Landscape of loess, millets and Boar: The environmental contexts of early cultivars in northern China

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Abstract

We reconsider the environmental backgrounds of early millet cultures in northern China that predate the Yangshao period (before ca. 5000 BC). Interactions among soils, millets, pigs and changing regional climate conditioned multiple early cultivation traditions. Vegetation changed in relation to Holocene climate that influenced the availability of wild millets versus other storable plants like tree nuts. Early millet cultivators were located in ecotone regions between sparser woodlands and steppe, incorporating local micro-environments that would have suited wild millets, and acquisition of wild boar that became domesticated as they were moved into newly sedentary settlements. Diverse local hydrological and soil conditions shaped different regional trajectories and multiple pathways to millet domestication. The search for agricultural origins in China needs to adopt a multi-centric geography and a paradigm of "protraction and entanglement" rather than pursuing a single origin. The pre-Yangshao cultures reviewed here appear to be in stages of increasing landscape management, the pre-domestication cultivation of millets, and with varied commitments to pig management. However, this does not entail that each cultural trajectory followed through to eventual millet domestication and full agricultural economies, and we expect various intermediate economies, some of which may have been dead-ends in agricultural origins.

Keywords: loess, millets, boars, northern China, pre-Yangshao period, domestication

1. Introduction

Recent research in different parts of the world has demonstrated multiple pathways to agriculture in a variety of local micro-environments. Agricultural origins in many regions experienced protracted episodes of change in human economies and the species that were domesticated (Asouti and Fuller 2013; Clement, et al. 2015; Fuller, et al. 2014; Riehl 2016; Smith 2015). Domestication was not rapid but took millennia (2000-4000 years) (Allaby, et al. 2017; Fuller, et al. 2021; Tanno and Willcox 2012). Similarly, *domestication* is not the same as *agriculture,* which indicates a change in the degree of reliance on food production and a shift in the scale of environmental impact and landscape modification (Belfer-Cohen and Goring-Morris 2011; Smith 2015). Rather than a single directional trend from foraging and gathering wild foods to food production of domesticated species, archaeology of western Asia suggests that a mosaic of "intermediate economies" (*sensu* Harris 2012) existed for millennia during which technology, economy and the genetic adaptations of species were ultimately changed piecemeal (e.g., Fuller, et al. 2018); similar mosaic patterns have been inferred for the Neotropics (Clement, et al. 2015), eastern North America (Smith

2015) and tropical India (Fuller and Murphy 2018). Instead of thinking about *a centre* of origin in which the whole process of agricultural origins took place, the evidence may better be understood as a mosaic of coevolution (*sensu* Thompson 2005) in which hot-spots of change for domestication and agricultural economy co-existed with cold-spots and local abandonments, but that exchange, both in terms of gene flow (Allaby, et al. 2017; Feldman and Kislev 2007) and technological exchanges (Watkins 2008) would have pushed regional meta-populations into domesticated species and into cultures of agriculture (Maeda, et al. 2016). For instance, recent large-scale genomic analyses of domesticated and wild populations of emmer wheat (Civan, et al. 2013) and barley (Poets, et al. 2015) indicate the signature of a multicentric mosaic in the domestication of both crops, while ancient genomes of maize suggest that its domestication was both temporally and geographically stretched out (Kistler 2018). A single centre of domestication is increasingly at odds with the data for several crops.

Nevertheless, many general treatments of the agricultural origins in China posit single origins for millet agriculture or even millet and rice together. Several scholars have attempted to draw parallels with western Asia by, for example, suggesting that the Younger-Dryas might have initiated rice agriculture (e.g., Bar-Yosef 2011; Bellwood 2005; Zhao 1998). Cohen (1998) further speculated that early Holocene spread of rice farming inspired millet domestication by the Peiligang culture in more northerly areas less suited to rice. Similarly, a single origin of farming has been postulated for regions between the Yellow and Yangtze rivers where wild foxtail millet (*Setara italica*) and rice (*Oryza sativ*a) overlap (Bellwood 2005: 118-119). More recently, Bar-Yosef (2011) has argued that millet cultivation in northern China should begin earlier, as an adaptation to more marginal environmental conditions, and taking into account more recent archaeobotanical evidence for the late (mid-Holocene) domestication of rice, with rice cultivation instead being inspired by the southward spread of millet farming. General treatments of Chinese plant domestication tend to accept separate northern millet and Yangtze rice origins (e.g., Zhao 2011), but research has focused on which of the pre-Yangshao culture of northern China really domesticated millet rather than questioning how similar or different these various cultural traditions really were (see Chen and Yu 2017; Liu and Chen 2012). The evidence for rice domestication now clearly indicates at least *two* distinctive regional trajectories to domestication, perhaps in the later early Holocene in the middle Yangtze, or its tributaries such as the Han River, and firmly in the middle Holocene for the Lower Yangtze (Deng, et al. 2015; Stevens and Fuller 2017). So does the model of a rapid, single centre of origins still appear relevant for Chinese millet agriculture? Bettinger et al (2010) argued that millet lent itself to a rapid domestication, as a storable food for mobile hunters and their hunting dogs, in contrast with other cereals like rice and wheat, but does empirical evidence support this? Fuller et al. (2016) questioned whether domestication traits of millet would have evolved under such circumstances and suggested instead that expanding woodlands, and increased availability of pigs may have been linked to a shift to sedentism and increased investment in cultivation, but does either palaeo-environmental or archaeological evidence support this, in some or all cases? Shelach et al. (2019) reported evidence from northeast China that the sedentism of the Xinglongwa culture emerged from 8100BP as the climate became wetter and involved cultivation of *Panicum miliaceum.* Compared to a rapid transition to sedentism, they emphasize that plant domestication took several millennia, further calling for reassessing the diverse trajectories to cultural processes and agriculture within and between different culture regions of prehistoric China.

There are three key elements in the emerging picture of comparative agricultural origins: protracted domestication, variable commitment across sites to various food production related practices, and feedbacks, or entanglements, between ecologies, species adaptations and human practices (Fuller, et al. 2016; Hodder 2018). Protraction and entanglement both reconceive the origins of agriculture not as a revolution but as an extended evolutionary process of niche construction (Fuller and Lucas 2017; Watkins 2017; Zeder 2016), in which both humans and other species progressively adapt to the ecologies they have inherited through the actions and adaptations of previous generations. In this framework the evidence from Southwest Asia has highlighted how the earliest sedentism is not directly tied to cultivation or commitment to a diet focused on food production, but clumps of reliable and sustainable plant resources (e.g., Asouti and Fuller 2013; Rosen 2013; Savard, et al. 2006; Shennan 2018). Also in this context social-economic investment in settlements and surrounding land would have facilitated various experiments with cultivation, that if sustained for many centuries led towards domestication, and sometimes to agricultural economies. Beyond just documenting the emergence of millet cultivation and domestication, we need to develop a framework for the ecological "domus", to borrow a phrase that Scott (2017) has applied to the West Asian Neolithic, and consider how animals (pigs and dogs), landscapes, including anthropogenic impacts and soil management, were linked to both regional palaeo-environmental context and foci of plant exploitation.

This article aims to lay the groundwork for rethinking the emergence of agriculture across northern China, based on domestication of millets (*Setaria italica, Panicum miliaceum*) and pigs (*Sus scrofa*) in terms of entanglements between changing human practices, the ecologies of targeted subsistence species, and environmental circumstances that were responding to both climate and human action. This article flags up likely entanglements between sedentarization, millet domestication, and pig-keeping in pre-Yangshao cultures (7th-6th millennia BC) of northern China, including the Dadiwan/Laoguantai, Cishan, Peiligang, Houli and Xinglongwa in broader defined geographic zones of Western Loess Plateau (WLP), Central Loess Plateau (CLP), North China Plain (NCP), Shandong, and the Liao River (Figure 1).

<Figure 1>

Focusing on the ecological diversity for early farmers during the pre-Yangshao period, we examine three lines of evidence: local environmental conditions, including climate and soils, millet ecology and exploitation, and ecology and exploitation of wild boar. By considering how these variables interact on different temporal and spatial scales, and in the specific contexts of each pre-Yangshao cultures, we develop new insights into how early millet cultivation traditions are likely to have flourished or failed across northern China. We first introduce the environmental parameters, including soils, climate, vegetation and inferred wild millet ecologies. Patchiness in wild resource distributions is emphasized as a trait that could encourage territoriality and cultivation (see Rosenberg 1998). The second part reviews recent discoveries of botanical and faunal remains in different regions and plots them onto a map relating these discoveries to the local environments. The third part considers correlations and inferred interactions of these variables.

2. Asian monsoons, loess and vegetation

Spatial and temporal variations of Asian monsoons play a decisive role in the shaping of natural landscapes of northern China. The early Holocene climate was dominated by an improved precipitation regime compared to the late Pleistocene, but with pronounced oscillations (An 2000; Chen and al. 2015; Wang, et al. 2005; Wu, et al. 2012; Zhang, et al. 2011). The latter has a deep effect in the shifting of ecotones in areas along the moving boundaries of the monsoons. We consider the relevance of shifting vegetation zones to wild millet availability before turning to related soil parameters.

2.1 Vegetation on regional and local scales

In broad vegetational terms northern China is the transition zone from the broadleaved temperate deciduous woodlands (rainfall >500mm) to the open grasslands of the steppe (rainfall <500mm), and the semi deserts of the northwest (Figure 2). The intermediate zone of parkland and its ecotones would have shifted geographically in response to Holocene climate changes. These are also areas where limits for rain-fed agriculture (~300mm) have been pushed back and forth. Within the open parkland habitats both wild *Setaria* and wild *Panicum* can be expected to have been more widespread than in either the heavily wooded zones or the open steppe.

<Figure 2>

While debate persists on whether true wild populations of *Panicum miliaceum* still exist (Stevens, et al. 2021; Xu, et al. 2019), the wild progenitor of foxtail millet is well established as *Setaria viridis*. Genetic analyses by Huang et al. (2014) indicate that it is Chinese *Setaria viridis* rather than those from elsewhere in Eurasia that have contributed the most to the genetic makeup of domesticated foxtail millet. More focused studies of Chinese germplasm indicate origins along the broad zone stretching from Gansu in the west and Chifeng in the Northeast (Jia, et al. 2013). Nevertheless, some caution is warranted with regards to whether modern *Setaria viridis* is entirely identical to that of early Holocene because weedy forms of *Setaria viridis* have probably evolved through occupying anthropogenic habitats with gene flow from cultivated populations. When modern wild populations are plotted on a map of potential vegetation zones, these are focused on the ecotone from the mixed deciduous forest zone and the steppe, mostly 400-600mm rainfall (Figure 2). This suggests that is around this ecotone, wherever it has shifted in the past, that initial foxtail millet cultivation ought to be sought. Recent genetic analyses suggest that weedy *Panicum miliaceum* var. *ruderale* includes population descended from the wild progenitor as well as feral forms originating from the domesticated *miliaceum* (Xu, et al. 2019). However, as modern occurrences are largely in anthropogenic/arable habitats this provides a poor analogue for the original habitats from which wild *Panicum miliaceum* was exploited by hunter-gatherers. As *P. miliaceum* is marginally more drought tolerant than *Setaria italica* (Dong and Zheng 2006) its origins might be sought somewhat further north into the steppe zones (to ca.300mm rainfall), with wild *Setaria* extending further south.

In more southerly wooded zones, dominated by trees such as oak, *Philodendron* and so on (cf. Li et al. 2011), millets would have been precluded from all areas with closed canopies, only focused instead on rare openings such as river valley margins. Also in the open grassland steppe, we expect these ecosystems to be dominated by non-millet grasses (*Stipa* spp. (tribe Stipeae), *Hordeum brevisubulatum* (tribe Triticeae), etc.), together with some sedges (*Carex* spp.), small shrubby legumes, drought tolerate shrubby Chenopodiaceae such as *Kochia,* and woody subshrubs like *Artemisia* (Wang 1961*).* One thing that is striking about this flora is the general absence of Panicoidae (millet grasses) and C_4 grasses or sedges. Thus, while the ecotone zone is where millet origins should be sought on more local scale wild millets likely never formed extensive stands but occurred as islands of wild millet in a sea of C_3 steppic grasses (Stipeae, Triticeae, Aveneae). This makes millets different than the large stands of wild cereals known to occur in the cases of wild wheat and barley (Hillman 1996), African sorghum (Harlan 1992), or wild rice (Vaughan, et al. 2005).

Pollen as main source of vegetation reconstruction does not provide direct evidence for the presence of millets among the grasses. Other wild pollinated taxa must be taken as proxies for the woodland and steppe areas. Two prominent wind-pollinated taxa are the suffrutescent *Artemisia*, associated with the more open steppe, and oak trees (*Quercus)* that feature prominently in better watered and forested zones. Figure 3 sketches out general trends of the abundance of *Quercus* and *Artemisia* pollen in northern China and its adjacent areas. The changing ratios of these two species show a positive relationship with other monsoon proxies and provide a proxy for the shifting frontier between more wooded and more open habitats, the ecotones where millets are probable. Some of the better known pre-Yangshao cultural sites fall right on the edge of the deciduous woodland zone, where 5-10% *Quercus* pollen frequency overlaps with ~30% *Artemisia.* We would suggest where wild millets would have occurred most often, at least in local patches. Actual vegetation patterns would be more scattered, as they are complicated by local soil and hydrological conditions, but the broad patterns in pollen evidence allow for the following hypotheses with regard to the distribution of small seeded-grasses, including millets, versus edible tree nuts, such as acorns (further details in Table S1).

On the Loess Plateau, vegetation was dominated by herbaceous plants in the early Holocene, but in lowland areas and valley bottoms, forests characterized by broad-leaved trees started to grow, facilitated by increasing precipitation. Such woodlands would have offered increased availability of nut foods. At Dadiwan in the WLP, tree pollen density falls sharply 7,600-7,000 cal. BP and is dominated by conifers. But this conifer-forest expansion is periodic, and herbaceous plants remained dominant throughout the time. This would have been the ecotone with steppe, where millet would be expected.

<Figure 3>

On tablelands of the CLP, dry grassland prevailed between 8,800-5,600 cal. BP. Thus it would have been lowlands, with more trees, that were more attractive to early farmers who continued to gather and hunt (e.g., *Quercus* and *Castanea*). In the Peiligang culture of southern NCP, in addition to the predominant herbaceous plants, ferns appeared during 8,500-7,000 cal. BP; and despite low percentages, many of the arboreal species were of high potential for plant food exploitation. At the Beifudi site in northern NCP, a sparse mixed forest was the main vegetation type, comprised of trees and many grassy species during 8,000-7,800 cal. BP. From 7,800 to 7,400 cal. BP, the percentage of conifer pollen and drought-tolerant taxa pollen decreased, while pollen indicative of early land clearance appeared. This implies that, despite the absence of archaeobotanical evidence for local cultivation, cultivation was likely widespread on a regional scale. Also, pollens of wet habitat taxa increased, which would imply increased micro-habitats for wild millets on the distal edges of wetlands..

In west Shandong, pollen cores show a typical forest-grassland vegetation dominated by herbaceous plants, with percentages of arboreal plants steadily increasing from ca. 9,200-7,500 cal. BP, but with more local variations and short-term fluctuations. This might have been partly related to the well-developed lakes and oxbows in this area which were important niches for sub-tropical plants with their relatively better hydrological conditions probably including wild rice (*Oryza rufipogon*). These wetlands were places that attracted early Neolithic people.

The last area of concern is the Xinglongwa culture area of the western Liao River. In this transitional landscape from the loess area to the steppes, the early Holocene vegetation is a mixture of temperate deciduous broad-leaved forest and steppe-grassland (Table S1), especially during a wetter period that occurred ca. 8100-7900BP that lasted for c.400 years before it became drier again (Shelach-Lavi, et al. 2019). Forest further advanced and expanded during the middle Holocene, taking over some previously desertic areas.

2.2 Loessic environments

When the Asian summer monsoons are strengthened, loess accumulation is reduced and soil formation is promoted, *vice versa* when the Asian winter monsoon becomes dominant. The loess deposits are thickest and most continuous on the CLP (Figure 1). Such loess-mantled landforms are gradually broken up into smaller pieces of land (He, et al. 2004)). These mosaic-like loessic landforms are linked to the lowlands via loessic slopes. In the eastern part of its distribution area, reworked loess, mainly carried by the Yellow River water, comprises the building blocks of the massive NCP and the Liao River (Liu 1985). Often the late-Pleistocene loess is deposited on the hillslopes or mountainous regions, alternating with colluvial materials.

Due to its relatively coarser particles (normally silt-sized) and thick deposition, the loess in the CLP promotes deep penetration of groundwater. The good porosity of loess allows abundant fluid water to be held. Often well-preserved palaeosols serve as local aquifers, providing enough water for plants with deep rooting abilities. Although it is well known that loess is vulnerable to erosion, the abundant grassy plants which are pre-adapted to surface disturbance may develop resistance to erosion. Thus, loess and the grassy plants play a crucial role in maintaining the equilibrium of local ecosystems. In other areas where loess deposition is not as thick, the situation of groundwater is more complicated. Next to river floodplains where the groundwater level is constantly high (e.g., the Yuezhuang site of the Houli culture, Zhuang, et al. 2013a), the horizons rich in fine particles become hard when they are dry and serve as effective aquifers. Plants prosper here. But the situation changes radically when it moves to upper catchments of the rivers. The typical fluvial deposits consist of reworked loess and very coarse materials. Groundwater runs out of local geologies in the form of springs. This results in a minimal surface vegetation cover and an ecosystem vulnerable to aridity. In the areas marginal to the loess zone, represented by Xinglongwa, the deposition of loess is quite scare, the topsoils are very thin, lacking rich organic matter, and the river systems are not as well developed as in other regions. These lead to the concentration of water resources in the foothills. Because of these characteristics, the vegetation is largely grasslands, and is extremely sensitive to disturbance; a problem that would have also been faced by the early millet farming communities (see below).

2.3 Ecological importance of loess to millet farming

Loess has long been considered fertile ground for early farmers in European loess zones and in the CLP (Catt 2001; Gregg 1988; Ho 1969; Pulleman 2002; Sherratt 1980; Shiel 1999). It has a vertical uplifting property that prevents waterlogging and its windblown genesis provides sufficient nutrition for sustainable prehistoric farming practices without the need for intensive manuring (Liu 1985; Sui 2007). The two most important favourable properties of loess are: abundant calcium carbonate and many other mineral elements (e.g. K, Ca, Mg and S) (Blumler 1994; Connor, et al. 2011) in the form of water solution travelling through the aggregate and thus facilitating direct nutritional uptake of plants; and aggregate stability that benefits long term cultivation (Pulleman 2002). Abundant exchangeable calcium forms a chemical compound of organic molecules, clay minerals and Ca-humates in high pH conditions, which are resistant to further decomposition and thus serve as an "efficacious stabilizing agent" for organic matter (Schaetzl and Anderson 2005, 354-355). In addition, excremental granules coalesced with fine materials are often found in loessic soils (Zhuang et al. 2016), which help to maintain soil aggregate stability because of the linkage of clay colloids and aggregates provided by Ca^{2+} and humus (Connor, et al. 2011, 175).

In the CLP with low precipitation limits organic leaching and stratification of the profile, and leaves an abundance of mineral nutrients in a highly available condition. This humic nutrient-rich condition is mainly responsible for the crumb structure (Allison 1973; Mellor 1986) beneficial to farming. The relatively low rainfall in the CLP also compensates for the lower efficiency of grass-dominant vegetation, compared to tree/litter conditions, in providing constant organic matter. The use of fire would have also accelerated the bio-cycling of organic matters into pedogenetic processes by releasing bases otherwise trapped in top horizons (Schaetzl and Anderson 2005, 358). As millet cultivation might have required fallows every third year (Ho 1975, 49-54) likely involving burning, we can expect regular bio-cycling in this zone. Studies of micro-charcoal from the CLP suggest that natural wild fires were more frequent during the early Holocene, 12000-8500 BP, facilitated by more open, steppic vegetation (higher in *Artimesia* and C3 grasses) whereas fires decreased through middle Holocene as woodland expanded (Huang, et al. 2006; Tan, et al. 2015). These wildfires were likely concentrated in spring, prior to the summer rains when millet would grow or be sown. The earlier period would have therefore naturally promoted conditions conducive to millet cultivation—open, nutrient cycled soils, that early cultivators could take advantage of. Later through the middle Holocene more localized fires are likely to have been anthropogenic efforts to acquire more land for cultivation, an indicator of increasing human management of the landscape for the purposes of cultivation.

Another critical factor influencing crop yields in loess areas is water efficiency (Fitter and Hay 2002; Yang and Shao 2000). Ho (1975) suggested that moisture availability would have been a limiting factor on productivity, with better watered loess soils requiring less frequent fallow (e.g. 1 in 3 years) whilst drier conditions required more frequent fallow (e.g. 1 in 2 years). Loess is very homogeneous in porosity (Schaetzl and Anderson 2005), which improves its water retention ability and conductivity (He and Tang 1999); whereas the clay-rich Bt horizons and/or CO_2 re-precipitation Ck horizons result in perched water. The zone between the ground surface and the perching layer is a functional water layer that facilitating plant growth. Nonetheless, threshold correlation values between soil moisture and effective water may exist (Li 2006; Veihmeyer 1972). This is confirmed by studies of the relationship between winter wheat and water efficiency in the same area, indicating deep soil water is hardly used for the growth of wheat (Li and Zhang 2000). Such circumstances favour the shallower rooting, small-grained millets (cf. Weber, et al. 2010).

3. The archaeobotany of millet domestication: a working summary

Where and when early millets were cultivated as opposed to gathered, and over what period the domestication process of millet took place remains controversial, but there has been some progress. Two issues should be addressed. First, where *Panicum* and/or *Setaria* were cultivated initially within their wild distribution. Second, whether evidence for morphological change indicating domestication processes (which imply cultivation) is evident. The admittedly limited archaeobotanical data suggests that *Panicum miliaceum* more often dominates over *Setaria italica* in most pre-Yangshao cultures (Qin 2012; Stevens and Fuller 2017), although *Setaria italica* may have been more important within the Peiligang culture (Bestel, et al. 2018) and *Setaria* appears to have been the cereal at Donghulin near Beijing. The Donghulin site (ca. 9000-7000BC) produced seed remains dominated by Chenopodium, Phelodendron and wild grasses like *Poa,* consistent with an ecotonal setting between the oak woodlands and steppe zones. The majority of the 25 *Setaria* grains are of typical wild *Setaria viridis* shape (length:width ratio); but some are of plumper shape, like *Setaria italica,* although still smaller than later-period *Setaria* (Zhao, et al. 2020). This implies an early stage of pre-domestication cultivation selecting for shape change for at least some of the foxtail millet (Figure 4). More ephemeral evidence of millet processing and consumption indicates that wild millets (*Setaria* and *Echinochloa* spp.) were among the resources already exploited by late Pleistocene foragers in some regions, for example at Shizitan (Bestel, et al. 2014), and evidence from starch grains and phytoliths has been offered to suggest some early Holocene cultivation in the northeast CLP (e.g., Yang, et al. 2012), although the credibility of cultivation as opposed to gathering is still debatable. Nevertheless, the starch evidence must be seen alongside the grain evidence as suggestive of pre-domestication cultivation of *Setaria* at Donghulin, even if this was not the apparent staple food resource.

Domestication of millets, as with other well-documented cereals, would have involved morphological changes, including loss of natural seed dispersal and grain size increase (Fuller, et al. 2014; Harlan, et al. 1973). Wheat, barley and rice all suggest processes of 2000-3000 years for the evolution of non-shattering, 3000-4000 years for change in grain size, with both traits potentially preceded by a more elusive lead in early pre-domestication cultivation. Recent data on Chinese *Panicum miliaceum* (Stevens et al. 2021) suggests initial gradual change of grain shape and size, followed by a more rapid increase (Figure 4), a pattern similar to African Pearl millet (Fuller, et al. 2021). There is a marked shift towards fatter grains (lower L:W ratio) from 8000-7000BP, followed by a longer period of continued grain enlargement but also increased variability between sites upto ca.5000BP. The period of marked L:W ratio change (also characteristic of domestication in wheat, barley and rice) can be inferred to be taking place during entrenched pre-domestication cultivation (*sensu* Fuller, et al. 2018), alongside evolution of non-shattering. In the case of *Panicum miliaceum* this appears to be in the 6th millennium BC (8000-7000BP) in both the southern CLP and the Liao Basin. Later continued grain size improvement took place amongst early domesticated forms, as indicated in Yangshao period *Panicum miliaceum.* A similar stage for *Setaria italica* shape change may extend back earlier to the period of Donghulin but was widespread by the 6th millennium BC.

<Figure 4>

Pre-Yangshao periods did not have what could be regarded as fully domesticated millets, but those undergoing domestication with human groups carrying out routine cultivation. The pre-Yangshao cultures can be regarded as falling in the pre-domestication stage as recognized in other regions (Fuller, et al. 2018; Harris 2012). How much earlier, if at all, such cultivation might have begun remains elusive, and it seems reasonable to assume the emergence of these regional pre-Yangshao cultures was correlated with increased commitment to cultivation, i.e. the entrenched stage, which tends to see intensified selection for domestication traits (Allaby, et al 2017; Fuller, et al. 2018). Soil working tools are commonly found in pre-Yangshao cultures and there is also widespread evidence of stone harvesting knives at some pre-Yangshao and Yangshao culture sites (Stevens and Fuller 2017; Wang 1988).

In contrast, archaeobotanical data from the Yangshao period (7,000 - 5000BP) and the contemporaneous Dawenkou period is widespread and extensive, and unambiguously indicates agricultural economies dominated usually by *Setaria italica*, with second place taken by *Panicum miliaceum* (Jin, et al. 2016; Lee, et al. 2007; Stevens and Fuller 2017). Grain size continued to evolve to larger forms over the course of the early-middle Yangshao period (Figure 4), suggesting that evolutionary processes that began during domestication before 7000BP but continued to improve grain weight and crop yield to a point of maximization around 5000BP for *Panicum miliaceum* (Stevens, et al. 2021). Data for *Setaria italica* also suggests a similar pattern. The dominance of millets and sometimes small amounts of rice (*Oryza sativa*) adopted from the south ca.6000BP makes it clear that that the economy can be regarded as agricultural, dependent in the main food production from the early Yangshao period; prior to this we may have intermediate economies in which gathered and hunted resources were equally or more important.

Millets are more efficient than wheat and many other plants in absorbing water from soils (Dong and Zheng 2006; Weber, et al. 2010) (Table S2). In addition to advanced rooting ability, the drought-tolerance of millets is well illustrated by their physiological microstructure – their protoplasm has high hyrophilicity and strong hydration (Dong and Zheng 2006). They are also well-suited to wind-borne sandy environments and poor soils (Dong and Zheng 2006, 335). In extremely dry years, they are also able to mature about two months, a considerable advantage compared to many other crops (de Wet, et al. 1983), especially during drought spells. This explains why millets, especially broomcorn millet, were cultivated in areas like the western Liao River and WLP.

At both Yuezhuang and Xihe in Shandong, a wide variety of weedy plants were found in the archaeobotanical assemblages, primarily composed of two types of grasses: *Echinochloa crus-galli*, and Paniceae grasses indicative of wet habitat; and *Setaria* sp., *Eleusine* sp., common grasses in drylands (Crawford 2011; Jin 2011). Such a co-existence of dryland and wetland weeds is also seen at other sites. At Xinglongwa location I in the western Liao River, wild seeds account for more than 80% of the 10,000 charred grains (Zhao 2006), belonging to plants indicative of upland dry and well-drained conditions (e.g., *Cerastium glomeratum, Chenopodium,* both edible) and plants growing in lowland wet soils. Pre-farming land clearance may have created a man-made habitat on the hillslope areas around the settlement favourable for the growth of both crops and weedy plants that were gathered for food. Meanwhile, the management of low-lying land (e.g., for gathering or other activities) was simultaneously practiced, bringing plants to the site. It is less clear what role wildfires might have played in this region, but as with CLP this is expected to have been more frequent in the early Holocene and more targeted and anthropogenic from the Yangshao period.

Other pre-Yangshao weed assemblages are dominated by seeds from the Chenopodiaceae, Paniceae and other open, steppic indicators (Song 2011). These plants have fruiting times spanning from summer to autumn (June to October), with the majority probably fruiting and being harvested in August (Song 2011), in accordance with the proposed growing season of millets in northern China.

4. Pig husbandry and environments

It seems clear that pigs were domesticated by the Yangshao period (Cucchi, et al. 2016; Hongo, et al. 2021; Wang, et al. 2015). At many sites they represent a sizable minority (20-30%) of meat consumption, alongside continuing importance of hunted game like deer (Liu and Chen 2012; Yuan and Campbell 2009; Yuan and Flad 2002), while at a few sites they may account for as much of 70-80% of mammal bones (Song 2012).

Pigs are well known for being adaptable to different kinds of environments as generalized omnivores (Albarella, et al. 2006). Wild boars eat plant roots and stems, fruits, grasses, insect larva and carrion, and so forth (Bösl, et al. 2006; Hu, et al. 2009; Wang, et al. 2002). However, pigs cannot adapt to hot and dry climates (Wang 2011), a factor that could have affected prehistoric pig husbandry strategies. *Atlas of Boar Species in China* lists nine subspecies of boar in China, with wide-ranging geographic locations (Luo 2007, 73). However, despite the widespread geography of wild boars, mitochondrial DNA data suggest it was only one main clade that has contributed to domesticated pigs in China (Larson, et al. 2010). Most wild boar populations did not contribute to domestication. This is contrary to the situation in Europe, where domesticated pigs were introduced from Anatolia in the Neolithic but gradually became swamped by local European wild boar genotypes through interbreeding and the capturing of wild females or their litters (Larson, et al. 2007). In Chinese pigs there is some evidence for introgression from wild males into domesticated populations (Ji, et al. 2011), a process that can be expected at Neolithic frontier settlements, but the female domesticated line remained consistent. This highlights a very different pattern of pig-keeping in Neolithic northern China, which was focused on keeping pigs within settlements rather than allowing them to range into woodlands. Pigs as household animals and household waste disposers is also indicated by the stable isotopic evidence that most pigs had millet-rich (C_4) diets and that these diets became increasingly like local humans throughout the Yangshao and Longshan periods (Cucchi, et al. 2016; Hongo, et al. 2021).

Zooarchaeological evidence for domestication remains disputed, but it has generally been suggested that some pigs with domesticated morphology (smaller size) and managed culling patterns (higher levels of immatures) are to be found in pre-Yangshao cultures, including Xinglongwa, Cishan and Dadiwan (e.g., Barton, et al. 2009; Hongo, et al. 2021; Yuan, et al. 2008). Currently there is evidence related to various aspects of this relationship: morphological changes brought about by domestication as an evolutionary process, human management brought about by a shift in human behaviour, including culling patterns and feeding with a human-like, millet-enriched diet (presumably from scraps), and phylogenetic evidence for derivation of particular wild lineages that became the widespread domesticated groups of pigs.

Morphological changes resulting from prolonged breeding under human control may under-estimate the beginnings of this relationship, much as morphological domestication in plants marks the end of an evolutionary process. Traditional evidence for this mainly includes size reduction in pigs, indicated by average tooth measurements (e.g. molar M_3), and potentially tooth crowding. As these are population level variables, larger sample sizes and time series data are needed to interpret them. In addition, size variation in wild boar populations must be accounted for, with boars tending to be larger as they move north (following Bergmann's rule). Thus time series should be assessed on a regional basis (Figure 5). Such data indicate some reduction in average size of pigs in northeastern China only in the Bronze Age. More clear reductions of pigs in the Yellow river basin are indicated at Dadiwan, Xishuipo and Xipo (i.e., early Yangshao period), while the Lower Yangtze evidence is more ambiguous but suggests size reduction at the Shazui and Saidun sites (c. 6000-5000BP). These data suggest two or three regionally distinctive evolutionary processes that could correspond to separate pig domestication events, although the migration of domesticated pigs from one region to another is hard to rule out. More recently geometric morphometrics have allowed a new approach to assess overall tooth size (centroid size) for M_2 (Cucchi, et al. 2016): these data indicate wild type (larger pigs) at Xinglongwa and Zengpiyan (early Holocene Southern China) and domesticated (smaller) pigs at Jiahu, Xishuipo and later Yangshao and Longshan period sites. The M_2 evidence therefore agree with the large M_3 dataset to suggest a domestication in central China, including both the Yellow River basin in pre-Yangshao times and the adjacent upper Huai river. In Northeast China and the Yangtze River it is plausible the domesticated pigs were introduced from the central region.

<Figure 5>

Nevertheless, domestication in one region does not preclude some earlier management in other regions. Contexts, such as burials, may indicate a close association with humans, but this could also be close symbolic associations of wild animals with hunters. For example, burials of pigs at Cishan, associated with phytolith evidence of millets, has been taken as indicating pig keeping and association with agriculturalists (e.g., Yuan, et al. 2008), but these data are ambiguous and can easily be explained as economic and symbolic importance of certain wild plants and animals. Likewise, at Xinglongwa, there was also a custom of burying whole pigs in pits, prompting to a similar opinion that the pigs here were also domesticated (cf. Song 2012). As wild millets and sedges or C_4 Chenopodiaceae are unlikely to constitute a regular part of wild boar diets, millet-focused diets reconstructed through stable isotopes are most likely if pigs are feeding on human food waste/excreta. As pointed out by Barton et al. (2009) similarity of diet with people implies a close "domestic" association between pigs and human households. Indeed, stable isotopes on pigs from the Yangshao and later periods typically show a substantial intake of C_4 (millet) foods in pigs, but pre-Yangshao millet diets are less common in pigs: such are absent from Dadiwan (Barton et al. 2009) and Xinglongtou (Liu et al. 2012) for example, whilst pigs from the Yuezhuang site display a wide dietary range, including consumption of C_4 plants (Hu, et al. 2008). Morphological data, unfortunately, are not available to connect the early management of pigs at Dadiwan or Xinglonggou to local domestication; rather, morphological data from Xinglonggou, as discussed above, argued against a local domestication (Cucchi, et al. 2016).

Age profiles provide evidence for when pigs were culled and is often taken as evidence for when people began to manage animal herds as opposed to hunting (cf. Zeder 1999). In the case of pigs this often includes killing large numbers of young and suckling pigs, which would be harder to hunt from the wild as they hide away at wild nesting sites. As with size change, shifts in age profiles over time in particular regional sequences are especially informative. A shift to younger *Sus* age profiles are known, for example, from the sequence at Tianluoshan in the Lower Yangtze (7000-6300BP) (Zhang 2015). The pig remains recovered at Cishan are reported to have a bias towards young pigs that suggests deliberate management (Yuan and Flad 2002; Yuan, et al. 2008). Based on the finding that 81.4% of pigs being culled under the age of two (note bones from different cultural periods are lumped together) at Jiahu, Luo concludes that they were already "domesticated" (2007). We would rephrase this as culling evidence for pig herd management, while the tooth size data indicates that this does contribute to a local domestication process over the subsequent centuries (Cucchi, et al. 2016). However, though pig meat already accounted for 27% of the meat consumption at the site, hunting other animals was still the primary source. This makes pig management also part of an "intermediate economy" between hunting and husbandry.

At Dadiwan the culling age (focused on 1-1.5 years) again suggests some human management (Luo 2007; PIACRG 2006), but the pigs might not have relied on much human-feeding yet, if we assume the humans were already eating more C_4 millet (cf. Barton, et al. 2009). Shandong is a potential centre for early pig husbandry. Apart from the similar cultural phenomena observed at a number of sites, including burying whole pigs in pits, pig meat appears to represent a larger proportion in meat consumption than in other contemporary regions (Table S3). At Xihe where well-planned houses were unearthed showing semi-permanent occupation of the site, pig remains account for 40% of the faunal assemblage. Even though there is evidence of concentrated, young culling ages, researchers consider that the pig bones are of primitive or semi-domesticated forms, very close to their wild forms (Song 2012, 43-44).

Taken together, these data raise the likelihood that pig-keeping was established in multiple pre-Yangshao cultures across northern China (Xinglongwa, Dadiwan, Cishan, perhaps Peiligang and Houli). Even if genetically domesticated pigs derived from only a subset of these traditions (e.g., Cishan, Peiligang and/or Jiahu), our consideration of millet pre-domestication cultivation and domestication processes should therefore factor in pigs as commensals and increasingly part of settlement activities. Pre-Yangshao cultures were consistently engaged in some forms of pig management. Given the smaller catchment range of these sedentary settlements and the clearance of woodland for cultivation which would have limited wild foods available to pigs, populations of managed pigs might have been constrained to smaller numbers, or required feeding by people to maintain captive/managed pig populations. In such contexts domestication traits, including smaller sizes would be expected to evolve in pigs. Subsequently, as sedentary population grew and millet cultivation expanded, more intensive feeding of pigs may have become necessary as indicated in the more consistent millet signature in most pig diets of the Yangshao period (e.g., Hongo, et al. 2021; Pechenkina 2018; Zhang, et al. 2010).

5. Landscape and environmental contexts of early cultivars: a synthetic consideration

5.1 Plant succession and landscapes in different pre-Yangshao regions

The relatively flat highlands of the CLP are characterized by land-surface stability and relatively thick topsoils. The natural vegetation is largely determined by a hydrological regime primarily relying on precipitation. Only drought-tolerant grasses are sustained. The intermediate zones between slopes and lowlands are places for both the removal and accumulation of sediments. The landscape in such places is in constant adjustment for ecological equilibrium. Grasses, particularly those with robust physiologies (in terms of water and nutrient need) and adaptive to disturbance are predominant here. Such a scenario also resembles the local ecosystems at Xinglongwa and Cishan and their adjacent contemporary sites in the West Liao River and north NCP, respectively. Long-term farming practices on hillslopes where both soil and hydrological conditions were most optimal served to transform the local landscape into one that is dominated by grassy plants of millets and their relatives (cf. Lu 1998 for how quickly *Setaria viridis* grows densely on bare or sterile soils), a trend that once achieved would be hard to reverse. As discussed, in the early Holocene these more open micro-environments could have been promoted by spring wildfires, as well as pre-domestication cultivation activities, that worked synergistically. Fires and clearance of undergrowth would also have driven boar out of refuges making them easier to hunt or capture and perhaps pushed them towards foraging and rooting around cultivated and fallow plots and more commensal settings near human settlement.

River terraces develop when alluvial incision prevails. Riverine landscapes are characterized by periodic alternations between alluvial incision and aggradation. Riverine hydrological conditions are complicated by great landform changes and variable water retention abilities of soils and sediments. Vegetation patterns on river terraces frequently undergo dynamic changes. Many Laoguantai culture sites in the southern CLP are located in such environments. The pre-Yangshao farming activities were quite scattered with minimum management and did not play a determinant factor in transforming local landscape. This hypothetical pattern is entirely different from the modern cultivated landscape widespread in this region, which is characterized by intensive farming, complete removal of original vegetation and severe surface erosion (Li 2007). Admittedly, however, this is highly speculative and should be examined along with other evidence (e.g., charcoal concentration) in future studies.

On the river floodplains, both the hydrological regimes and soil nutrients are at their best conditions although a high frequency of seasonal floods plays a paramount role in influencing vegetation change. Perennial trees and annual herbaceous plants might have been widespread in river valley bottoms. The landscape here thus is one dominated by constant surface instabilities when floods take control, punctuated by short-term surface stabilities when floods retreat. Many sites of the Houli culture in the northern Shandong are situated next to river floodplains and geoarchaeological investigations have revealed the importance of such volatility for the local subsistence (Zhuang, et al. 2013b). Whether such landscape volatility contributed to a cultural history with less obvious continuities into the later Dawenkou culture could be an avenue for future investigation. Despite the use of both millets and rice indicated by Houli datasets, there is less clear evidence that these were part of a long-term regional domestication trajectory (cf. Stevens and Fuller 2017).

5.2 Pig husbandry and ecological impacts

Animal grazing and husbandry affects must also be taken into account (cf. Hester, et al. 2006). Pigs, like dogs, despite being omnivores and eating whatever is available from local environments, also have certain moving ranges. As discussed, the wild boars or early pigs during the pre-Yangshao would have been more likely free-ranging around settlements unlike the later inclusion of pigs in pens. Contrary to the generally positive effect of nutritional contribution of herbivores to soils, out-door pig farming often substantially reduces nitrogen (Williams, et al. 2005; Williams, et al. 2000; Worthington and Danks 1994). In addition, pig trampling and rooting may either compact or loosen soils, affecting water infiltration, with variable effects on hydrology depending on pig husbandry strategies and sensitivities of environments. Danell et al. (2006) suggests that often in arid environments, if the soil surface is sealed with biotic crust, trampling will increase water infiltration by breaking the crust and promote seed colonization. This means that in drier context rooting pigs could have a positive impact on the local ecosystem and plant (millet) domestication. Pig rooting, like spring wildfires, could be seen as creating suitable conditions for small millet growing plots.

Foraging wild pigs may have been attracted by the construction and occupation of the pre-Yangshao settlements in both the CLP and the Central NCP as the settlements would have offered ideal foraging environments for wild pigs, especially as human waste accumulated. In Shandong, the emergence of open habitats around river floodplains (see section 5.1 and also cf. Smith 2007), where most pre-Yangshao culture sites are located as a result of hunting-gathering and possibly farming, might have generated suitable niches for both weed plants and some animal populations. The seed dispersal and germination of wild millets would have been greatly accelerated by trampling and other foraging activities of pigs. Millets and their weedy relatives, which do not typically form large stands but small patches may have begun to greatly expand into new patches after pig disturbance in local systems.

5.3 Niche construction theory and the loess environment

The interactive processes of soils, early cultivars and landscapes in northern China can be better understood through the niche construction theory (Altman and Mesoudi 2019; Smith 2016). First, the soil and vegetation were disturbed around settlements. The eroded materials were transported to lowland areas by both alluvial and colluvial processes, greatly influencing soil nutrient replenishment and small-scale hydrological factors which in turn had a large impact on regional vegetation spread and regeneration. While climatic conditions may have promoted seasonal wildfires, people could have augmented these, both to facilitate more natural or sown millet patches, but also to increase access to wild pigs. Farming also contributed to vegetation evolution. Fallowing, regardless of the remaining controversy of its periodicity, would have gradually transformed the field into a weed plant-dominant niche which is well elucidated by the ethnobotanical work at Xinglongwa (Zhao 2006). This resembles the 'anthropogenesis of vegetation' proposed for Holocene Japan by (Crawford 1997), but with increasing emphasis on cultivation and pig-husbandry in early Holocene China. When climatic conditions shift towards the Middle Holocene Optimum that should promote less fire-prone forests, anthropogenic fire would have been used to facilitate the continued creation of early successional grassland with enhanced soil nutrients. Such habitats would attract deer and boar in the later summer, while controlled fires may have aided in their capture in the spring. Similarly, as aforementioned, pig husbandry through trampling and other activities could also create niche habitats that are highly beneficial to seed succession, including for wild millets, and species diversity. These changes at local sites were connected to climatic variations, geomorphologic (e.g., alluvial and colluvial) processes, and diversified hydrological and topographic conditions, which triggered the modification of regional landscapes. At Guobei, we have illustrated a mixed pattern of land uses during the occupation periods, including farming, related management (e.g., the possible maintenance of small ponds for farming), grassland, and sparse tree growth (Zhuang, et al. 2016). Together, these cultural activities would have together played an important role in the shaping of local niches, forming the basic units for the creation of a new type of landscape around human settlements.

An important characteristic that defines niche habitats for domestication is the constant equilibrium adjustment of loess ecosystems. The loess tablelands with relatively stable soil and hydrological conditions may have adapted to disturbance brought about by humans, animals and wildfires before the onset of large-scale farming activities. While under climax mixed deciduous forests such landforms would have been highly stable, with limited suitable habitats for wild millets. *Setaria. viridis* would have been highly localized to those more open sites that were maintained by either regular disturbance (e.g., on steep riverbanks) or periodic natural disasters (e.g., landslides and forest fires). As such wild millet resources would have been patchy and potentially quite scarce. Wild *Panicum miliaceum* might have been present on naturally thinner soils and the drier margins of woodland-steppe. Therefore human clearance for settlements, with wood clearance for building and fuel would have served to provide suitable niches for wild millets to expand in wooded zones and become further established around settlements even if occupied seasonally rather than year-round. Cultivation is merely human recreation of such patterns to intentionally expand such open areas within the deciduous woodland. Involvement of either fires or pigs would ensure increased openness and soil disturbance; these factors start the selection for increasing seed size and reduced dormancy (Harlan, et al. 1973; Stevens, et al. 2021). Once these processes are repeated over several years, with even just some supplemental seeding by people, the pre-domestication cultivation evolutionary process is underway that will lead to the emergence and increase in morphological domestication indicators.

The apparent focus of pre-Yangshao settlements on slopes, piedmonts and river terraces means that places received severe natural and cultural disturbance prior to the initiation of farming (see Blumler 1998). Once vegetation including wild millets was established, a new proto-agricultural grassland climax became dominant, maintained in part through increased early Holocene spring wildfires, and in part through continual human wood demands, and probably also human strategies to increase species like millets and boars. Human harvesting practices can be expected to have aided dispersal of wild-type shattering spikelets in the short term and domesticated non-shattering forms in the longer term (see Stevens et al 2021). All of the above changes would have slowly and perhaps imperceptibly increased the value and yield of harvested millets. Cultivation practices, including sowing from stores or soil preparation and tillage, and investment in tools like hoes and harvesting knives would have both intensified the selective forces for domestication traits, initiating the entrenched Pre-Domestication Cultivation stage in which the trajectory towards domestication and intermediate economies moved away from hunter-gather mindsets towards agriculture would have begun.

6. Concluding remarks: multiple origins and slow domestication of early cultivars in northern China

Increasing management, pre-domestication cultivation, pig husbandry and eventual domestication were stages involved in the long-term interactions between soils, early cultivars and landscapes. The intrinsic diversity in local cultural traditions and environmental contexts contributes to a new understanding of the multiple origins of early millet cultivars in different centres across northern China. While management and disturbance triggering the creation of new niches for plants and animals were unprecedented, the magnitude of such management varied. In some cases, the management of the farmland niches significantly reduced the competition from perennial grasses (e.g., by disturbing their seed banks) and other weedy plants and thus favoured the fast growth of cultivated crops (cf. Willcox 1999 for experimental and archaeobotanical studies in the Near East). Meanwhile, the relationship between pigs and humans was drawn closer in the new niches, leading to the eventual domestication of the former. However, in other cases, the creation of new local landscapes was characterized by the predominance of weedy plants rather than cultivated crops (anthropogenesis), which was the result of the combined effect of cultural activities and selection and special environmental conditions such as those of the early Holocene that shifted the steppe-woodland ecotone and promoted increased spring wildfires. These different can be proposed for various pre-Yangshao contexts across northern China where millet cultivation began.

Furthermore, based on our detailed unpacking of environmental contexts, settlement patterns, dichotomy of pig diets (C_3 and C_4 based), and different growing habitats of early crops, we propose a slow domestication of early millet cultivars (contra Bettinger, et al.

2010), comparable to the model seen in rice domestication in southern China. In particular, such a slow domestication was closely intertwined with the loess environment and how it responded to both climate change and human activities. Since ecological conditions of loess within the mixed deciduous zone and at the ecotone with the steppe occurred widely in northern China, the conditions for initiating millet cultivation occurred across many areas and cultural traditions. As the maps indicate Xinglongwa, Dadiwan and Cishan all fell nearer to the inferred ecotone. As such we would expect wild *Panicum* to be more prominent in such environments, and this appears to be confirmed in the available archaeobotanical data, as reviewed above. By contrast the Peiligang and Houli cultures, also Donghulin, fell more squarely in the mixed deciduous woodlands, where clearing can be expected to have been particularly favourable for *Setaria viridis.* Not all of these early Holocene engagements of human and millets (and pigs) necessarily persisted for long-enough to lead to entrenched Pre-Domestication Cultivation and ultimately domestication. For instance, climate changes, as indicated in the comparison of pollen distribution suggests that between the 6th millennium BC and the Yangshao period, the Houli area became wetter and more forested, which in turn may have made this region less favourable for continuity of these forms of early millet exploitation; the region also suffered alluvia landscape instability. Disentangling the diversified interactions between people, landscape, and the environment is the key in each of these regions to understand pathways to millet-pig agriculture as well as non-agricultural pathways.

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For Figure 2 climatic data was downloaded from worldclim.org and then processed in QGIS v.3.10. For Figure 3, georeferenced polygons of ecoregions were downloaded from the WWF (https://www.worldwildlife.org/publications/terrestrial-ecoregions-of-theworld), and then group and assigned patterns fills. Millet grain measurements were in part made or compiled by Chris Stevens; this and other initial work on this paper was supported in part by the Comparative Pathways to Agriculture Project to DF (European Research Council no. 323842).

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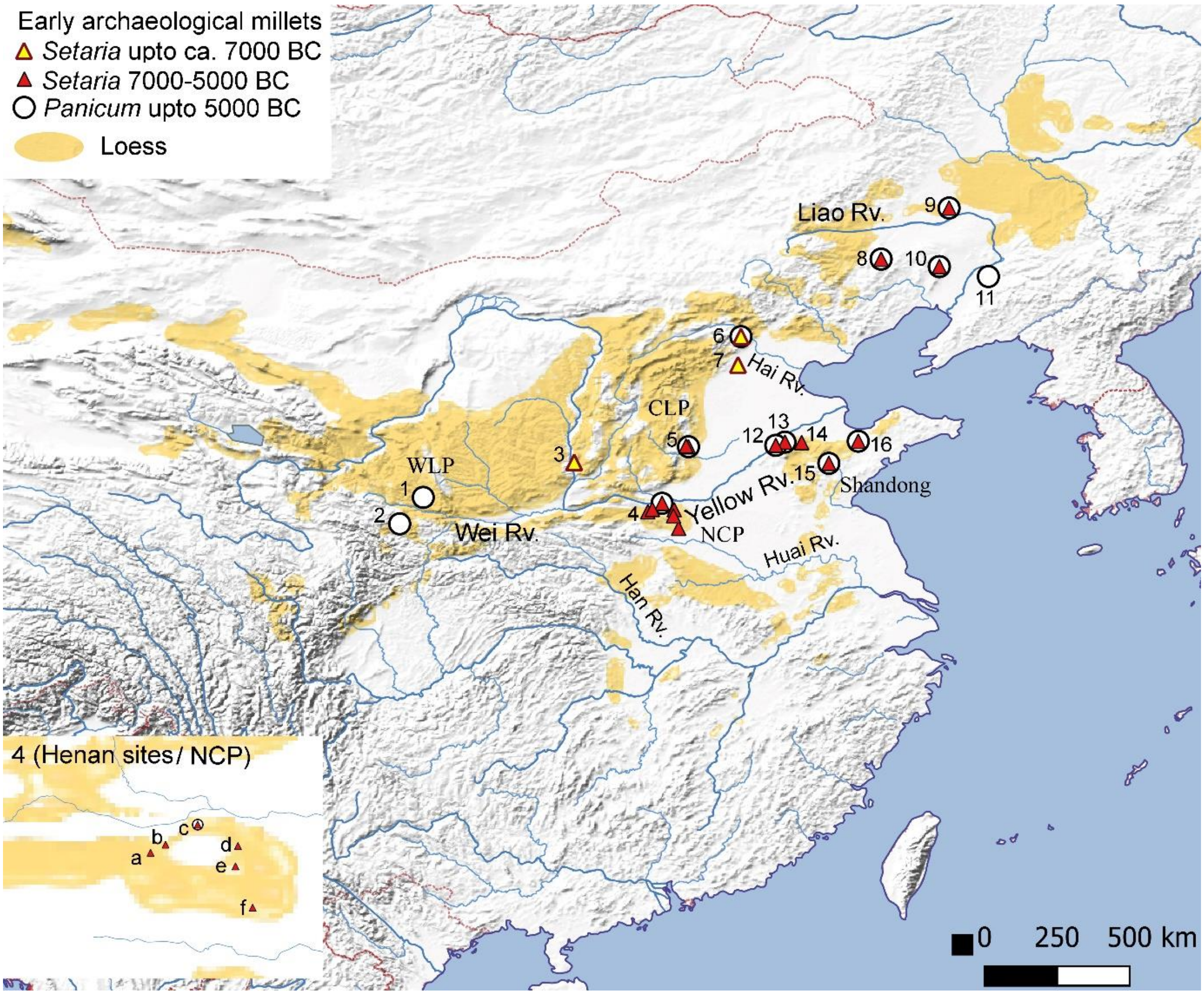

Figure 1: Distribution of loess and early archaeological millets in different geographic regions of northern China. The distribution of loess here refers to wind-blown loess only, but note that in the vast North China Plains, reworked loess through alluvial activities or other geomorphological

processes is also present widely. WLP: Western Loess Plateau; CLP: Central Loess Plateau; NCP: North China Plain. (See Supplementary Table S1)

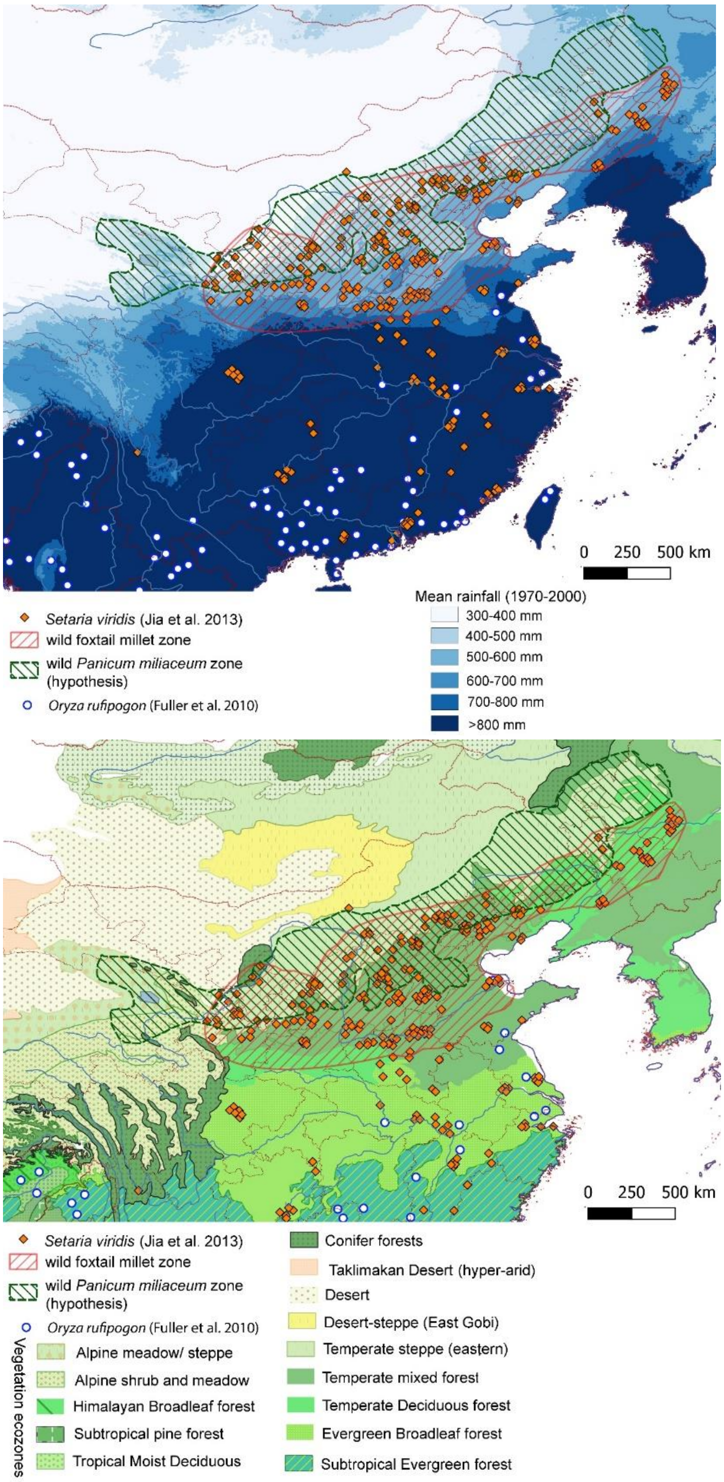

Figure 2: Distribution of wild millets (*Setaria viridis*) in different geographic zones. These include the wild *Setaria viridis* (Jia, et al. 2013), and an inferred core wild zone for foxtail millet, as well as hypothesis of wild *Panicum miliaceum* zone. **A**: distribution of wild millets in different rainfall zones. Note the inferred wild *Panicum miliaceum* zone is situated further north to that of wild foxtail millet one. **B**: the reconstructed wild foxtail millet zone and hypothetic *Panicum miliaceum* zone plotted in different vegetation zones. Note in both figures the presence of wild rice distribution (including historically extirpated populations) for comparison (Supplementary Table S3).

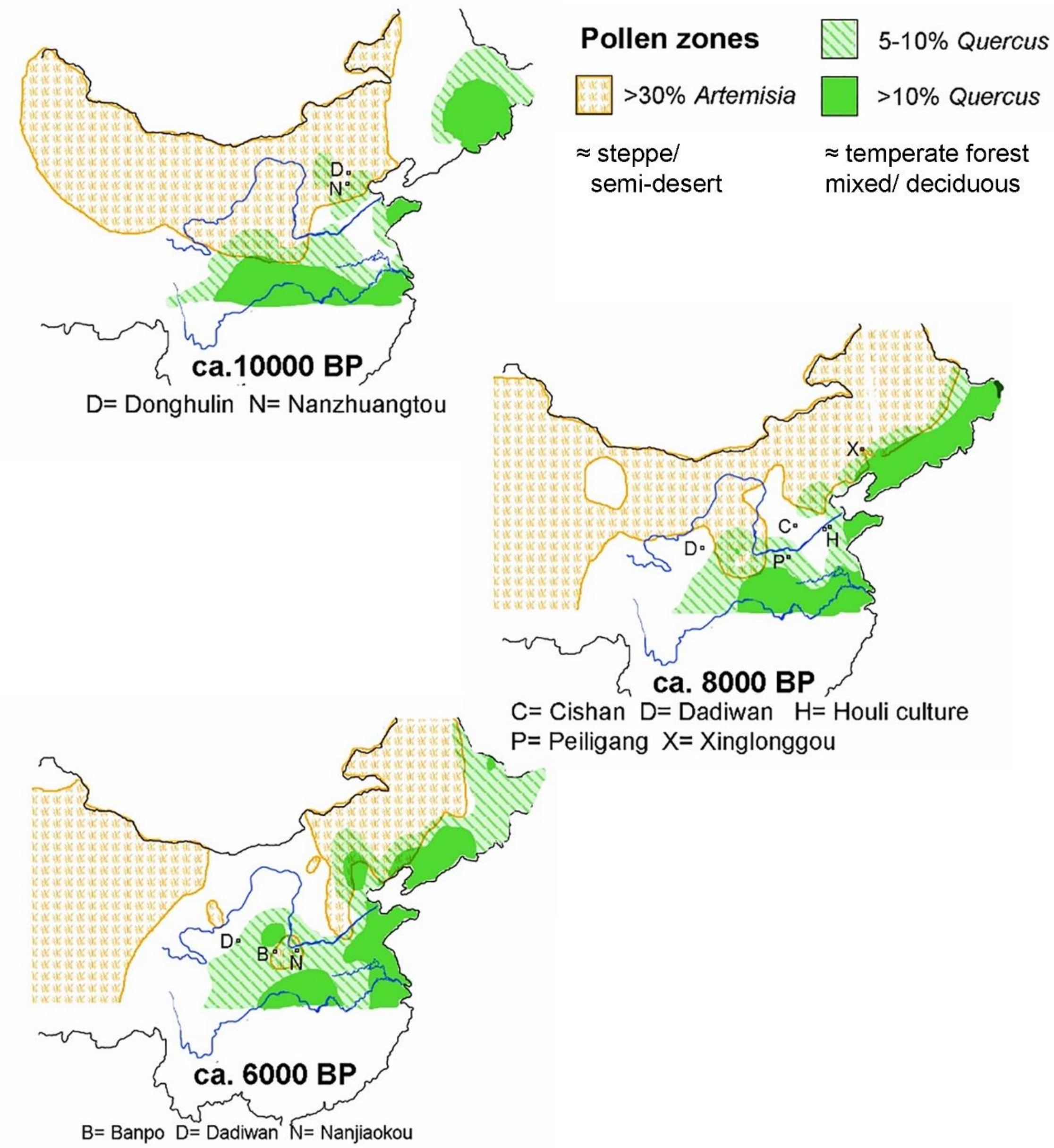

Figure 3: Inferred shifting vegetation zones of stepping and broad-leafed woodland, based on two main species represented in pollen datasets (after Ren and Beug 2002), *Quercus* and *Artemisia*, during the pre-Yangshao and Early Yangshao periods.

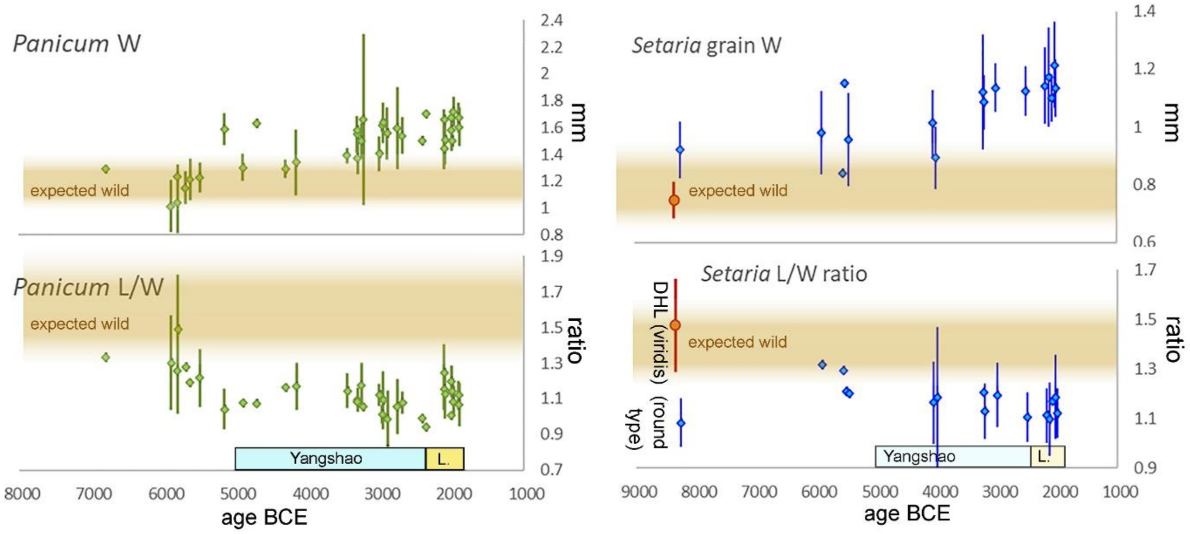

Figure 4: Time series of millet metrical data suggesting processes of domestication in the pre-Yangshao era, including grain width and length: width ratio. Mean and standard deviation of archaeological sites are plotted as median age estimate for site/phase. Donghulin (DHL) *Setaria* data are plotted as two distinct populations defined by shape (after Zhao, et al 2020). Expected wild mean or core range indicated by brown shading. *Panicum miliaceum* data after Stevens, et al 2021. *Setaria italica* data includes published and unpublished data (see supplementary Table S4). Yangshao and Longshan (L.) horizons indicated as guides, but may include data from other contemporaneous cultures.

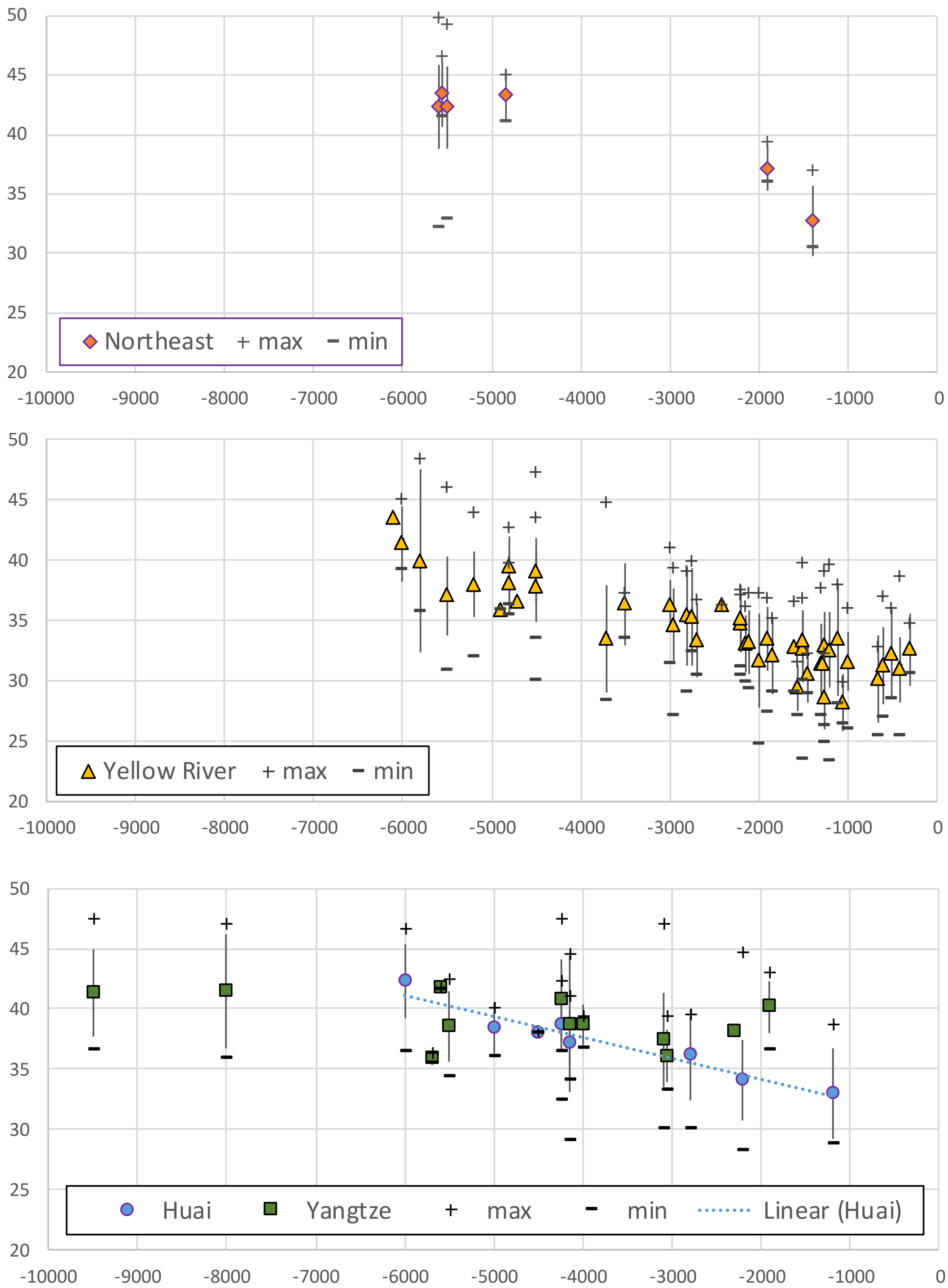

Figure 5: Change of M_3 length of late Pleistocene to Holocene pigs in different regions across China, including Northeast China, the Yellow River valleys, and Southern China (the Huai River and the Yangtze River valleys). Y axis represents average length (mm) of M_3 whereas the X axis is the date (BC). Raw data from Luo 2007 (Supplementary Table 6).

Comments

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The Yellow River was a major homeland for millet agriculture, pig domestication, the Sino-Tibetan language family, the Sinitic-speaking populations of most of modern China, and the Tibeto-Burman-speaking populations of the Tibetan Plateau, western Southeast Asia, and the southern fringes of the Himalayas (see a selection of recent references for archaeology, linguistics, and ancient DNA in Bellwood 2024). In terms of the creation of the historical Sinitic-speaking peoples, the Yellow River represents their heartland, the source of their history.

The authors discuss the development of the millet and pig raising early Neolithic economy that drove these Yellow River developments from the viewpoint of a paradigm of "multi-centric entanglement and protraction", set within a theoretical stance based on "niche construction". As a presentation of data concerning the environmental and cultural backgrounds to millet and pig domestication, especially during early Holocene period of climatic amelioration and wild millet expansion prior to 5000 BC, the paper is detailed, well researched, and informative. Valuable insights are presented about the role of loess soils in millet domestication. The emphasis on the importance of pre-domestication (i.e., "protracted") millet cultivation and pig management in pre-Yangshao contexts is well justified.

Less clear is why it is necessary to load the presentation with debates about "entanglement" and "niche construction", although I can see value in the concept of "protraction" towards a state of full domestication for broomcorn and foxtail millet. These tangential debates hide the wood behind the trees, given that human behaviour obviously operates and presumably always has done so through modes of entanglement and niche-construction. The latter may well have its merits, but the underpinning logic is little more than common sense. Niche construction describes but does not explain, for instance, how and why global food production was predominantly a Holocene rather than a Pleistocene phenomenon, or why some regions developed more powerful crop and animal combinations than others in terms of human population growth.

The debate about niche construction also leads the discussion towards an opposition of "multi-centricism" versus "single origins" for Yellow River food production. The authors refer somewhat negatively to a twenty-year-old book by me as suggesting a single origin for agriculture in China. This is partly true, in that I then referred to China as a whole, when compared to other major regions such as the Fertile Crescent and Mesoamerica, as a "single center, albeit large and diffuse" (Bellwood 2005: 119). But the authors do not refer to the rewritten second edition of this book that was published last year (Bellwood 2023; and see also Bellwood 2017; 2022 for additional discussion of East Asian agricultural origins). In this new edition, as also in 2005, I do not claim that food production, and the humans who developed its various manifestations in China, evolved in just one place and spread entirely out of only one region. A vast quantity of archaeological, ancient DNA, phylogenetic linguistic, and domesticated crop and animal research would make such an idea untenable. However, I do suggest that "it is difficult to regard the processes of millet and rice domestication as being entirely independent of each other" (Bellwood 2023: 130). I still hold to this view.

My questions for Zhuang and Fuller thus concern scale, a topic that I perhaps view differently from the authors. They consider many regional and small scale transitions to millet and pig production across a large area of northern China, and when they do so they find protraction, entanglement, sometimes success and sometimes dead ends. That is how humans behave.

On the other hand, and on a scale greater than that of just the millet zone of northern China, I still see it as valid, as I did in 2005, to consider East Asia as a whole as a single homeland region for food production with respect to the other regions of the world where similar developments occurred. The relationships in material culture (especially pottery and ground stone implements) that occur throughout the archaeologically-known regions of the early Neolithic Yellow and Yangtze basins, and in the regions in-between these two major rivers, make it perfectly obvious that people were in contact across wide areas (see, for instance, Fig. 3 in Cohen 2011). While the authors do make occasional reference to interaction between different communities, this is usually only as an aside to the main stance of multi-centricity.

As for "protraction and entanglement", my own view has always been that some transitions to food production might have been protracted, but not necessarily all (Bellwood 2023). As also emphasized by Jared Diamond (1997) and many others, some people had access to situations that encouraged domesticatory activity, some did not. Access to wild plant and animal species that were responsive to domesticatory management was essential. Furthermore, there is one central topic that this article appears to avoid, and this relates to human population growth and expansion. Although the densest Neolithic food producing populations developed in northern China during Yangshao and Longshan times, that is after 5000 BC, the archaeological data presented in this paper suggest that pre-Yangshao human populations were already increasing in numbers and density from the end of the Pleistocene onwards, and throughout the early Neolithic. I suspect that pigs and millets were not only being slowly domesticated in multi-centric ways, but were also continuously being spread between different regions with the relevant management techniques in vogue at the time, and at different morphological stages in their domestication. These spreads could have occurred either through exchange, or through actual human migration under conditions of population growth. More likely perhaps, both processes occurred in combination.

Despite these comments, I wish to finish on a positive note. The authors synthesize their basic evidence succinctly, and I congratulate them on presenting a useful statement about the beginnings of food production in northern China. I am also impressed that Zhuang and Fuller can combine both Western and Chinese approaches to the origins of food production in a readable and informative way. My reservations are with higher-level issues of scale and perspective, rather than the finer details of the millet and porcine economy that created the early Neolithic of the Yellow River Valley in China.

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Zhuang and Fuller provide a fascinating discussion of niche construction and the gradual domestication of millets and pigs. Their “protraction and entanglement” approach is a welcome addition to other recent research that looks at domestication in East Asia in terms of ecological entanglements with landscapes, other species, and even objects like ceramics (for a few examples, see: Berger et al. 2021; Bleed and Matsui 2010; Guedes and Butler 2014; Wang 2023; Zhao et al. 2021). From a zooarchaeological perspective, Zhuang and Fuller provide much food for thought regarding pigs. I highlight a few points about the ancient DNA (aDNA) record that could be expanded. I also argue that in addition to pigs, other animals such as dogs and deer likely played important roles in early experiments with management.

The authors discuss zooarchaeological evidence for pig management in several regions, but argue that the genetic data point to a more limited geographic origin for the ancestors of modern Chinese domestic pigs in the Yellow River Valley. Although current data suggest that Chinese domestic pigs descend from closely related boar populations (Peng et al. 2022; Zhang et al. 2022), there is still much we do not know about East Asian pig genetics. There are two additional important aDNA studies by Wang et al. (2022) and Zhuang et al. (2022) that are relevant to debates about domestication in China’s northeast. While some studies (e.g., Xiang et al. 2017) have argued that unique haplotypes in northeastern pigs might result from independent domestication, aDNA indicates that pig haplotype diversity may also reflect the presence of wild boar among archaeological samples (Wang et al. 2022) or introgression with boar (Zhuang et al. 2022). Zhuang et al.’s (2022) analysis of ancient pig mitogenomes also reveals that female effective population size increased 7000 years ago and again 4000 years ago (Zhang et al. 2022). These periods of pig population growth correspond to periods of human population growth and agricultural expansion (Dong and Yuan 2020), reflecting the close ties between human and pig demographic histories. We need additional well-dated aDNA samples to clarify the origins of Chinese pigs. This work might also help identify ghost populations hypothesized from modern genomic data (e.g., Peng et al. 2022). Ghost populations existed in the past, but did not make significant contributions to modern breeds. Ghost populations might be likely if experimentation with pig management took place across multiple regions.

Ancient DNA might also help clarify pig raising practices. As Zhuang and Fuller note, long-term genetic continuity in the female line may result from limited admixture with wild boar (Larson et al 2010). However, selection of a few females for breeding while using the remaining animals for meat would also produce a pattern of low mitochondrial DNA diversity (Price and Hongo 2020; Zhang et al. 2022), and even if sows were kept penned or isolated, they may still have had some interaction with male wild boar. There are currently no published genome-wide aDNA studies of Chinese pigs to help resolve these questions about admixture and the degree of penning/isolation of managed populations.

Zhuang and Fuller raise exciting questions about animal management that are worth exploring for other species in addition to pigs. Isotope data at pre-Yangshao Dadiwan show that pigs were not eating millets, but some dogs were (Barton 2009). Ancient DNA studies of dogs also show an effective population size increase 7500 years ago along with the expansion of human sedentism and millet cultivation (Zhang et al. 2020). Zooarchaeological data for pre-Yangshao dogs is limited, but perhaps more attention should be given to their roles in niche construction and millet domestication.

Deer should also be given greater consideration, both for their potential contribution to millet domestication and for the counterpoint they offer to the “free-range” management model proposed for pre-Yangshao pigs. Deer, especially sika (*Cervus nippon*), are more common than pigs in the faunal assemblages of most pre-Yangshao sites (Brunson and Lander 2023; Lander and

Brunson 2018). Both boar and deer are attracted to mosaic and human-modified landscapes at edges of settlements and fields. Hunting these animals would have provided people with meat while also protecting their crops from being eaten or damaged. Like pigs, deer might have disturbed soils in ways that promoted millet growth.

The relative importance of pigs vs. other species like deer in Zhuang and Fuller's model for pre-Yangshao niche construction depends on whether you argue that the pig bones found at various sites represent hunted wild boar in a commensal relationship with humans or represent experiments with intentional animal management. Based on current zooarchaeological evidence, we should not rule out the possibility that most pig bones from these early sites still represent boar that were trapped or hunted at the edges of fields and settlements just like deer were. Changes in pig tooth size/morphology are only detectable at a few sites, including Jiahu and Kuahuqiao (Dong and Yuan 2020; Price and Hongo 2020). Some pigs with C_4 dietary signatures have been identified at sites such as Yuezhuang (Hu et al. 2008), but this could have been due to eating millet in fields rather than foddering. In terms of age profiles, Zhuang and Fuller note how some hunting strategies might be hard to distinguish from intentional management/penning (Price and Hongo 2020; Zeder and Lemoine 2023). Hunting and commensalism at the edges of settlements likely involved multiple species. People may have hunted and/or experimented with managing both pigs and deer in various ways, but most of these experiments did not lead to domestication (Bleed and Matsui 2010). Why were pigs ultimately domesticated and not deer? As Zhuang and Fuller note, once agricultural lands expanded, pigs were increasingly managed and raised within settlements, providing meat and manure for agriculture (Wang et al. 2018; Yang et al. 2022). Deer were gradually pushed away from human population centers, but still remained the most important hunted animals throughout the Neolithic and Bronze Age because they were suited to living within the human-modified landscapes of lowland north China (Brunson and Lander 2023).

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I find this broad landscape perspective on the intensification of human-millet and human-boar interactions in Neolithic North China compelling. There is well-reasoned support for the argument for a protracted process of engagement that resulted in a “multicentric mosaic” of emergent domestication. I commend the authors for their marshalling of existing data on millets and pigs and agree that the landscape level perspective provides a useful vantage point for framing the way we think about the questions of “where” and “when” these processes occurred. I found the rhizome metaphor particularly useful in thinking about how the actual practices and activities of early community members might have merged in the process of transforming foodways across space and time. The mosaic they propose is an important facet of the “geographically contextualized totality of interactions between humans and the environment” (Flad and Chen 2013: 1) that constitutes the very notion of landscape. There are elements of the argument that could be examined further, and my comments here are intended to bring these up for consideration.

One of the themes that is ubiquitous in many studies of early agriculture is the consideration of the “push” and “pull” factors that may have been involved in encouraging the intensification of a particular human-animal or human-plant relationship. It seems that this topic is mostly secondary in the discussions of millet and pigs by Zhuang and Fuller. The one explicit discussion of push factors concerns how exchange of genes and technologies can have causative effects on plant populations. But overall the argument for a protracted entanglement involving an extended period of niche construction seems to be one in which domestication processes are generally accidental – or perhaps so highly varied that it seems only worthwhile investigating them within site-specific contexts. Do the authors agree with this? Furthermore, to what extent do they feel that the millet and boar at issue in this entanglement may have been agents in the processes that lead to the entrenched stage of cultivation that eventually takes hold (Wang 2023). Fuller's comments on Wang's 2023 *Current Anthropology* article suggests that the protracted, landscape orientation advocated here is an alternative to the posthumanist one she advocates, and it would be interesting to have the authors clarify their position on this issue.

Concerning the millet entanglement process, I found the data presented in Figures 1 and 2 quite useful, as is the notion of patchy islands of wild millet as a means to conceptualize the environment in which these early settled communities were encountering the millet plants. In the niche construction processes they propose, fire plays a pretty important role, and the potential impact of both wildfires and anthropogenic fires come up repeatedly. It may be the case that data on fire prevalence at the various sites of the pre-Yangshao period and contemporaneous environmental cores has not been investigated for evidence of fire. I would think this would be a fruitful avenue of future research and would like to know what sort of patterns the authors would propose should exist in environmental fire data that might correspond to their model.

On the topic of pigs, there are aspects of the data set that might require additional evidence in order to better support the interpretations proposed. Specifically, the authors look at the size of M3 molars from several sites and separate these into regional groups in time series (Figure 5 and Supplemental Table 7). When discussing these data, they state that they "indicate some reduction in average size of pigs in northeastern China only in the Bronze Age." While the data don't contradict that reduction, they don't really indicate it either. For one thing, there are only four early sites in the region from which M3 size data are provided, and while the three Xinglongwa culture sites (Xinglonggou, Baiyinchanghan, and Xinglongwa itself) have reasonably robust data sizes, only three specimens come from the Zhaobaogou site representing the subsequent chronological period. Those three specimens aren't evidently smaller, but do reflect a very small n. Furthermore, there are no intervening sites that post-date Zhaobaogou until the Lower Xiajiadian remains from Dadianzi, about 3000 years later. Furthermore, given the authors' point that northern boar may have been larger to begin with, and having no pre-Xinglongwa specimens to compare, the data are simply insufficient to make a confident judgement about when the average size of pigs in this region really started to diminish. It is useful to see the authors, in the same section, recognize that other behavioral data, such as the burial of whole pigs in pits and burial of pigs in graves, suggest aspects of human-pig interactions that reflect certain types of management or engagement that complicate a binary perspective on "domestication." A recent PhD thesis by E. Dalyn Grindle about human-elk relations in North America (Grindle 2023) provides a thorough interrogation of the ease with which the concept of "domesticate" is often used when it comes to distinguishing certain types of human-animal relations. The variability that is suggested for human-pig relationships in the pre-Yangshao North China contexts can be considered as another lens through which to critically examine the notion of domestication, rather than as incomplete evidence for or against it. Likewise, the overall argument that this paper makes for a landscape perspective draws our attention to the potential for mulit-centric and multi-stranded, rhizomic processes of interactions between humans and various plants and animals, and I think that this aligns with a need to confront the real complexity of these processes in the past.

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Agricultural Entanglements, Niche Construction, and Low-Level Food Production

Zhuang and Fuller document the intertwined domestication histories of millets and pigs in North China, making four connected arguments: the process of domestication is slow and extended, the combination of theories of entanglement and niche construction is productive in explaining domestication, domestication results in multiple trajectories for subsistence economies, and ecotopes (the smallest spatial unit of ecological function) that sit along ecotones (boundaries between larger ecological units) are particularly productive locations to study for the origins of domestication. None of these, individually, is a new insight. It has been well established based on both genetic (Allaby, Ware, and Kistler 2019) and archaeological (Fuller, Asouti, and Purugganan 2012; Purugganan and Fuller 2011) evidence that processes of initial domestication of both plants and animals are slow and protracted, regardless of taxon or world area, including specific evidence for broomcorn millet (Stevens et al. 2021). The connection of niche construction with theories of entanglement to explain both initial domestication (Fuller and Stevens 2017) and agricultural development (Eriksson and Arnell 2017; Marston 2021) has offered insights into the processes leading to increasing reliance on domesticates. Multiple economic trajectories resulting from domestication have similarly been acknowledged for decades, with “incipient agricultural” (Steward 1949) economies and societies engaging in “low-level food production” (Smith 2001) two terminologies for the “middle ground” between hunting-gathering and agriculture. The unique valuable environmental dynamics of ecotopes located at ecotones have been documented ecologically (Troll 1950), culturally (Turner, Deur, and Mellott 2011), and archaeologically (Spengler, Frachetti, and Fritz 2013).

If none of these arguments is new, then what are the original contributions of this article? Zhuang and Fuller unite these four key arguments to illustrate, for the first time, the full complexity and diversity of millet and pig domestication in North China. One particular strength of their argument is the depth of ecological study that underlies their geographic analysis of sites of early domestication. Rather than focusing only on macroecology, such as the ecotones between forest and steppe, the authors incorporate detailed study of climate and soil character in locating particular ecotopes that supported millets uniquely well. Attention to soils, especially the dynamics of loess deposits in particular locations (e.g., hillslopes versus river plains), helps to establish the affordances of specific ecotopes for human interactions with plants that may have led to domestication relationships. Such attention to soils is rare in domestication studies, but explains agricultural dynamics in other regions, such as in India (Bauer and Kosiba 2016; Bauer 2023) where the affordances of soils in their responses to human action set in motion a chain of economic relationships that became regionally culturally entrenched. Such analysis helps us to focus, as Zhuang and Fuller argue, on landscape as the object of study rather than centering human actions or plant or animal biology alone, as in prior approaches. The advantage of a landscape approach is that it permits a more comprehensive understanding of the factors that led to the diversity of early agricultural practices seen in the archaeological record. Together, these factors help us to understand why early millet domestication occurred *where* it did, an important contribution.

This study does leave additional questions unanswered. Perhaps chief among these is why domestication of millets and pigs occurred *when* it did. Earlier scholarship linking climatic change at the end of the Pleistocene and beginning of Holocene to the domestication of plants offers incomplete explanations for the timing of this phenomenon, even when incorporating cultural processes (e.g., Richerson, Boyd, and Bettinger 2001). Zhuang and Fuller argue that reductions in natural fire during the mid-Holocene led to the need for human-mediated disturbance (either via fire or pig rooting) to maintain millet-rich ecotopes, which might explain the timing in both additional investment in millet management and in increasing control of pig populations. This does not, however, explain the timing of the ultimate origins of millet domestication, which requires additional research.

Another question yet unanswered is what happens when initial domestication does *not* result in the development of an agricultural economy? Zhuang and Fuller usefully observe that such cases appear in their datasets, but view these as "dead ends" that failed to persist "for long enough to lead to entrenched Pre-Domestication Cultivation and ultimately domestication," such as in the case of Houli. Such a perspective treats agriculture as an end state, but it might be more useful to consider that low-level food production making limited use of domesticates may in itself be a desirable end state, rather than a failure or "dead end" on the way to agriculture (Marston 2017; Smith 2001). Further attention to the question of how such alternative outcomes of domestication arise is warranted.

To do so, I suggest that alongside concepts of entanglement and niche construction, this discussion would benefit from the integration of broader concepts of ecological and cultural inheritance, which can prove advantageous in considering how and why certain agricultural trajectories arose. Legacy effects, the "persistent impact of ecological interactions" on a landscape that structure its current form (Cuddington 2011), are of particular value here, as they are more broadly in agricultural studies (Marston 2021). We can find legacy effects in this case study in growing human dependence on mosaics and ecotones that require fire or animal disturbance, land clearance of food-producing trees resulting in cultivated cereals shouldering a greater caloric burden, and shifting soil hydrology that favors specific plants over others. Similarly, it would be useful to conceptualize tipping points or thresholds (ecological or cultural) that lead to one outcome (e.g., agriculture) versus another (e.g., low-level food production), from an original landscape in which many agricultural opportunities are available (Marston 2015; Walker and Meyers 2004). Parallel structures of agricultural dependence may arise from such tipping points, which, if identified archaeologically, might help us to understand better why certain elements of domestication occurred when they did: e.g., why did seed size change or animal size change when it did and not earlier. I suggest that such consideration will give us greater insights into the complexity of domestication and early food production.

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Research on the origins of and the development of sedentary agricultural communities is as old as the science of archaeology, as are questions about the interactions of humans and their environment. While new methods of recovery and analysis are developed and new data is constantly accumulated, it is very difficult to say something entirely new about those old research questions. Under those limitations Dorian Fuller and the colleagues he is working with are conducting work that can propel this field forwards. By documenting the long domestication process of different plants (see references in the paper), their work has generated the deep understanding that domestication was not a 'discovery' or an 'event,' but rather a process that occurred many times in different parts of the world. Such insights are crucial for our understanding of some of the most fundamental aspects of human societies world-wide. The beginning of cultivation and the domestication of plants and animals, as well as the beginnings of sedentary ways-of-life, are interrelated (but not similar) processes which transformed human society. During this transition and as a result of the accumulated impact of those processes, human cultures, religions, food habits, family relations and all other aspects of the human experience were completely transformed. These processes also, as described in this paper, transformed over time the ways people interact with the environment and in many ways shaped the environment itself. Thinking about these issues should not be limited to a small group of archaeologists and archaeo-botanists specializing in this field. It is important, therefore, that a paper like this one is published in Current Anthropology and read and discuss by the anthropological community at large.

Zhuang and Fuller should be commended for extensively presenting, evaluating and discussing the most up-to-date relevant data on the early stages of plant (millet) and animal (pig) domestication in north China. Firmly locating those processes in the environmental contexts in which they occurred is a very important achievement of this paper. I concur with Zhuang and Fuller that, because the long transition to agriculture and sedentary way of life occurred differently in different regions, our first task is to unpack the details of those processes in each region before we can start drawing more general conclusions. I also agree that this process embodied substantial inter-regional diversity and cross-cultural contacts, and like their rhizomatic approach. My comments below should not be read as a criticism of this excellent paper, but rather as encouragement of a broader anthropologically-oriented discussion on it.

Adopting niche construction (or more precisely, Cultural Niche Construction, CNC) as the main interpretive framework has many advantages, which Zhuang and Fuller highlights in the paper. However, to my mind, CNC also embodied three crucial disadvantages which can be harmful for future research on the important data Zhuang and Fuller have accumulated. First, using CNC as the main explanatory model produces a homogeneous description of the processes over a very large region. This goes against the argument presented in the paper's introduction which emphasizes diversity. Second, CNC tend to produce a static (or punctuated) picture of the past: In a nutshell, natural or anthropogenic causes disrupt the existing equilibrium, a niche is constructed, and then a new equilibrium is achieved. This tendency is due in part to the fact that CNC is based on the biological concept of niche construction, which was developed to explain the adaptation and evolution of animal and plant species (Laland et al., 1999; Smith 2011). This leads me to the third point: while CNC fits well with the currently popular multi-species and post-humanist approach, and without ignoring the importance of this approach to anthropology, our responsibility as anthropologists (archaeologists included) is to understand the human side and cultural aspects of this process (Preucel 2021; Shelach-Lavi 2023). Focusing on the cultural side of the process will open up a host of new questions and allow for a much more varied and nuanced understanding of the process subsumed under the general title of 'transition to agriculture.'

In their introduction, Zhuang and Fuller alluded to some of the differences in the material culture of pre-Yangsho societies from different sub-regions of north China. Future research should deepen our understanding of those differences and, in particularly, reveal more about the development of different kinds of social, technological, economic, and religious norms: How did such norms, formulated at the dawn of sedentary-agricultural societies, shape the socio-political trajectory of each region for the following millennia? For example, the societies that followed the Xinglongwa period in northeast China exhibit settlement and village patterns, modes of worship and types of artistic representations that are very different from what we see among contemporaneous societies in other parts of north China (Peterson and Lu 2013). Was this divergence predetermined by processes that started during the long "intermediate" period? Do such divergence represent the emergence of alternative forms of socio-economic and political organization? How did intercultural and interregional interactions work to level or exacerbate those differences, including economic and technological differences? And finally, are there differences between the types of interactions between human societies and their environments and how did such differences affect both human societies and the environment over the long-run (Shelach-Lavi 2022).

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Zhuang and Fuller provide an insightful discussion of the ecological setting of the origins of millet and pig cultivation in East Asia. Relying on a robust dataset, spanning multiple methods in the archaeological sciences, they demonstrate that there was increased investment in cultivation practices just predating the Yangshao. They identify soil-working tools and stone harvesting knives as indicators of this behavior. They further illustrate that Yangshao period (7000-5000BP) peoples were fully engaged in agricultural activities, but that wild resources remained a prominent attribute of the economy. More importantly, the authors seek to fit the narrative of millet domestication into the protracted-autonomous model, which has rapidly grown in popularity over the past decade. They state: “The search for agricultural origins in China needs to adopt a multi-centric geography and a paradigm of ‘protraction and entanglement’ rather than pursuing a single origin.” In particular, they draw upon three key elements of the protracted-autonomous model: “protracted domestication, variable commitment across sites to various food production related practices, and feedbacks, or entanglements, between ecologies, species adaptations and human practices”. I commemorate the authors on their re-envisioning of the earliest steps towards millet and pig cultivation, and their detailed synthesis of the literature.

An Ecological Approach

The importance of an ecological approach is evident in the authors' discussion of the habits and ecological dynamics of millet progenitors. They theorize about the ecological setting of millet domestication, stating, "while the ecotone zone is where millet origins should be sought on a more local scale, wild millets likely never formed extensive stands but occurred as islands of wild millet in a sea of C3 steppic grasses". The author's recognition of insular ecologies and the significance of mosaic landscapes in the progenitor's habitats is an important step forward, and a more detailed assessment of these ecological variables is needed in domestication studies globally (see Spengler 2022 on insularity and ecological release).

The authors recognize that anthropophilic plants are exapted to cultivation (see also Spengler et al. 2021), because they evolved on highly disturbed landscapes, begging the question of what caused such disturbances before human intervention. I have theorized elsewhere that the key to answering this question can be found in the progenitor seed-dispersal mechanisms; in the case of small-seeded annuals, I resurrected Janzen's (1984) Foliage as Fruit Model (Spengler 2020). That said, the River Floodplain Hypothesis is an enticing alternative. The River Floodplain Hypothesis was originally pulled together by Sauer (1952; and others Anderson 1952; Hawkes 1969) and promoted by Smith (1992). Zhuang and Fuller state: "On the river floodplains, both the hydrological regimes and soil nutrients are at their best conditions although a high frequency of seasonal floods plays a paramount role in influencing vegetation change." They go on to state, "The landscape here thus is one dominated by constant surface instabilities when floods take control, punctuated by short-term surface stabilities when floods retreat." The River Floodplain Hypothesis seems to hold popularity among North American scholars, who grapple with the question of why and how humans brought small-seeded annuals that do not form dense wild stands (as cereals do) under cultivation.

Niche Construction and Entanglement Theories

Given that the authors have so successfully fit their research into an ecological framework, I worry that their attempts to also integrate with academic cliques or archaeological social groupings does more to hinder than advance their goals. Specifically, they try to fit their ideas into NCT and Entanglement Theory (neither of which are true scientific theories), as well as Landscape Archaeology. The authors are describing ecological processes, therefore Darwin's "tangled bank" is a far more appropriate metaphor than Hodder's "entanglement of things". Hodder (2018:58) envisioned a feedback mechanism of consumerism, stating: "the thingness of things, including ideas and institutions, consist of interconnections, the lack of independence, the relationality of entities. Things cannot be separated from the idea of things and vice versa." Clarifying the language, he claims that humans innately desire "things" and when they have things, they need more things to support those things. When Zhuang and Fuller discuss "feedbacks, or entanglements, between ecologies, species adaptations and human practices", they are describing ecology (the relationship between organisms and their surroundings). They also state, "we require a more holistic landscape perspective, which can be framed in terms of Niche Construction Theory." I have commented on NCT elsewhere (Spengler 2021), and I will not take to my podium now, beyond to say that the authors are essentially using NCT as synonymous with the term "cultivation", specifically citing selective hunting practices, anthropogenic soils, and fire clearing. In addition, the authors fall into the trap of claiming that NCT provides something unique from "conventional Darwinian theory"; this was a marketing strategy employed by proponents of NCT, and it remains a widely propagated fallacy (Spengler 2021). The author also call for a "landscape perspective", claiming that such an approach would include the use of ethnographies and more nuanced accounts of interactions between humans and nonhumans. I, of course, agree wholeheartedly with their call for more comparative methods and detailed studies, but I already consider these methods as residing at the heart of archaeology. I am not convinced that Landscape Archaeology needs to be segregated as a separate subsection of archaeology.

Culture History and Cultural Evolution

Possibly the most important critique that the authors make is a subtle jab at Culture Historical approaches and the idea of ethnogenesis. The authors call for a new perspective on cultural change, pushing for a "more rhizomatic rather than arborescent model of culture (traditions merging rather than diverging)". The authors' critique here is timely, as Culture Historical narratives of the emergence and terminus of culture groups still dominate Asian archaeology. The metaphor of a dendritic pattern in cultural development, which the authors are justly retaliating against is, in part, a legacy of the use of evolutionary terms to describe culture change and has been propagated through the construction of discreet culture groups. The authors astutely point out that cultures do not branch into isolated lineages, but rather divide, merge, and divide again. In Chinese archaeology, Culture Historical approaches remain strong, and hopefully Zhuang and Fuller's call for a revision will bring heuristic changes. This paper is a strong contribution to the field and will go on to shape domestication studies into the future.

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Zhuang and Fuller present a compelling hypothesis linking millet cultivation, sedentism, and early pig management as mutually reinforcing practices leading to the development of farming communities in North China. They argue that during the pre-Yangshao period, woodland clearance for human settlements not only created suitable niches for wild millets but also restricted forest resources for boars. This led to boars becoming commensal animals with humans, foraging around settlements and cultivated fields. Boar trampling and rooting of millet fields, in turn, positively influenced millet cultivation by enhancing water infiltration and creating habitats conducive to millet growth. This approach is innovative and commendable for considering multiple non-human agents—millet, pig, and soil—as entangled actors shaping historical processes.

I would argue, however, that although archaeological evidence supports a synchronous development of millet domestication and pig management, the proposed scenario may not be the only plausible explanation. I present my argument in two ways, one grounded in current archaeological data and the other offering an alternative scenario.

Zhuang and Fuller argue that wood clearance for millet cultivation reduced forest resources available to boars, attracting them to settle near human settlements and millet fields. While plausible, direct evidence linking early pig management and millet cultivation is still lacking. It remains unclear to what extent forest clearance actually impacted wild resources for boars. Archaeobotanical data from pre-Yangshao sites, such as Peiligang, Dadiwan, and Xinglonggou indicates that wild plants, including edible tree nuts like acorns, remained predominant even after millet cultivation was established (Li 2018; Wang et al. 2018; Liu, Zhao, and Liu 2015; Liu et al. 2015). If these forest resources were available to humans, they were likely accessible to boars and other animals. More importantly, stable isotope data from pre-Yangshao pigs shows a predominant C_3 diet (Liu 2012; Hu et al. 2008; Barton et al. 2009), suggesting that they were feeding on extant vegetation beyond millet fields, possibly free-ranging in mast-producing woodlands (Liu and Jones 2014:4).

Therefore, I suggest that the authors consider an alternative scenario involving early pig management in woodlands – a niche construction practice beyond human settlements. Boars thrive in woodland habitat, relying on acorns and beech-mast as their main food sources (Grigson 1982). This dietary preference persisted even after domestication, as seen in classical Rome, where pigs were guided to roam in oak forests to forage on acorns, nuts, and other wild foods (Columella 1954; White 2011). Similarly, during medieval Europe, swineherds drove swine into the woods every autumn to fatten on the mast, a practice known as *denbera* in the Anglo-Saxon and *pannage* in Noman (Wealleans 2013; Grigson 1982). In this mast-feeding system, oak forests were protected, and their values were determined by the number of pigs they could support (Fumagalli 1994:146).

Could it be plausible that the pre-Yangshao people encountered wild boars in woodlands and subsequently managed them outside their settlements? Allowing boars to roam freely near settlements could pose potential risks, given that their rooting and trampling behavior can damage agricultural fields – an issue that remains pertinent today and causes significant economic losses worldwide (Poudyal et al. 2017; Gaskamp et al. 2018). By herding boars in the broader landscape beyond settlements, millet fields are protected from potential damages caused by boar rooting.

Zhuang and Fuller also introduce a “multi-centric geography” approach to understand the origins of millet agriculture, challenging the “single origin” model that attributes the transition solely to the Yellow River Valley. I endorse this approach, especially considering current archaeobotanical data that no longer aligns with the single origin and diffusion model (Zhao 2010; Bestel et al. 2017; Crawford et al. 2016). However, establishing a strawman argument of this nature requires a more thorough evaluation of existing literature.

While an earlier generation of archaeologists once advocated for the single-origin model (e.g., An 1989; Yan 1992; Shi 1986), this perspective was based on limited evidence at the time and no longer prevails in recent research. Archaeological discoveries over the past two decades, especially from the Liao River valley, have challenged the traditional view that the Yellow River serves as the core area for millet agricultural origins (Shelach 2000; Zhao 2004; Crawford 2006). The geographic analysis by Liu and colleagues (2009), published fifteen years ago, provides further support for the multicentric model, demonstrating early millet sites predominantly located in the north-south running hilly flanks at the plateau-floodplain boundary rather than along the Yellow River.

Finally, the authors' critique of works seemingly representing supporters for the single-origin model is misplaced. Liu and Chen (2012:82–82; 127–151)'s description of early millet sites in North China illustrates the diversity in local cultural traditions reflected in material culture and settlement patterns. Chen and Yu (2017)'s paper portrays the Neolithic transition in China as a "quiet," gradual process that varied across different locations, aligning with the idea of "protracted domestication" advocated in this paper.

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We are delighted to see that our paper has generated renewed discussion on the domestication of millets and pigs in North China and its intricate relationships with diverse cultural and environmental processes. Limited by the space, we are not able to address all the important questions raised by our distinguished colleagues. Instead, we respond to these comments from three aspects, namely, scale, species behaviours, and processes.

Scale

Professor **Bellwood** stresses the importance of viewing China as a broader region of Neolithic interaction, echoing Professor **Shelach-Lavi**'s call for considering the differences in material cultural practices across the broader pre-Yangshao regions. We fully embrace these calls for deeper research into regional and inter-regional cultural and environmental differences that influence or even modulate the various agencies and actants in natural and anthropogenic niches – this is part of a rhizotic view of cultural evolution. There is more in common across in North China compared to regions such as the Andes, New Guinea Highlands or the Fertile Crescent. Shared ancestral similarities are to be found in pre-Neolithic cooking traditions, as throughout this region and beyond in Northeast Asia, ceramics were innovated for boiling long before crop domestication (Fuller and Rowlands 2009; Chen and Qu 2017). However, the inter-regional differences also become increasingly pronounced in many recent archaeological discoveries. For example, the discoveries of ceramic face masks in houses at Beifudi, the turtle shells with small stones in tombs at Jiahu, and the popular residential burial practices at Xinglongwa culture sites (Liu and Chen 2012) represent just a small fraction of diverse domestic rituals, early religious beliefs, and mortuary practices that vary between the pre-Yangshao cultures. Variation in food processing and storage methods, settlement layouts, and local environments, are all the crucial aspects that need to be scrutinized in future research in order to avoid a "homogenous description of processes over a very large region", a danger of the 'Cultural Niche Construction' according to **Shelach-Lavi**, which we agree.

In terms of the biological and geoarchaeological factors, we still lack sufficient fine-grained data to track processes of niche construction and domestication and the extent to which they differed in rates of evolution or ordering of different aspects of change. Nevertheless, contrary to **Bellwood**, we see analytical utility in contrasting rice and millet cultivation origins: the two crops and their wild progenitors have divergent ecologies, soil and water needs, human practices and labour demands. These entanglements shaped very different patterns of cultural practice and resulting landscapes. The archaeological record is clear that millets and rice were utilized wild and brought into cultivation in very different ecologies by distinct cultures many hundreds of km apart. These domestication processes need to be analyzed on their own terms. The consequences of the development and expansion of rice and millet farming also differ. The much higher yields of wet rice mean that communities can grow more readily, reducing the frequency of expected migration (Qin and Fuller 2019). In contrast, millet agriculture once established is expected to be geographically expansive. Such an expansion might have been intrinsically linked to the vast loess environment and soil conditions which we deal with in our article.

Species behaviours

We agree with Dr. **Brunson** that research needs to move beyond pig and millets in early agrarian landscapes to a wider research net that captures other species in the human niche, including dogs but also commensal 'pests', and those like Sika deer that may have flirted with commensalism but over long-term were not domesticated. It is striking that some early deer samples from northeast China and the Huai River are found to have a C_4 signature (e.g. Liu et al. 2012; Dai et al. 2019), whilst such evidence is absent from other regions (e.g., Chen et al. 2016), hinting at regional differences. This supports our multi-regional framework of millet domestication across northern China and its close relationship to fostering beneficial habitats or 'human-constructed ecosystems' attractive to deer in and around early farming settlements (Brunson and Lander 2023). Indeed, professor **Flad** raises a similar issue about 'human-elk' relationship and the need to rethink the concept of 'domesticate'. The pre-Yangshao and Yangshao was a crucial period when the 'use' of deer resources intensified (see Table S6 in our article for identified species from important sites such as Guantaoyuan). Scholars have long proposed a so-called 'semi-domesticated, semi-herded' status of Sika deer, roe deer, and other species (e.g., Hu S.M. in Shaanxi Provincial Institute of Archaeology and City 2007: 312, cited in our article). Wang et al. (2014)'s study of Sika deer remains from the Yangshao site of Wayaogou further suggests that Yangshao people developed a hunting strategy that tended to promote sustainability by targeting more male than female individuals, and few of prime age (2-4 years old), similar to niche construction identified in West Asian gazelle hunting (Rowley-Conwy and Layton 2011). The human-deer relationship represents another complex conundrum to be tackled, whether in the context of the landscape approach we propose here or the posthumanist approach advocated by Wang (2023). Only through compiling kill-off profiles and metrical data can the long-term trajectories of deer versus pig adaptation be more effectively compared.

Dogs were a very important component of these anthropogenic landscapes, with aDNA evidence cited by **Brunson** indicating that an important and widespread pair of dog genetic lineages traces its origins to the region and period of early millets (Zhang et al. 2020). Genomic data suggests that East Asian dog breeds can be traced back to common village dogs of Neolithic times, from Chow- chow dogs to old Japanese breeds, Tibetan mastiff sand, and even the dogs of Siberian reindeer herds (Yang et al. 2017). The estimated coalescence ago of all these lineages at ca. 8000 BP is strikingly coincident with the period of early millet domestication. Genetic studies in Europe suggest a major population turnover in dog populations between the Mesolithic and Neolithic dogs (Bergstrom et al. 2020; Ollivier et al. 2018). The aDNA of Chinese dogs indicates something similar. Thus, sedentarization and advent of cereal cultivation, including millets in our region of focus, completely transformed selection on dogs, in terms of their diet, to become more reliant on starch-based foods, which makes little sense for a wild carnivore or a hunting dog, and presumably their behaviour. Dogs would have become more about village protection, as warning systems for the arrival outsiders, wild animals or predators.

Process

On process of pig domestication, Dr. **Wang** raises a concern that wild boar would be destructive of crops, citing modern agronomic assessments of how boar and pigs may damage crops. Below the surface of these modern studies, however, are fundamental differences from the Neolithic examples: such as intensive damage to tuber crops like potatoes in Poland, maize (with large sweet cobs) in Spain or sweet potatoes in Korea (Herero et al. 2006; Lee et al. 2018). Pigs lack the ruminant digestive system that would attract them to millet leaves or cereal spikelets as food. Instead, the shift in pig stable isotopes to more C_4 plant consumption (from the Early Yangshao onwards) indicates pigs getting millets that were already processed for digestibility by human cooking. In addition, as already noted, Neolithic dogs can be expected to have served to deter some herbivores from millet fields. We posit such damages to cereals crops are a result of the advanced domestication of these cereals that allowed dense planting.

A key change with domestication in cereals is increased apical dominance: more concentrated ears (with heavier and more enlarged grains) on the tip of fewer, straighter culms (Fuller 2007; Doust 2007). This means that trampling, aided by the heavy ears, is prone to cause era and grains to rot on the ground. Wild millet contrasts with many thin diverging stalks, with small spikes and would have required wider spaced planting, more resilient to trampling. So when would apical dominance of millet likely have evolved allowing close planting of dense monocrops, more prone to damage by trampling? This is not a trait directly amenable to archaeobotanial study, although some studies suggest that this trait for rice emerged around 6000BP at the end of the domestication process (Fuller and Qin, 2009; Weisskopf et al. 2015).

Wang also draws on historical European pig management, like English pannage, to suggest that pigs might have been managed free-range in woodlands consuming "acorns and beech nuts". Certainly, this has been common in many European management systems. None are more iconic than the *dehesa* system of Southwest Spain, where extensive oak-grass parklands are managed largely for the production of pigs fatted on acorns which yield highly valued *iberico ballota negra* hams (Parsons 1962). However, is such a system, with poor agricultural soils and low human population likely to underpin the increasing sedentism and demographic growth in Neolithic China, especially in the loess plateau where the extent of forest cover is debated (e.g. Lv et al. 2003)?

In Europe those traditions were influenced by the model of transhumant pastoralism based on caprines and cattle. In contrast, within the China the only pre-exiting model for animal keeping was the dog, rather more associated with the home/village, as all-purpose settlement-space cleaners and scavengers. This fundamental difference in pig management trajectories in West and East is implied by the differences in genomic patterns too. Contrasting to the genetic evidence implying routine interbreeding of European pigs in the woodlands with wild boar and recruitment of sows or piglets from this route (Larson et al. 2007), genetic data from China indicates a high diversity of wild boar haplogroups absent from the mitochondrial diversity of domesticated pigs, including ancient DNA samples (Larson et al. 2010). We need to develop a distinctive East Asian model that is more of a commensal pathway to domestication rather than a prey pathway. We agree, however, that detailed consideration of assemblage age profiles, sex and size variability is required, along with more stable isotope work to place these in Neolithic food webs (along the lines of Yang et al. 2022).

Another important process in Niche Construction concerns fire, a point raised by **Flad** and **Marston**. Charcoal is an important environmental proxy in palaeo-environmental studies in the Loess Plateau and neighbouring regions. However, patterns and changes of Holocene fire regimes are patchy and differ between regions. Additionally, although progress has been made to differentiate wildfires from man-man ones based on charcoal size, linking Holocene fire records with human activities such as land clearance and farming remains difficult. Whilst we suggest more frequent fire events during the early-Holocene on the Loess Plateau compared to the succeeding Yangshao period, but such patterns are not consistent in all regions and datasets (compare Du et al. 2022 and Xu et al. 2021). Further work is needed to determine how off-site charcoal records can be correlated meaningfully with on-site records, such as archaeobotany, in establishing site and regional histories of farming and landscape modification, taking into account factors such as tillage, fallows, agricultural intensification and settlement expansion. A more holistic understanding of fire in human ecosystems alongside cultivation, animal husbandry, and settlement is integral in defining human niches.

Dr. **Spengler** draws attention to his hypothesis that grazing herbivores are central to crop domestication. We agree that evolution of domestication in millets is another example of co-evolution in which human practices need to be taken into account alongside the wider ecology and alternative selection pressures that could include herbivores. Certainly large herbivores may have played a role in shaping the distribution of wild plants, including some crop progenitors. While some seeds have adaptations, like small size, thick seeds coats or thick grass husks, that facilitate survival of herbivore digestion, including many small legumes, *Chenopodium*, and some small grasses, these are not the species that underpinned many early cultivation systems, including northern China. The nature of foregut fermenting herbivores (including bovids and cervids) is such that only very small seeds, generally 1 to 1.5mm wide can pass from the foregut to the hindgut and end up on dung, larger seeds are either chewed up and damaged for spit out (Gardner et al. 1993; Sridhara et al. 2016). Experiments with wheat and barley indicate that grains in spikelets are readily digested by sheep (Wallace and Charles 2013) and these are therefore unlikely to be dispersed by herbivores. Larger wild *Panicum,* such as *P. maximum,* which is smaller than the wild progenitor of *P. miliaceum* had very low germination rates from cattle dung (Gardener et al. 2003). Bristle grasses, including wild *Setaria* species are adapted against herbivore consumption by their bristles (James et al. 2009). Instead wild dispersal often relies on mechanical dispersal aids such as awns, as is the case of wheat, oats (and presumably barley) (Peterson and Kellog 2022) or the buoyancy provided by rice awns (Amarasinghe et al. 2020). We therefore conclude that seed dispersal by herbivores is not relevant to the adaptation of many wild cereals, including Chinese millets. Instead, domestication is about how the morphological adaptations of millets evolved in response to the human practices (harvesting, soil preparation, sowing), which has genetic legacies in the plant population just as they had landscape legacies in the pedosphere. Finally, in evaluating legacy of this multi-regional framework to later-period agricultural developments, we agree with **Marston** that the limited use of domesticates in some cases might be ‘a desirable end state rather than a failure or ‘dead end’ on the way to agriculture’.

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