Feature Article

Beginning of pig management in Neolithic China: comparison of domestication processes between northern and southern regions

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Implications

- China was one of the centers of the domestication of pigs. Morphological characteristics and pathological evidences found in pig bones excavated from Neolithic sites in the Yellow River Valley in the north, Yangtze River Valley in the south, and in the region between these two major river valleys suggest that management of pigs had begun around 9000 BP, possibly in multiple places in China.
- Dietary analyses using carbon and nitrogen isotopes in the bone collagen of pigs indicate that a small number of pigs with C4 plants in their diet appeared in northern China in the Early Neolithic between 9000 and 7500 BP. Many *Sus* samples of the Middle Neolithic Yangshao Period, when millet cultivation became the dominant form of farming in northern China, show an intake of C4 plants in their diet. Nitrogen isotope ratios were also elevated, suggesting that many pigs received fodder which included both C4 plants and kitchen wastes.
- *Sus* with enriched nitrogen isotope values were also found among the Early Neolithic samples from the Yangtze Delta sites. Most pigs from the southern sites had a diet dominated by C3 plants even after millets were introduced to the Yangtze River Valley. The pig managements in southern China were more extensive than those in the northern Neolithic sites, probably because of the abundance of wild plants in the vicinity of the settlements that could be used as fodder for pigs. Hunting of wild animal resources also continued.
- In northern China, the human control over the diet and breeding of pigs was more intensive, and hunting of wild pigs was rare. The isotope ratios of *Sus* samples from Huai and Han River Valley sites were variable, suggesting that each site had a versatile strategy in food production.

Key words: China, domestication of millets, isotope analysis, management of pigs, Neolithic

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Introduction

The relationship between humans and wild boar (*Sus scrofa*) in the process of their domestication has been diverse and complex because of the behavioral and dietary flexibility of *Sus*. Several "pathways" to pig domestication have been proposed (Zeder 2012). Variations in management strategies and intensity of human control over behavioral and reproductive aspects of the life history of pigs resulted in the different trajectories of the domestication process that influenced the rate of phenotypic changes associated with domestication. Pigs were domesticated independently in at least two locations of the world: in northern Mesopotamia by c. 10500 Before Present (**BP**) and in China by c. 8000 BP (Price and Hongo 2019).

In China, sedentary communities emerged by around 11000 BP both in the Yellow River Valley in northern China and the Yangtze River Valley in the south (Liu 2005). These settlements provided the setting for the beginning of domestication of pigs, where some wild pigs took advantage of the anthropogenic niche and the "commensal" pathway proposed by Zeder (2012) could have started. The Neolithic cultures in China are grouped according to the two major geographical regions: those in the Yellow River Valley in the north and those in the Yangtze River Valley in the south. Generally, the east–west line between the Qinling Mountains and Huai River is regarded as the border between these two regions. Wild millets were initially exploited in the northern region, where domestic types of millet were attested by 7800 to 7500 BP (see below), then dryland framing of millets became the main form of agriculture from the Middle Neolithic. Rice (*Oryza sativa*) was the main crop in the southern Neolithic, where the domestic form of rice was reported as early as 8000 to 7000 BP at Kuahuqiao 跨湖桥 in the Lower Yangtze delta. Agriculture developed in the form of intensive production of rice in the irrigated paddy-field. In the initial stage of the Neolithic, wild plants and animals occupied a significant portion of food resources in both agricultural zones. By the Middle Neolithic Yangshao Culture period, dry-land farming of millets combined with pig husbandry supplemented by occasional hunting was the typical form of subsistence in the north. In the south, rice-paddy agriculture and pig management were combined with fishing, hunting, collecting of nuts and other plant resources. Increasing interaction between northern and southern Neolithic cultures in the Yangshao Period promoted southward expansion of millet and northward expansion of rice. The development of social complexity and urbanization supported by increased agricultural productivity can be observed in the Late Neolithic Longshan period in both the north and south. In the Longshan Period, crops and domestic animals of West Asian origin, wheat, cattle, sheep and goats were first introduced to northern China. (See Figure 2 for chronology of major Neolithic cultures in China.)

Zooarcheological data suggest different historical trajectories of pig management practice, based on environmental settings in the north and south. In addition to the differences in major crops, the way that animal husbandry practice was integrated in the agricultural economy could be different in the two regions. We propose that pig management developed as part of overall intensification of agriculture in the north incorporated in the effort to increase productivity, while in the south pigs were added to broad-spectrum utilization of both wild and domestic food resources.

In this article, we will examine the different regional trajectories of pig husbandry practices in the course of Neolithic development in China. The sites mentioned in this article are shown in Figure 1 and Table 1. We will review the evidence of domestication of millets in northern China and discuss the timing and process of intensification of pig management in relation to the beginning of agriculture. The evidence of pig management in the Yellow River Valley and the Yangtze River Valley, where rice was the major crop, will be compared based on morphological and isotopic evidence of carbon, nitrogen and strontium analyses. We will also examine the pig husbandry practices in the fertile region between the two major centers of development of Neolithic cultures, along the Huai and Han rivers. This region functioned to connect the northern and southern Neolithic cultures and became the third important center of Neolithic developments in the Middle and Late Neolithic periods.

Morphological Evidence of Pig Domestication in China

Evidence of management of *Sus* in various degrees of intensification are reported from both the Yellow River Valley and Yangtze River Valley Neolithic sites, starting from around 9000 BP. However, we have little information about the hunting strategies of wild *S. scrofa* or the initial stages of management of *Sus* in China. Also lacking are comprehensive data on the regional variation of the size of wild pig populations, that makes it difficult to assess the size reduction of pigs in the early stage of domestication. Metric data of *Sus* excavated from Neolithic sites in both northern and southern China are gradually accumulating that give us some information about the timing and process of domestication of pigs.

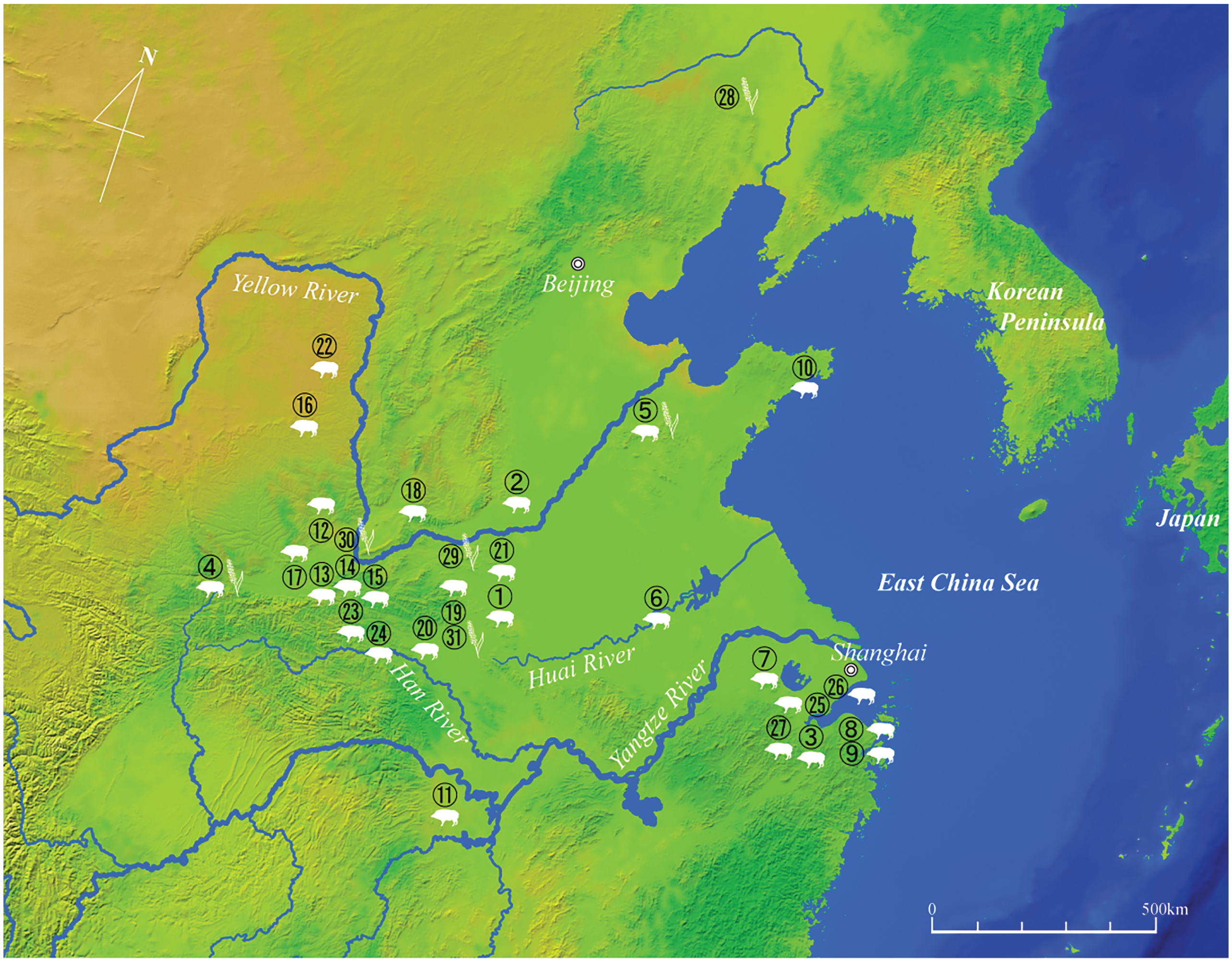
Yellow River Valley

The oldest evidence of management of pigs was reported from Jiahu 贾湖, Henan (9000 BP), located at the southern border of the Yellow River valley. Archeologists argued for pig-keeping being practiced at Jiahu based on the pathological characteristics found on their teeth (e.g., rotation of teeth and frequent occurrences of linear enamel hypoplasia [**LEH**]), as well as the age profile biased toward younger animals (Luo et al. 2008). Geometric morphometric analyses of three mandibular second molars (9000 to 7800 BP) from Jiahu by Cucchi et al. (2011) also suggested that domestic pigs were present at the site as early as 9000 BP in the Cishan/Peiligang Culture period. In the middle Yellow River Valley in Hebei, at Cishan 磁山, a decrease in the mean length of the lower third molar (41.4 mm) in 8000 BP compared with Paleolithic wild boar (45 mm) was presented as evidence for the beginning of pig management at the site (Yuan and Flad 2002). The mean length of over 41 mm at Cishan is, however, well within the range of Neolithic wild boar if we use the 37-mm threshold suggested by Cucchi (2016) to separate wild and domestic pigs at Xiawanggang 下王岗 in Henan.

The decrease of tooth size continued after 8000 BP. Wang et al. (2015) compared the breadth and length measurements of lower molar teeth of pigs from sites along the Wei River, located south of the Yellow River. The mean lengths of molars of pigs from Wayaogou 瓦窑沟, Jiangzhai 姜寨 I and II, Quanhucun 泉护村, in the Middle Neolithic, were smaller than that reported for Cishan (summarized in Price and Hongo 2019, Table 5), and a trend of size reduction of the mandibular third molar (M3) through time between 6300 and 3600 BP can be observed. Further shortening of teeth is observed at the Bronze Age site Donglongshan 东龙山 (4000 to 3600 BP) where the mean length of lower M3 was 33 mm, well within the range of domestic pigs. In addition, higher rates of LEH compared with modern wild boar were also reported from these sites (Wang et al. 2015).

Yangtze River Valley

In the lower Yangtze Valley, *Sus* occupied less than 10% of the faunal remains at Kuahuquiao (Peiligang Culture, 8000 to 7000 BP). The possibility of the beginning of pig management was suggested based on the presence of pathological specimens with rotated teeth (Yuan and Yang 2004). Wild mammals, mainly Cervidae, dominated the faunal remains in the early and middle Neolithic sites of this region. The proportion of *Sus* in faunal assemblages began to increase in the Songze



1. Jiahu 2. Cishan 3. Kuahuqiao 4. Dadiwan 5. Yuezhuang 6. Shuangdun 7. Luotuodun 8. Tianluoshan9. Hemudu 10. Beiqian 11. Chengtoushan 12. Wayaogou 13. Jiangzhai 14. Quanhucun 15. Xipo 16. Wuzhuangguoliang 17. Kangjia 18. Taosi 19. Wadian 20. Xiawanggang 21. Xinzhai 22. Shenggedaliang 23. Donglongshan 24. Qinglongquan 25. Dongjiaqiao 26. Longnan 27. Linagzhu (Bianjiashan, Meirendi, Zhongjiagang) 28. Xinglonggou 29. Zhuzhai 30. Baijia 31. Baligang

Figure 1. Map of Neolithic sites referred to in this text.

崧泽 Culture (6000 BP) period and subsequently replaced the Cervidae in the Liangzhu 良渚 Culture period (5500 to 4000 BP). Decrease of deer and increase of *Sus* were also reported at Longnan 龙南 in Jiangsu (Okamura 2000). There were, however, intersite variations in the faunal composition in the Yantze Delta sites (Dong and Yuan 2020), and the high proportion of pigs might be a phenomenon only at urban sites (see the discussion on Liangzhu sites below). Wang et al. (2015) studied the faunal remains in the Songze-Liangzhu period context at Dongjiaqiao 董家桥, Zhejiang, and reported that, although the proportion of *Sus* was about 30% of NISP, relatively young individuals between 6 and 24 months old were dominant. Together with the relatively small size of the *Sus*, they suggested the keeping of pigs at the site.

Matsui et al. (2016) compared the relative proportion of taxa in the faunal remains from Early (7000 to 5000 BP) and Late (5000 to 4000 BP) Neolithic sites in the Lower Yangtze River Valley and reported the drastic decrease of Cervidae and increase of pigs. The faunal assemblages at Early Neolithic sites of Hemudu 河姆渡 and Tianluoshan 田螺山 are characterized by high proportions of Cervidae. The Late Neolithic *Sus* remains from three localities of Liangzhu Archaeological Ruins 良渚古城 (LAR), Bianjiashan 卞家山, Meirendi 美人地, and Zhongjiagang 钟家港 were investigated in detail. The *Sus* remains occupied more than 90 % of identified mammal remains both at Meirendi and Bianjiashan (Matsui et al. 2016; Kikuchi et al. 2020). The mandibular M3 length measurements of *Sus* samples range c. 22 to 26 mm at Meirendi and 28.42 to 42.84 mm at Bianjiashan, suggesting that hunting of the wild boar continued, while domestic pigs were kept and consumed at this site. The investigator proposed that the individuals with M3 length over 40-mm might be wild boar (Zhang 2014; Kikuchi

Table 1. List of Neolithic sites referred to in the text

Region	Site	Culture	Age (BP)	Reference
Yellow River	Cishan 磁山	Cishan 磁山	8100–7000	Zhou (1981)
	Yuezhuang 月庄	Houli 后李	7500–7200	Hu et al. (2008)
	Dadiwan 大地湾	pre-Yangshao (Dadiwan 大地湾 Culture)	7900–7200	Barton et al. (2009)
		Yangshao 仰韶	6500–4900	Barton et al. (2009)
	Beiqian 北阡	Dawenkou 大汶口	6100–5500	Wang et al. (2013)
	Xipo 西坡	Yangshao 仰韶	5800–5500	Ekaterina et al. (2005)
	Wuzhuangguoliang 五庄果梁	Yangshao 仰韶	5500–5000	Guan et al. (2008)
	Wadian 瓦店	Longshan 龙山	5000–4000	Chen et al. (2017)
	Taosi 陶寺	Longshan 龙山	4400–3900	Zhang et al. (2007), Chen et al. (2012)
	Kangjia 康家	Longshan 龙山	4300–4000	Ekaterina et al. (2005)
	Xinzhai 新砦	Longshan 龙山	4100–3800	Wu et al. (2007), Zhang et al. (2015)
	Shengedaliang 神圪垯梁	Longshan 龙山	3800–3600	Chen et al. (2018)
Huai and Han River	Jiahu 贾湖	Peiligang 裴李岗	9000–7500	Luo (2012)
	Shuangdun 双墩	Shuangdun 双墩	7300–6500	Guan et al. (2011)
	Qinglongquan 青龙泉	Yangshao 仰韶	5500–5000	Luo (2012)
		Qujialing 屈家岭	5100–4600	Guo et al. (2011), Chen et al. (2015)
		Shijiahe 石家河	4600–4000	Guo et al. (2011), Chen et al. (2015)
	Xiawanggang 下王岗	Yangshao 仰韶	6600–5400	Cucchi et al. (2016)
		Qujialing 屈家岭	5400–4500	Cucchi et al. (2016)
		Longshan 龙山	4600–3900	Cucchi et al. (2016)
Yangtze River	Kuahuqiao 跨湖桥	Kuahuqiao 跨湖桥	8000–7000	Yoneda et al. (2016)
	Luotuodun 骆驼墩	Majiabang 马家浜	7300–5900	Guan et al. (2019)
	Tianluoshan 田螺山	Hemudu 河姆渡	7000–6000	Minagawa et al. (2010)
	Liangzhu 良渚	Liangzhu 良渚	5300–4500	Yoneda et al. (2016)

et al. 2020). The metric data, however, do not separate clearly into large and small size groups at Tianluoshan, or at the three localities of LAR (Kikuchi et al. 2020: Figure 3-3). The age profile of the *Sus* from three LAR sites, indicated that young adults between 1 and 2 yr of age were most frequent, although both young individuals and adults over 2 years were present (Zhang 2014; Matsui et al. 2016; Song 2019; Kikuchi et al. 2020). Specimens with tooth pathology, such as rotation of teeth, periodontal disease, and frequent linear enamel hypoplasia (90 of 273 molars from Bianjiashan), were found among the *Sus* assemblages. The zooarcheologists concluded that many of the *Sus* found at Tianluoshan and LAR sites were at the early stage of domestication under extensive management. Wild pigs were also hunted, and hybridization between domestic and morphologically wild individuals occurred frequently, resulting in the mixture of wild and domestic morphological characteristics among the *Sus* bones in the assemblage (Zhang 2014; Matsui et al. 2016; Kikuchi et al. 2020). The management of pigs did not seem to intensify in the following Qianshanyang 钱山漾 Culture period (Neolithic-Early Bronze transition). Deer was dominant in the faunal assemblages, suggesting the exploitation of wild resources continued (Kikuchi et al. 2020).

Multiple origins of pig domestication in China have been suggested based on the different pace of morphological changes observed in the Neolithic pigs in northern and southern China (Luo and Zhang 2008; Yuan 2008). Recent accumulation of genomic evidence can also be interpreted to support a multiregional process of domestication (Xiang et al. 2017). We still do not yet have enough data to make a diachronic or intersite comparison of morphological and demographic changes during the critical period between 9000 and 6000 BP, but the evidence at hand suggests more intensive management strategies of pigs at the sites in the Yellow River Valley.

Domestication of Crops and Development of an Agricultural Economy

The different pace of morphological changes in pigs between the north and south discussed above reflects the regional difference in the degree of human control over *Sus* populations. The management strategy of pigs must have been an integrated part of the regional agricultural economy and was related to the aspects of work allocation and resource availability. We will briefly review the domestication of major crops in northern and southern China, since Neolithic plant cultivation and animal husbandry developed in the process of adapting to the different ecosystems of the two regions in the effort to efficiently utilize their resources.

Domestication of Millets in the Yellow River Valley

Both foxtail millet (*Setaria italica*) and broomcorn millet (*Panicum miliaceum*) were domesticated in the Yellow River

Valley in northern China. Archeobotanical evidence suggests that wild millets had been exploited in the final Paleolithic/initial Neolithic (see the summary by Stevens et al. 2020). Secure archeobotanical evidences of both *Panicum* and *Setaria* were associated with the Cishan Culture period (8100 to 7600 BP) at Cishan, Hebei, the site where the beginning of domestication of pigs in 8000 BP was also suggested (see above). Direct C14 dating of carbonized grains suggest that domestic-type millets began to be found by around 7500 BP in the Yellow River Valley sites (Stevens et al. 2020). Early examples of charred *Panicum* and *Setaria* grains were reported from Yuezhuang 月庄 (Houli 后李 Culture, 8000 to 7700 BP) in Shandong (Hu 2008; Crawford et al. 2016). Remains of rice were also found from Yuezhuang, although whether of a wild or domestic status was ambiguous (Crawford et al. 2016). *Panicum* grains were also reported from Xinglonggou 兴隆沟 (Xinglongwa 兴隆洼 Culture, 8000 to 7500 BP) in Inner Mongolia (Zhao 2011).

In general, broomcorn millet (*Panicum miliaceum*) was dominant among the millet remains at pre-Yangshao period sites and foxtail millet (*Setaria italica*) was relatively scarce. Carbonized grains of *Panicum* were rare, and no *Setaria* grains were found in the pre-Yangshao Dadiwan 大地湾 Culture contexts (7500 to 7200 BP) at Dadiwan in Gansu. Both *Panicum* and *Setaria* grains were attested in the Yangshao period contexts of 6500 to 4900 BP at the same site (Liu et al. 2004). At Beiqian 北阡, a Dawenkou 大汶口 Culture site (6100 to 5500 BP) in the eastern periphery of Yellow River Valley on the coast of Shandong Peninsula, *Panicum* was dominant, although *Setaria* was also found. The latter became increasingly common through time and became a dominant variety of millet during the Yangshao period when millet cultivation became wide spread in northern China (Barton et al. 2009; Lu et al. 2009; Crawford et al. 2016; Jin et al. 2016; Bestel et al. 2018).

Domestication of Rice in the Yangtze River Valley

In the Yangtze River Valley in southern China, a domestic form of rice was reported as early as 8000 to 7000 BP at Kuahuqiao 跨湖桥in Zhejiang, and rice became the main crop of Neolithic plant cultivation. A shift from exploitation of wild food resources to more intensive subsistence strategies including rice production in irrigated fields and reclaimed land, occurred in the Late Neolithic. Millets also began to be cultivated after 6000 BP. Carbonized grains of foxtail millets were attested in the Daxi 大溪 Culture period contexts (5800 BP) at Chengtoushan 城头山 in Hunan in the middle Yangtze River Valley (Nasu et al. 2007; 2012). Chengtoushan is a site surrounded by moats, where both rice and millet were found. Rice was probably cultivated in the small paddy fields as well as in the wetland of flood plain around the site, while millet was cultivated on the dry farmland on the upland terrace area in the site.

Plant Cultivation in the Huai and Han River Valleys

The environment of Huai and Han River Basin between the two major river valleys was suitable for both dry-land farming of millets and paddy-field rice cultivation. Archeobotanical evidence of rice comes earlier than millet. The rice grains found from Phase 1 of Jiahu (c. 9000 to 8500 BP) were identified as an "early cultivated form with some surviving wild rice characteristics" (Zhang & Hung 2013: 50). Evidence of early pig management was also reported from Jiahu (see above) where isotope analyses of pig remains also provide supportive evidence (see below). Barnyard millet (*Echinochloa* sp.), a C4 plant, was found at Jiahu, but was identified as a wild rice-paddy weed (Zhang & Hung 2013). Over 70% of spikelet bases of rice recovered from pre-Yangshao contexts of Baligang 八里岗 (c. 9000 to 8500 BP), Henan, were of a nonshattering domestic form (Deng

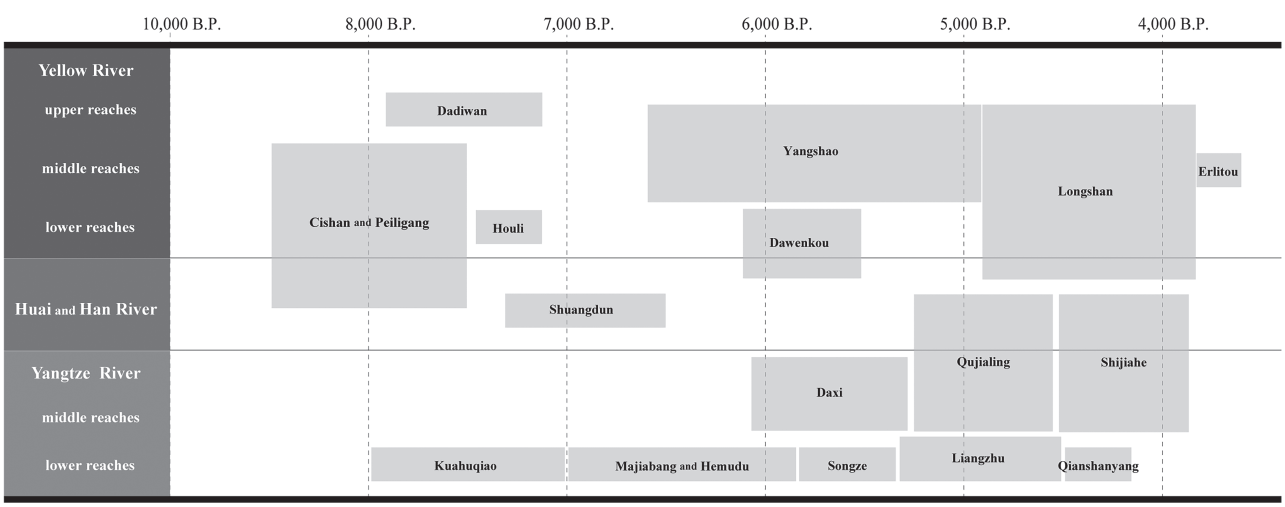


Figure 2. Chronology of Neolithic cultures in China.

2015; Zhang & Hung 2013). Both Jiahu and Baligang are located within the northern limit of distribution of wild rice in the Early Holocene (Fuller 2011: Fig. 1). Charred grains of millets (*Panicum*) were recovered from Zhuzhai 朱寨 (Peiligang 裴李岗 Culture) in Henan (Bestel et al. 2018), and Baijia 白家 (Dadiwan Culture) in Shaanxi, that were directly dated to c. 7700 to 7500 BP (Yang et al. 2016). Evidence of mixed farming of rice and millets (both *Panicum* and *Setaria*) was reported from the Yangshao Culture period context at Baligang (Deng 2015).

The evidence from the Huai and Han River basins as well as from Chengtoushan in the Yangtze River Valley suggest that millets began to spread southward from their center of domestication by the beginning of the Yangshao Culture period, and wherever the environment was suitable, dry-land farming was practiced alongside rice cultivation as part of intensification of agricultural production in the Late Neolithic.

Isotope Evidence as an Indicator of the Management of Pigs

Light stable isotope ratios of carbon and nitrogen in bone collagen can be a powerful tool in evaluating the degree of human influence over *Sus* populations during the early stages of domestication process. That is, when some pigs began to adapt to the anthropogenic niche, human induced selection pressure was not strong enough to cause phenotype changes (Matsui et al. 2005; Minagawa et al. 2005; Price and Hongo 2019). The diet of *Sus* could also shift by changes in the availability of natural vegetation due to expansion of agricultural fields, or intentional foddering by humans. The bone collagen of wild herbivores feeding exclusively on C3 plants, including deer and wild pigs that were exploited at the Neolithic sites in China, have $\delta^{13}C$ values between −25 and −20‰ and $\delta^{15}N$ values between 4 and 7‰ (Yoneda et al. 2016, based on the data of wild pigs from Neolithic southern China and Jomon period Japan). The $\delta^{13}C$ values in herbivores would change when the animals had C4 plants in their diet. Millets are C4 plants with c. 15‰ enrichment in the $\delta^{13}C$ value compared with C3 plants. Elevated $\delta^{13}C$ values in the bone collagen of *Sus*, therefore, have been interpreted as an indicator of human influence in their diet (Hu et al. 2008), for example, raiding a millet field or feeding in the field after harvest, or possibly the foddering of millet leaves or grains. We have to take some cautions, however, because wild C4 plants might be available in some places in northern China.

Since nitrogen isotope values reflect the trophic levels and are related to the protein intake in the animals' diet (Schoeninger & DeNiro 1984; Bocherens & Drucker 2003), the enrichment of nitrogen isotope ratios of *Sus* indicates the shift to a more omnivorous diet. Such a dietary shift could also occur under influence of humans, for example, when wild pigs had opportunities to scavenge settlement waste, or if some young pigs of wild origin were captured and penned for later consumption and provisioned kitchen waste.

The isotope ratio of strontium ($^{87}Sr/^{86}Sr$) in the hard tissue of animals is useful in investigating hunting and husbandry practice. Strontium is taken into animals' bodies through food and water, and its isotope ratios reflects the geological characteristics of the animals' habitat (Bentley 2006). Therefore, strontium isotope ratios of *Sus* give us some insight into the procurement or intersite transfer of animals and animal products.

Dietary Analyses of *Sus* From Neolithic Sites in China, Using Carbon and Nitrogen Isotope Ratios

Yellow River Valley

Carbon and nitrogen isotope data of *Sus* from Neolithic sites in the Yellow River Valley are plotted in Figure 3. The pre-Yangshao period samples are available from Phase 1 (7900 to 7200 BP) at Dadiwan (Barton et al. 2009: Figure 2B). Although only a few samples were analyzed, the $\delta^{13}C$ values concentrate around −20‰, and the $\delta^{15}N$ values range from 5 to 7‰. These values are similar to those of herbivores that mainly consume C3 plants. Another set of pre-Yangshao isotope data comes from the Houli Culture context (7500 to 7200 BP) at Yuezhuang in the lower Yellow River Valley, where millet and rice grains were attested as early as 8000 BP. One of the *Sus* samples from Yuezhuang had an enriched $\delta^{13}C$ value and another had a high $\delta^{15}N$ value. Some researchers argued for the beginning of cultivation of millet at this site (see above). Management of pigs could also have been initiated earlier in the lower Yellow River Valley than in upstream regions, but the sample size at Yuezhuang was too small to evaluate the possibility.

Also located in the northeast, some *Sus* samples from Beiqian (6100 to 5500 BP), a Dawenkou Culture site located on the coast of Shandong Peninsula, yielded somewhat elevated $\delta^{13}C$ values, but the values were lower than those of the *Sus* samples from contemporary sites in the middle Yellow River Valley.

Many of the samples in Phase 2 of Dadiwan (Yangshao Culture period, 6500 to 4900 BP) showed enrichment of both $\delta^{13}C$ and $\delta^{15}N$ values. This shift in the diet of *Sus* at Dadiwan took place by around 5800 BP, which was interpreted as evidence for the domestication of pigs beginning sometime between 7200 and 5800 BP. The dietary shift of *Sus* coincided in timing with the findings of carbonized grains of both foxtail and broomcorn millets at the site (see above). The $\delta^{13}C$ values, however, are scattered between −20 and −6‰, suggesting that the proportion of C4 plants in the diet of *Sus* varied widely. The samples with elevated $\delta^{13}C$ values also showed a tendency of higher $\delta^{15}N$ values, between 7 and 9‰, which were similar to those of dogs, suggesting that the *Sus* that were given millet leaves or even grains and also had access to settlement waste. The researchers suggested that the small number of individuals with intermediate δ13C and $\delta^{15}N$ values represent wild pigs or extensively managed individuals that had only occasional access to C4 plants and kitchen waste (Barton et al. 2009: 5526 and Figure 2B). Isotope data of the Yangshao Culture period were also available from Xipo西坡 in Henan, and Wuzhuangguoliang 五庄果梁 in Shaanxi. The *Sus* samples of these sites showed enrichment in both $\delta^{13}C$ and $\delta^{15}N$ values. In contrast to the wide range of variation in $\delta^{13}C$ observed

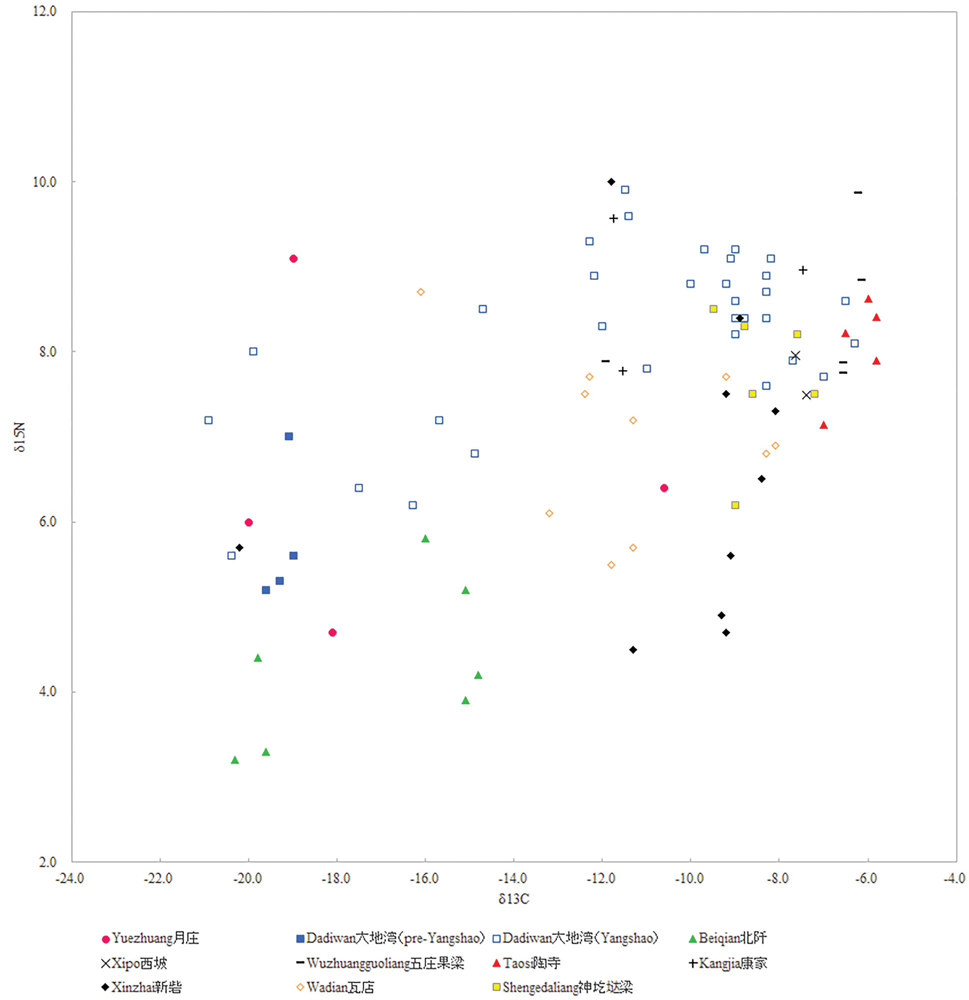


Figure 3. Carbon and nitrogen isotope ratios of *Sus* samples from Neolithic sites in the Yellow River Valley.

in Dadiwan, pigs from Xipo and Wuzhuangguoliang seemed heavily dependent on C4 plants (Figure 3).

The isotope data of *Sus* samples from the Late Neolithic Longshan period after 5000 BP in the middle Yellow River Valley were reported from Wadian瓦店 (5000～4000BP) and Xinzhai 新砦 (4100～3800 BP) in Henan, Taosi 陶寺 (4400～3900 BP) in Shanxi, and also Kangjia 康家(4300 to 4000 BP) and Shengedaliang 神圪塔梁 (3800 to 3600 BP) in Shaanxi (Chen et al. 2018). The Wadian samples showed a wide range of $\delta^{13}C$ values, but most samples from other sites had values between −10 and −6‰, indicating a considerable proportion of C4 plants in their diet. Only a few specimens from Xinzhai and Kangjia showed an intermediate $\delta^{13}C$ value of −11‰. One of the samples from the earlier phase of Xinzhai indicated a presence of *Sus* that had a value indicative of a herbivores diet of C3 plants, which might have come from a wild boar. This suggests that the natural vegetation around the site was dominated by C3 plants. Nitrogen isotope ratios are also high in most samples of the Longshan Culture period, but those from Wadian and the later phase of Xinzhai (3900 to 3800 BP) were variable. Thus, C4 plants were generally incorporated in the diet of *Sus* in the Yangshao Culture period, and by the Longshan Culture period, most of the *Sus* samples from the Yellow River Valley had high proportions of C4 plants in their diet. There are, however, some sites where carbon and nitrogen isotope ratios were variable, suggesting that each site took a different management strategy in regards to the foddering of pigs. The Longshan Culture period Taosi samples form a group of the highest $\delta^{13}C$ values among the Yellow River Valley sites, with values at −6‰ or higher. The nitrogen isotope ratios were also high (Zhang et al. 2007, Chen et al. 2012, 2017). Taosi is a site surrounded by a moat, and probably functioned as a local political and economic center. The high proportion of *Sus* remains at Taosi (more than 80% of the 4750 identified fragments) (Zhou 2015), as well as the elevated carbon and nitrogen isotope ratios with a narrow range of variation suggest more intensive and controlled management of pigs than that of contemporary Wadian in the same region. The variable carbon and nitrogen isotope ratios at Wadian suggest that some of the pigs were more extensively managed and had less access to settlement wastes and/or C4 plants. Wadian is a residential site located in the southern border of the millet farming zone, where the contribution of C4 plants in the diet could be more variable than Taosi on the northern bank of the Yellow River. Hunting of wild pigs was uncommon at either site, as none of the *Sus* samples had the isotope ratios typical of herbivores feeding on C3 plants.

Yangtze River Valley

Isotope analyses have been carried out at several Neolithic sites in the Yangtze Delta (Figure 4). Carbon and nitrogen isotope ratios of *Sus* samples from Luotuodun 骆驼墩, a Majiabang 马家浜 Culture site (7300 to 5900 BP), were not different from those of herbivores with C3 plant diet (Guan et al. 2019). Only the distribution ranges of the isotope values were available from Kuahuquiao (Peiligang Culture, 8000 to 7000 BP) and Liangzhu 良渚 (Liangzhu Culture, 5300 to 4500 BP). The earliest evidence of domestic rice and the claim of the management of pigs were reported from Kuahuquiao. Yoneda et al. (2016: Figure 3) compared carbon and nitrogen isotope ratios in the bone collagen of deer, dog, pigs, and humans from Bianjiashan and Meirendi in LAR with those from Kuahuquiao and Tianluoshan (data from Minagawa 2010). The pig samples from all four sites showed the $\delta^{13}C$ values of a C3 plant diet, but nitrogen isotope ratios had a wide range. Some *Sus* samples from Kuahuqiao included specimens with elevated $\delta^{15}N$ values around 8 to 10‰, which is comparable to the values of humans and dogs, while others showed no enrichment in the $\delta^{15}N$ values. A diverse pig diet was suggested at Tianluoshan and two localities of LAR (Minagawa 2010; Yoneda 2016), with the $\delta^{15}N$ values ranging between a ratio similar to that of deer and a ratio close to humans. There is no clear dichotomy among the samples that might be expected if both domestic pigs that were provisioned kitchen waste and wild pigs that fed on natural vegetation were present.

The results of isotope analyses suggest that human influence on the diet of pigs was variable in the Neolithic sites in the Yangtze Delta: while some individuals were either fed by humans or had frequent access to settlement wastes, others were free-ranging and/or subsisted mainly on C3 plants (Minagawa 2010; Yoneda 2016).

These isotopic results on *Sus* from Tianluoshan and the LAR sites corroborate the results of morphological studies at these

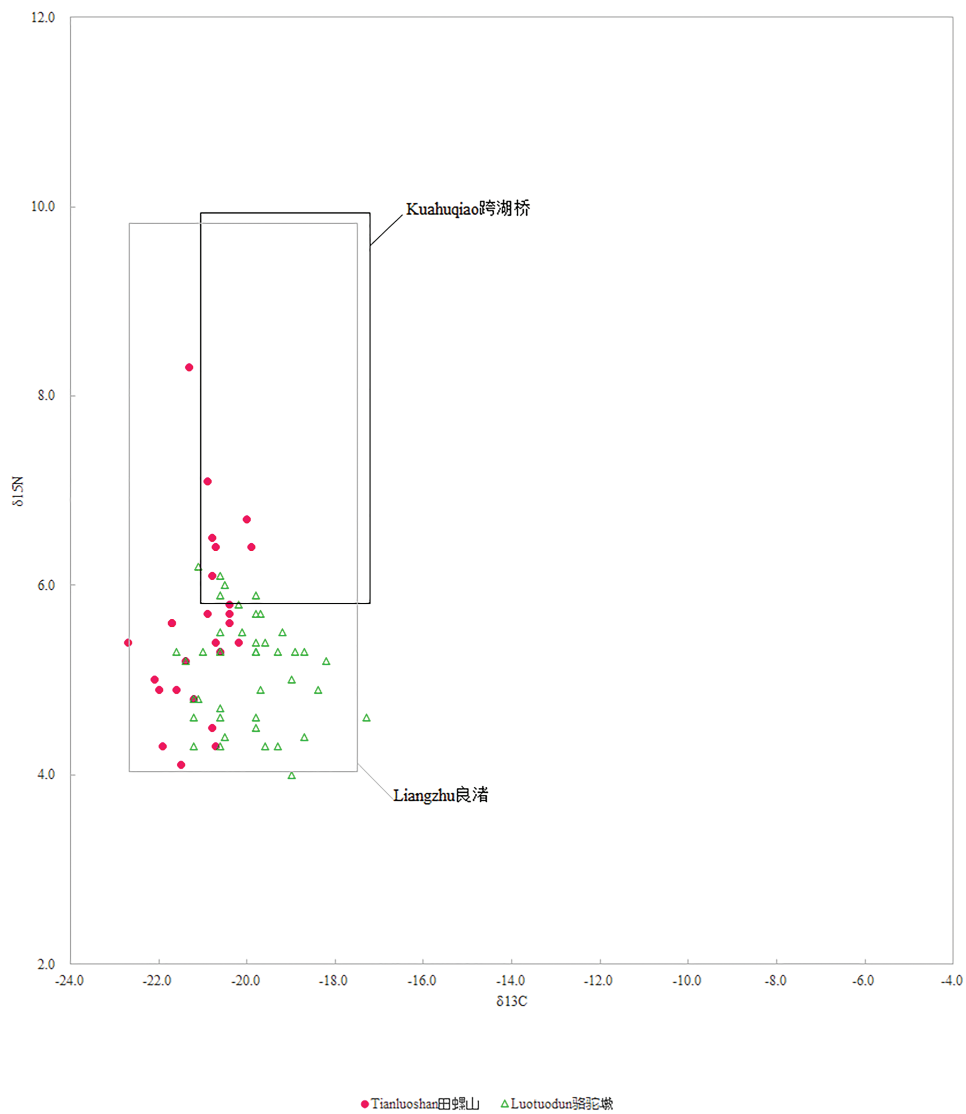


Figure 4. Carbon and nitrogen isotope ratios of *Sus* samples from Neolithic sites in the Yangtze River Valley.

sites, which was that although both wild and domestic pigs were present, the two groups could not be clearly distinguished based on morphological characteristics. Management strategies of pigs in the Yangtze Delta sites tended to be extensive ones, which took advantage of the rich natural vegetation in the region, without regular provisioning of fodder. Strict control over breeding was not practiced either, allowing hybridization between the managed pigs and the wild *Sus* population. Although millet cultivation began as early as 5800 BP in the middle Yangtze Valley (Nasu et al. 2007, 2012, see above), there is no indication of C4 plants in the diet of *Sus* in the Neolithic Yangtze Delta sites.

Huai and Han River Valley

In the region between the two major river valleys, pig management strategies exhibited various trajectories. Analysis of carbon isotopes in pig bones from Jiahu in Henan supports the claim based on morphological study of having the earliest evidence of pig domestication. A sample from Jiahu had elevated nitrogen isotope ratios (Luo 2012), and a few other samples showed the $\delta^{13}C$ values of a C4 plant diet (Figure 5). Although domestic millets have not been found at Jiahu, wild C4 plants have been identified (see above). The presence of a few specimens that showed the isotope values of herbivores with C3 diet, however, suggests that C3 plants were dominant in the natural vegetation around the site. Therefore, human influence on the diet of at least some pigs is strongly suggested at Jiahu. Samples from Shuangdun 双墩 (7300 to 6500 BP) also had a wide range of $\delta^{15}N$ values, between 4 and 8 ‰. There are also a few samples that had elevated carbon isotope ratios around −12‰, suggesting a mixed C3 and C4 plant diet. During the Yangshao Culture period and later, both carbon and nitrogen isotope values of *Sus* samples varied widely. Qinglongquan 青龙泉 (5500 to 4000 BP) located near Han River in Hubei, and Xiawanggang 下王岗 (6600 to 3900 BP, Cucchi et al. 2016) provide the long sequence of the Yangshao, Qujialing 屈家岭, and Shijiahe 石家河 or Longshan Culture periods. Carbon isotope ratios of *Sus* from the Yangshao phase at Qinglongquan indicate a diet of mainly C3 plants, but the $\delta^{13}C$ values became variable from the following Qujialing period, suggesting that C4 plants were incorporated into the diet of pigs. Increasing variability in the nitrogen isotope ratios, ranging between 4 and 7‰, is also observed starting in the Yangshao contexts. A similar tendency was observed at Xiawanggang. Samples with intermediate $\delta^{13}C$ values between C3 and C4 plants had already existed among the Yangshao period *Sus* remains. Clear separation between the samples indicating C3 and C4 diets was observed only in the Longshan period (Cucchi et al. 2016). The samples with elevated $\delta^{13}C$ values tend to also have higher $\delta^{15}N$ values at Qinglongquan during the Qujialing and Shijiahe Culture periods, which might suggest the foddering of both kitchen waste and C4 plants (Guo et al. 2011, Chen et al. 2015).

Strontium Isotope Analysis

The enamel of mandibular third molars of the *Sus* from the three localities of Liangzhu Archaeological Ruins (LAR), Bianjiashan, Meirendi, and Zhongjiagang, were sampled for strontium isotope analysis. The strontium isotope ratios were variable both within and between each locality, ranging from 0.71022 to 0.71290, and the total range of variation at the three LAR sites was 0.00268. The strontium ratio in the immediate vicinity of LAR was 0.713, and closer values to the *Sus* samples were found in the locations about 4 to 10 km from the sites. This result suggests that the *Sus* remains found at LAR sites were supplied from multiple locations to the sites for consumption.

The strontium isotope ratios of *Sus* obtained from the samples from Wadian and Taosi of the middle Yellow River Valley were more consistent, and were not discrepant from the geological values of the sites (Zhao et al. 2011, 2012). The total range of variation found among the samples was 0.00167, much smaller compared with the Yangtze Delta sites. The homogeneous strontium values suggest that the pigs consumed at the two Neolithic sites were locally obtained, and were possibly raised within the sites for local consumption. As discussed above, foddering of millets and kitchen waste to the pigs was suggested by the enrichment in both carbon and nitrogen isotope values of the samples from these two sites. Thus, a more controlled and intensive management of pigs integrated in the economic activities of the settlements was suggested at the Yellow River Valley Neolithic sites compared with that in the Yangtze River Valley sites.

Discussion: Regional Comparison of Pig Management Strategies in Neolithic China

Both morphological and isotopic evidences suggest that the Neolithic sites in the Yellow River Valley and the lower Yangtze delta adopted different strategies of pig management. In the Yellow River Valley sites, pigs were managed more intensively: they were probably penned, and kitchen waste and C4 plants were given as fodder. The contribution of C4 plants became significant from the Yangshao period, when millet cultivation became wide-spread in northern China, suggesting that pigs were either given millet stubble or allowed to feed in the millet field after harvest, if not being given the millet grains. The degree of enrichment of nitrogen isotope ratios varies between sites, but the values are relatively consistent within each site. Therefore, each site probably used a somewhat different combination of fodder according to their economy and the local vegetation. Hunting of wild pigs was rare.

In the Yangtze Delta sites such as Tianluoshan and Liangzhu Archaeological Ruins, pigs were managed more extensively than those in the Yellow River Valley sites. While some pigs had scavenged or were provisioned kitchen waste and perhaps penned, others mainly consumed C3 plants. Hunting of wild pigs continued and hybridization between wild individuals and extensively managed individuals was probably frequent.

The difference in the pig management strategies between the Yellow River Valley and Yangtze River Valley sites probably reflects the environmental differences in the two regions during the transitional period from the Hypsithermal to a drier and colder climate around 5000 BP. The Yellow River Valley sites in the north were more severely affected by the climate change

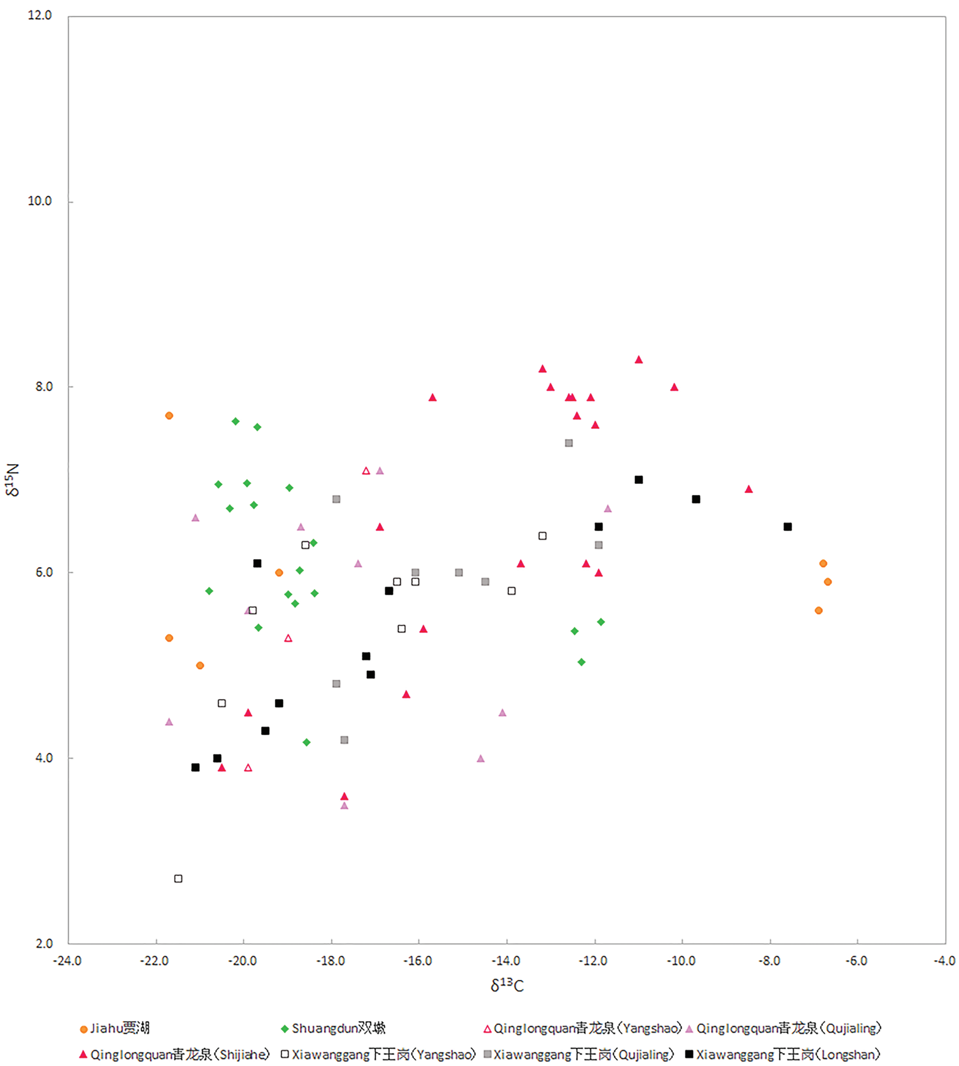


Figure 5. Carbon and nitrogen isotope ratios of *Sus* samples from Neolithic sites in the Han and Huai River Valley.

and had to take a more intensive strategy to increase production in both agriculture and animal husbandry to sustain the population. Foddering with C4 plants may have already started at the initial stage of domestication of pigs in the north, which became common practice in pig management. As more land was converted to farming fields in the effort to increase agricultural production, extensive management of pigs probably became impossible.

There is no indication of the foddering of pigs with C4 plants at the southern sites, even after millets were introduced to middle Yangtze River Valley sites such as Chengtoushan. Rice was the major crop, but not necessarily the major food in the tradition of broad-spectrum resource utilization in southern China. A wide range of food resources including nuts, water caltrop, fish, and wild mammals were procured alongside rice production in the Yangtze Delta sites throughout the Neolithic. Millets were added as another food resource where suitable farmland was available. In the middle Yangtze Valley, the effort to increase production took the form of more diversification of agriculture, while production of rice was intensified by technological innovations such as irrigation to expand the paddy fields. Millets and later wheat were added to the agricultural inventory, and gross agricultural productivity was increased by converting the terraces to farmland. In the course of diversification in agricultural development, pig management also found a suitable niche by efficiently utilizing the abundant natural vegetation as well as settlement waste for fodder, but control over pig population was rather extensive. The proportion of wild mammals in the faunal assemblages probably remained high throughout the Neolithic, as well as the Bronze Age, with the exception of urban sites in the Liangzhu Culture.

This contrasts with the more focused millet production in the Yellow River Valley where higher competition probably existed between animal husbandry and plant cultivation over suitable fields. Thus, pig management in the north took the trajectory of more intensive control over pig population including foddering of millet by-products and strict separation between wild and domestic pig population, possibly by penning of pigs at the sites.

The management strategies of pigs were more variable at sites in the Huai and Han River Basin between the two major river valleys. It seems that an extensive management strategy, similar to that in the Yangtze River valley sites, was employed at pre-Yangshao sites, but a small number of pigs at these sites were eating C4 plants. The variation in both δ^{13}C and δ^{15}N values starting from the Yangshao period indicates a versatile strategy probably taken at the household level.

Conclusion

Although we do not have enough data at hand to determine whether the initial process of domestication of pigs in China had either single or multiple origins, zooarcheological evidence suggests that management of pigs began around 9000 to 8000 BP in both north and south China. Different trajectories in the intensification of pig management between the northern and southern regions can be observed in the Middle Neolithic period, beginning around 6500 BP.

Morphological and metric data as well as the isotope data of archeological pig remains suggest a higher degree of control over pigs in northern China. Carbon and nitrogen isotope analyses of bone collagen of archeological *Sus* remains suggest a shift in the diet in northern China from the Yangshao Culture period, when dry-land farming of millets was widespread in the Yellow River Valley. In the north, pigs were likely penned at sites and given kitchen waste and C4 plants as fodder. The further intensification of pig management in the north which occurred during the Longshan Culture period may be placed in the context of overall intensification of food production in northern China in the transitional period from the Hypsithermal to a colder and drier climate, coinciding with the introduction of wheat, cattle, and sheep around 4500 BP (Yuan 2008).

In the Yangtze Delta sites, enrichment of nitrogen isotope ratios in the bone collagen of some of the *Sus* samples is observed as early as 8000 BP, but the hunting of wild boar seems to have continued, and morphological differences between domestic and wild pigs are not clear-cut. The abundance of natural vegetation in the warmer and wetter environment in southern China and availability of nuts (*Quercus* sp.) and probably root-crops made more extensive management of pigs possible. The high proportion of pigs at urban sites in the Liangzhu Culture Period suggests that the urban sites depended on pigs supplied to them from surrounding settlements. Hunting of wild boar and deer continued well into the Late Neolithic, and even during the Bronze Age. Although millets were cultivated in the Yangtze River Valley by 6000 BP, there is no indication of the foddering of millets or other C4 plants to the pigs. More intersite variation in pig management practice was observed at sites of the Huai and Han river basin, located between the two major river valleys. The region received influence from both northern and southern Neolithic cultures, and the environment was suitable for both dry-land farming of millets and rice paddy farming. We need, however, more pig isotope data from nonurban sites in the Yangtze River Valley, especially from the sites where millets were found to confirm the differences in foddering practice from the sites in north China.

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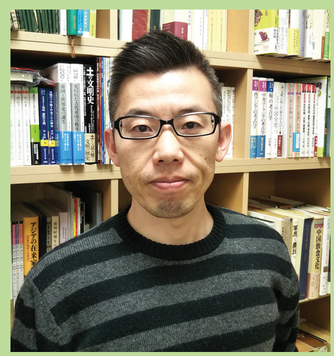

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