS radiocarbon dates on bone collagen from the Dadiwan site

Lab no.	prov	MS ID	rcybp	+/−	2σ mid	2σ +	2σ −
CAMS 134454*	M102	LM-001	1035	35	943	1055	832
CAMS 134455*	F14-A18	LM-009	4950	30	5670	5736	5605
CAMS 134456	H235-A137	LM-011	5010	35	5773	5892	5655
CAMS 134457	H235-A1	LM-012	4950	30	5670	5736	5605
CAMS 134458*	DDW05	LM-013	4955	40	5726	5855	5598
CAMS 134366	F361-A3	LM-025	4620	30	5379	5462	5297
CAMS 134367	F219-A2	LM-026	4835	30	5561	5644	5478
CAMS 134368	F347-A3	LM-029	4895	30	5646	5706	5586
CAMS 134369	F223-A1	LM-032	4760	35	5460	5589	5330
CAMS 134370	F347-A7	LM-034	4965	30	5677	5747	5608
CAMS 134371	F250-A35	LM-038	5010	35	5773	5892	5655
CAMS 134372	F361-A7	LM-045	4850	30	5568	5652	5485
CAMS 134373	F222-A29	LM-047	4855	30	5570	5654	5486
CAMS 134420	F382-A28	LM-063	4970	40	5741	5879	5603
CAMS 134421	F229–19	LM-067	4875	30	5621	5657	5585
CAMS 134422	H398-A127	LM-081	6615	35	7503	7569	7438
CAMS 134423	H398-A377	LM-082	6645	30	7524	7579	7470
CAMS 134424	M224-A1	LM-086	6580	30	7495	7560	7429
CAMS 134425	M224-A1	LM-087	5165	30	5884	5993	5775
CAMS 134426	H398-A273	LM-096	5625	30	6393	6471	6315
CAMS 134427	H398-A275	LM-097	6280	30	7214	7264	7164
CAMS 134446	H398-A4	LM-099	4835	30	5561	5644	5478
CAMS 134447	H359-A1	LM-101	4440	25	5081	5278	4885
CAMS 134448*	H363-A50	LM-102	6390	30	7342	7418	7265
CAMS 134449	H363-A66	LM-103	4620	130	5244	5598	4890
CAMS 134450	H359-A12	LM-104	4240	80	4779	5029	4529
CAMS 134451	Uncertain	LM-106	6050	35	6894	6992	6795
CAMS 134452	H363-A43	LM-107	6720	40	7587	7665	7509
CAMS 134453	H398-A147	LM-109	6690	40	7565	7650	7479

The archaeological provenience (prov) corresponds to locations named during original excavations. $\delta^{13}C$-corrected radiocarbon ages (rcybp) are based on the 5568 Libby half-life. All calibrations are with OxCal 4.0 by using the INTCAL 04 calibration curve. Asterisks denote samples removed from the interpretations presented here, either because the dates are outside our range of interest, or because the stable isotope analysis returned flawed results or no results at all. The Mass Spectrometer IDs (MS ID) correspond to samples presented in SI Table 1.

Table S3. Complete list of known radiocarbon dates from the Dadiwan site

Lab no.	Material	prov	MS ID	rcybp	+/−	2σ mid	2σ +	2σ −	Source/ref.
CAMS 134454	bone collagen	M102	LM-001	1035	35	943	1055	832	This study
CAMS 134379	charcoal	DDW03		3770	35	4117	4245	3990	50, 51
CAMS 134450	bone collagen	H359-A12	LM-104	4240	80	4779	5029	4529	This study
BK 84080	charcoal	F901		4392	100	5022	5315	4729	34
BK 81050	charcoal	F405		4392	80	5064	5288	4841	34
Beta 197628	charcoal	DDW02		4420	40	5072	5277	4867	50
BK 84081	charcoal	F901		4421	100	5075	5313	4838	34
CAMS 134447	bone collagen	H359-A1	LM-101	4440	25	5081	5278	4885	This study
BK 93177	?	F902		4499	80	5155	5436	4875	34
BK 81049	charcoal	F405		4538	80	5175	5464	4886	34
WB 80–50	charcoal	H366		4557	200	5183	5717	4650	34
CAMS 134449	bone collagen	H363-A66	LM-103	4620	130	5244	5598	4890	This study
BK 84082	charcoal	F901		4606	100	5281	5584	4978	34
CAMS 134366	bone collagen	F361-A3	LM-025	4620	30	5379	5462	5297	This study
CAMS 134369	bone collagen	F223-A1	LM-032	4760	35	5460	5589	5330	This study
BK 93180	?	F400		4757	85	5479	5644	5313	34
WB 80–52	?	F17		4761	95	5504	5709	5300	34
BK79027	charcoal	H202		4761	100	5508	5720	5296	34
CAMS 134367	bone collagen	F219-A2	LM-026	4835	30	5561	5644	5478	This study
CAMS 134446	bone collagen	H398-A4	LM-099	4835	30	5561	5644	5478	This study
CAMS 134372	bone collagen	F361-A7	LM-045	4850	30	5568	5652	5485	This study
CAMS 134373	bone collagen	F222-A29	LM-047	4855	30	5570	5654	5486	This study
WB 80–51	charcoal	F330		4854	95	5602	5881	5324	34
BK 93181	?	F411		4854	100	5604	5887	5322	34
BK 93182	?	F709		4868	90	5607	5887	5327	34
CAMS 134421	bone collagen	F229–19	LM-067	4875	30	5621	5657	5585	This study
CAMS 134368	bone collagen	F347-A3	LM-029	4895	30	5646	5706	5586	This study
CAMS 134455	bone collagen	F14-A18	LM-009	4950	30	5670	5736	5605	This study
CAMS 134457	bone collagen	H235-A1	LM-012	4950	30	5670	5736	5605	This study
CAMS 134370	bone collagen	F347-A7	LM-034	4965	30	5677	5747	5608	This study
CAMS 134458	bone collagen	DDW05	LM-013	4955	40	5726	5855	5598	This study
CAMS 128457	charcoal	JB1		4965	40	5738	5875	5601	50, 51
CAMS 134420	bone collagen	F382-A28	LM-063	4970	40	5741	5879	5603	This study
BK 93183	?	F229		4990	140	5751	6173	5330	34
BK 79024	charcoal	H201:20		4995	90	5753	5915	5590	34
WB 80–53	charcoal	F332		5000	90	5754	5917	5591	34
CAMS 134456	bone collagen	H235-A137	LM-011	5010	35	5773	5892	5655	This study
CAMS 134371	bone collagen	F250-A35	LM-038	5010	35	5773	5892	5655	This study
CAMS 128452	charcoal	LY03		5030	35	5778	5895	5662	50, 51
CAMS 128455	charcoal	DDW04		5040	35	5783	5902	5663	50, 51
CAMS 128447	charcoal	DDW03		5080	40	5826	5915	5736	50, 51
CAMS 127100	charcoal	DDW05		5080	30	5828	5910	5746	50,51
CAMS 128456	charcoal	DDW04		5095	35	5832	5917	5747	50,51
CAMS 128454	charcoal	DDW04		5105	35	5835	5921	5749	50, 51
WB 80–32	?	F229		5097	85	5854	6095	5613	34
CAMS 110291	charcoal	DDW02		5145	35	5871	5990	5753	50
CAMS 134425	bone collagen	M224-A1	LM-087	5165	30	5884	5993	5775	This study
BK 79028	charcoal	F400		5090	100	5888	6173	5602	34
WB 80–54	charcoal	F232		5106	90	5894	6174	5615	34
BK 93185	?	F246		5138	120	5901	6189	5614	34
WB 80–30	charcoal	F17		5150	85	5921	6179	5664	34
WB 80–31	charcoal	H227		5170	95	5926	6189	5664	34
BK 79025	charcoal	Y202		5170	150	5947	6277	5616	34
CAMS 110292	charcoal	DDW02		5195	40	6034	6174	5893	50
BK 93176	?	F714		5374	160	6122	6491	5753	34
ZK 0742	charcoal	Trench 301.2		5520	90	6261	6501	6020	34
CAMS 134426	bone collagen	H398-A273	LM-096	5625	30	6393	6471	6315	This study
BK 79029	charcoal	Y300		5620	80	6457	6630	6283	34
ZK 2219	plaster/ash paste	F405		5730	110	6539	6775	6302	48
ZK 2220	white ash	F415		5780	85	6593	6785	6402	48
BK 93178	?	F820		5860	150	6734	7152	6317	34
CAMS 134451	bone collagen	?	LM-106	6050	35	6894	6992	6795	This study
CAMS 134427	bone collagen	H398-A275	LM-097	6280	30	7214	7264	7164	This study
?	charcoal	H363		6474	165	7336	7665	7007	49

Lab no.	Material	prov	MS ID	rcybp	+/−	2σ mid	2σ +	2σ −	Source/ref.
CAMS 134448	bone collagen	H363-A50	LM-102	6390	30	7342	7418	7265	This study
CAMS 134375	charcoal	DDW03		6465	35	7371	7435	7308	50, 51
BK 80007	charcoal	H363		6540	90	7428	7579	7277	34
BK 81021	charcoal	H398		6579	80	7457	7592	7323	34
CAMS 127099	charcoal	DDW04		6580	30	7495	7560	7429	50, 51
CAMS 134424	bone collagen	M224-A1	LM-086	6580	30	7495	7560	7429	This study
CAMS 128453	charcoal	DDW04		6595	35	7498	7566	7431	50, 51
CAMS 128450	charcoal	DDW04		6615	40	7503	7570	7436	50, 51
CAMS 134422	bone collagen	H398-A127	LM-081	6615	35	7503	7569	7438	This study
Beta 197626	charcoal	DDW02		6650	40	7515	7587	7444	50
CAMS 134423	bone collagen	H398-A377	LM-082	6645	30	7524	7579	7470	This study
CAMS 128451	charcoal	DDW04		6685	35	7550	7612	7489	50, 51
BK 81024	charcoal	H397		6690	80	7553	7671	7435	34
CAMS 134453	bone collagen	H398-A147	LM-109	6690	40	7565	7650	7479	This study
CAMS 134452	bone collagen	H363-A43	LM-107	6720	40	7587	7665	7509	This study
BK 81022	charcoal	F371		6740	80	7587	7731	7444	34
CAMS 134374	charcoal	DDW03		6860	50	7705	7819	7592	50, 51
BK 80025	charcoal	H10		6950	90	7786	7950	7622	34

The archaeological provenience (prov) corresponds to locations named during original excavations. Radiocarbon data from the original excavations are drawn from the excavation report (34) and the radiocarbon database of the Institute of Archaeology, Chinese Academy of Social Science (48). Additional information can be found from each reference. Question marks indicate data gaps. Unreported sample types (material) are most likely charcoal. It is unclear how many of the dates from the original excavation were δ^{13}C-corrected. Though use of the 5570 half-life is standard procedure in Chinese radiocarbon labs, all radiocarbon ages (rcybp) This study reflects the 5568 Libby half-life. All calibrations are with OxCal 4.0 using the INTCAL 04 calibration curve.