Pig domestication and human subsistence at the early Neolithic site of Guanjia (6100–5500BC), Central China

Yue You[a], Xianglong Chen[c], Anke Hein[d], Cunyu Qin[e], Yanan Zhao[f], Jiaxin Zhang[g], Tianyang Liu[h], Wenquan Fan[b], Guangkuo Yuan[a, *]

[a] School of History, Capital Normal University, 100089 Beijing, China; [b] Henan Provincial Institute of Cultural Heritage and Archaeology, 450000 Zhengzhou, China; [c] Institute of Archaeology, Chinese Academy of Social Sciences, 100027 Beijing, China; [d] Institute of Archaeology, University of Oxford, OX1 2PG Oxford, United Kingdom; [e] School of History and Culture, Henan University, 475001 Kaifeng, China; [f] China Agricultural Museum, 100125 Beijing, China; [g] Department of Archaeology & Museum Studies, Renmin University, 100872 Beijing, China; [h] Cultural Relics and Archaeology Institute of Xinjiang Uygur Autonomous Region, 30063 Urumqi, China

* To whom correspondence may be addressed: Guangkuo Yuan
Email: wide2007@163.com;

Yue You: https://orcid.org/0000-0002-1009-6435
Anke Hein: https://orcid.org/0000-0002-5052-1504

Abstract

This case study of the early Neolithic Guanjia site (6100–5500BC) combines zooarchaeological, paleobotanical, and isotope research to investigate how humans raised pigs and incorporated them in their overall subsistence system. Although the teeth (M_2) of *Sus scrofa* from Guanjia were all larger than domesticated pigs dating to the middle Neolithic (Yangshao period, 5000–3000 BC) and early Bronze Age (2000–1000 BC), which would suggest that Guanjia pigs were not domesticated pigs morphologically if body size is a key criterion to identify domesticated animals， we still argue that there was human management of pigs via feeding and culling strategies. We base our argument on the following observations: (1) *Sus scrofa* accounts for 34.2% (n=41) of NISP and 22.2% (n=4) of MNI; (2) most individuals were younger than two years at time of death (mandible n=5, epiphyseal fusion n=14) and most are female; (3) distorted alignment of teeth, a deformation related to early domestication, was found on one left mandible; (4) compared to pure C_3 diets seen in deer ($\delta^{13}C=-21.0\pm0.7‰$, n=3), the majority of *Sus scrofa* consumed some C_4 plants ($\delta^{13}C=-17.4\pm0.8‰$, n=6), probably from C_4 wild grass or cultivated millets; (5) Panicoideae starch grain, broomcorn millet (*Panicum miliaceum*) and foxtail millet (*Setaria italica*) phytoliths were found at Guanjia, further supporting our argument that *Sus scrofa* accessed C_4 millets and human environments. This study also reveals that animals in the early stages of domestication and domestic plants only accounted for a small proportion of human subsistence, thus people still relied heavily on hunting and gathering at Guanjia.

Keywords

Ancient China, Early Neolithic, Pig domestication, Peiligang culture, Subsistence

Statements and Declarations

Competing interests

The authors declare no competing interests.

Conflict of interest

The authors declare no conflict of interest.

Pig domestication and human subsistence at the early Neolithic site of Guanjia (6000–5500BC), Central China

Introduction

How pigs (*Sus scrofa domesticus*) were domesticated and the process of their domestication are key topics in zooarchaeology (Hongo and Meadow 1998; Redding and Rosenberg 1998; Ervynck et al. 2001; Yuan and Flad 2002; Larson et al. 2005; Albarella et al. 2006; Zeder 2011, 2012; Cucchi et al. 2011; Liu 2014; Dong and Yuan 2020; Price and Hongo 2020). Both zooarchaeological and ancient DNA research shows pigs were independently domesticated in multiple regions (Larson et al. 2005, 2010; Albarella et al. 2006; Zhang et al. 2022). In East Asia, China was a crucial centre for pig domestication (Yuan and Flad 2002; Larson et al. 2010; Dong and Yuan 2020). The earliest putative evidence of pig domestication in Central China[1] dating to at least 6600 cal. BC was found at Jiahu, Henan Province, which is attributed to the Peligang culture period (early Neolithic, 7000–5000 BC) (Luo and Zhang 2008; Cucchi et al. 2011; Luo et al. 2015). Although the status and the extent of domestication for Jiahu pigs are still under discussion (Price and Hongo 2020; Hongo et al. 2021), partly because opinions on the appropriate criteria for the definition and identification of domestication from animal bones differ between scholars (Albarella et al. 2006; Vigne 2011; Zeder 2012; Price and Hongo 2020), the zooarchaeological research of Jiahu nevertheless sheds light on our primary understanding of the relationships between humans and animals and human subsistence. At Jiahu there was significant reliance on fish but not on mammals, and more consumption of wild deer than domesticated animals (Luo et al. 2015). Except for Jiahu, little on pig domestication of Peiligang is known because no other site has been researched, limiting our understanding of various pathways towards pig domestication in the early Neolithic.

Archaeological material dating to the Peiligang period provides evidence of permanent settlement, regular production and use of ceramics for preparing and storing food, alcohol making from grains, music, and potentially ritual activities (McGovern et al. 2004; Liu 2014), and Peiligang profoundly influenced the following Yangshao culture (5000–3000 BC). During this period, broomcorn millet (*Panicum miliaceum*), foxtail millet (*Setaria italica*), and rice (*Oryza sativa.*) were cultivated, but their ratios were still low compared to wild species of plants (Zhang et al. 2012, 2018; Liu 2014; Wang et al. 2017; Bestel et al. 2018; Zhao 2020), suggesting humans were just starting to shift from hunting-gathering to farming subsistence. This argument is also supported by isotopic analysis showing that C_4 plants, such as cultivated millets, only accounted for a very small number of human diets and pig diets in early Neolithic central China, for example, isotope data from human bones ($\delta^{13}C = -17.8 \pm 0.3‰$, $\delta^{15}N = 9.0 \pm 0.6‰$; n=10) at Xiaojingshan and pig bones at Yuezhuang ($\delta^{13}C = -16.9 \pm 4.3‰$, $\delta^{15}N = 6.6 \pm 1.8‰$, n=4), Shandong Province (Hu et al. 2008), and pig bones at Cishan ($\delta^{13}C = -18.6 \pm 3.1‰$, n=6), Hebei Province (Hou et al. 2023). Unfortunately, C_4 signals of human diets or pig diets have so far not been reported from other Peiligang sites besides Jiahu, making it difficult to fully understand how millet farming and animal husbandry developed in the early Neolithic.

In this paper, we present Guanjia as a case study of early Neolithic subsistence practices based on various scientific analyses including (1) zooarchaeological analysis of taxa frequencies, ages at death, sex ratios, comparison of teeth measurements, and pathological observations, (2) C/N isotope analysis of *Sus* and cervid bones, and (3) paleobotanical findings such as starch grains and phytoliths found on the inner surface of pottery sherds, to investigate pig domestication and human subsistence in early

---

[1] Central China refers to the plains around the lower Yellow River, including Henan, Shandong, and Heibei provinces.

Neolithic of central China.

Materials and Methods

The Guanjia Site

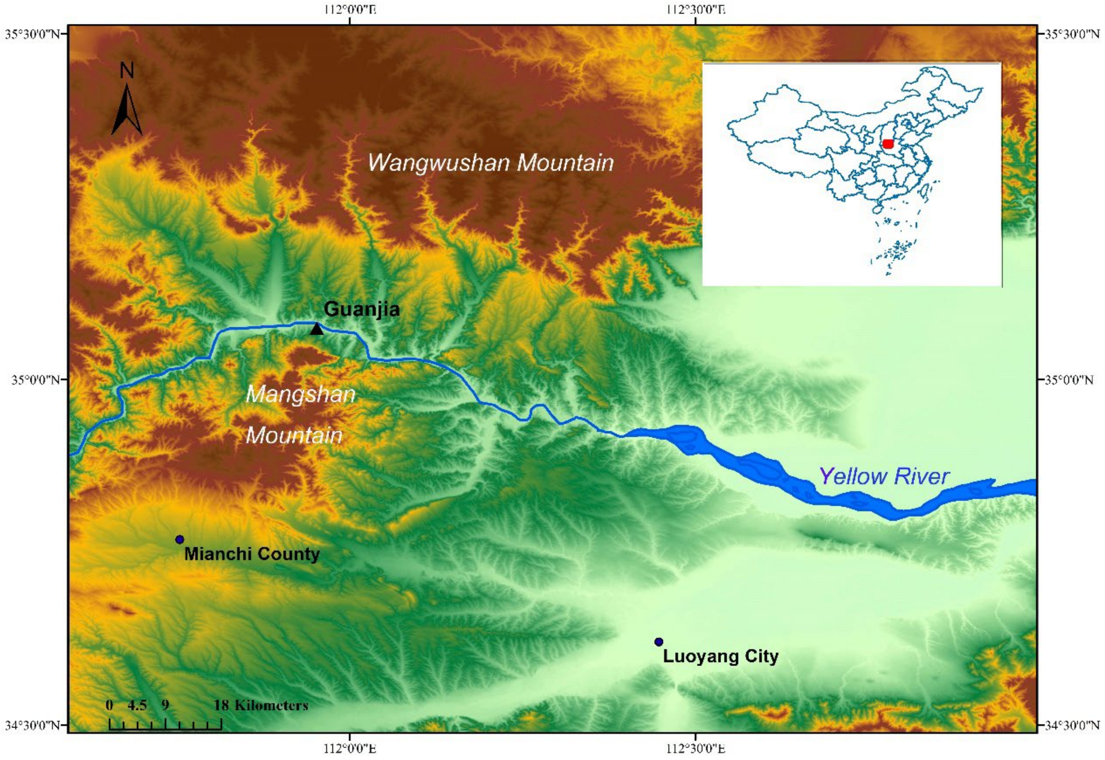

Fig.1 Site location of Guanjia

The Guanjia site (111°57′08″E, 35°04′28″N; 254.9–266.8m a.s.l; **Fig. 1**) was located on a terrace on the southern bank of the Yellow River (**Fig. 2**. a–c), about 70 kilometers northeast of Mianchi County, Henan Province (Fan and Qin 2022). The site is 450 meters long from east to west and 200 meters wide from north to south, covering an area of about 90,000 square meters. In connection with the construction of the Xiaolangdi Reservoir of the Yellow River, the Henan Provincial Institute of Cultural Heritage and Archaeology conducted a rescue excavation from October 1998 to June 2000, discovering PLG, Yangshao, Longshan, and Erlitou cultural relics. After the reservoir was completed, the site was flooded by the river.

The Peiligang features and finds were distributed in the western part of the excavation area, consisting of 87 pits with potteries (**Fig. 2**. d–f), stone and bone tools **(Fig. 2**. g), and animal bone fragments inside. Altogether 1250 animal bones were found in 38 Peiligang pits, with carbon dating results of these bones showing dates of 6100–5500 cal. BC. Isotope analysis of human bones from graves dating to the later occupation period of the middle Yangshao period (Dong Yu et al. 2017) suggests C_4-dominated diets ($\delta^{13}C$=–8.0±0.6‰, $\delta^{15}N$=6.2±0.7‰, n=21) probably strongly related to millet agriculture. Since no Peiligang human bones were found at the site, research on diets in the following focuses on animals.

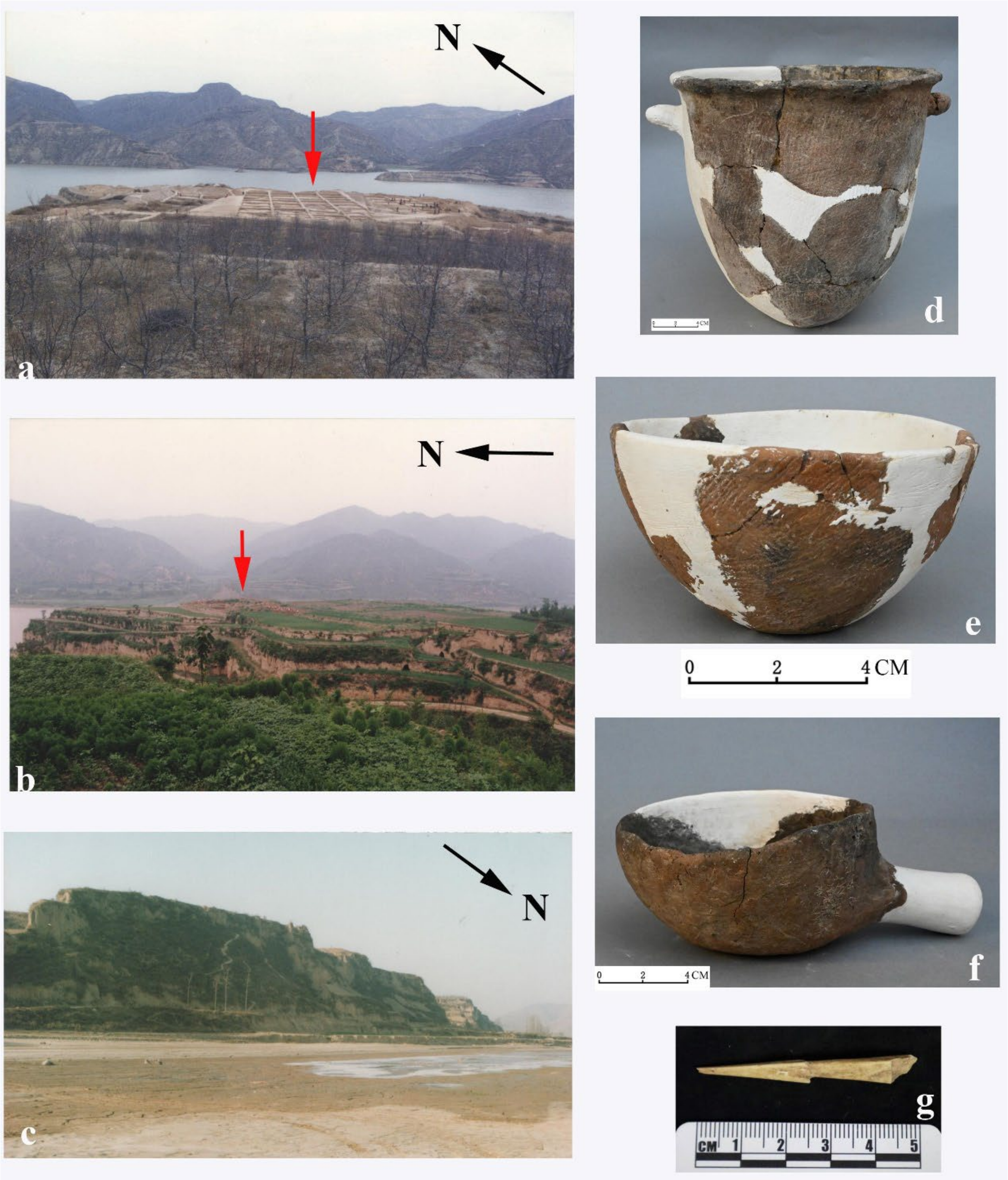

Fig. 2 Site location and artifacts: a) view of the site from south to north; the Yellow River and the Wangwushan (王屋山) mountain is located to the north; b) view of the site from west to east; c) view from the alluvial plane, from north to south; d) pottery *guan* (罐) jar, (T20H147 Cai (采):2) collected from the surface; e) pottery *bo* (钵) bowl (T62H362 Cai (采):1) collected from the surface; f) pottery *shao* (勺) ladle (T20H147 Cai (采):4) collected from the surface; g) bone harpoon (T68H403)

Zooarchaeological Analysis

The Guanjia faunal assemblages underwent initial classification at the Xinzheng workstation, Henan Provincial Institute of Cultural Heritage and Archaeology, and then analyzed further in the zooarchaeology lab, School of History, Capital Normal University. They were not washed due to poor preservation. Ancient and modern comparative collections in the zooarchaeology lab of Henan Provincial Institute of Cultural Heritage and Archaeology, and several bone catalogs (Hillson 1992; France 2009;

Cohen and Serjeantson 2015) were used for identification. The species were identified as Amur catfish (*Silurus asotus*), Grass carp (*Ctenopharyngodon idella*), pig (*Sus scrofa*), dog (*Canis familiaris*), Chinese bamboo rats (*Rhizomys sinensis*), Chinese muntjac (*Muntiacus reeves*), Chinese water deer (*Hydropotes inermis*), Roe deer (*Capreolus pygargus*), Sika deer (*Cervus nippon*), Père David's deer (*Elaphurus davidianus*). We would like to point out that we use "*Sus scrofa*", but not "*Sus scrofa domesticus*", because the sizes of the pig teeth found at Guanjia were larger than domesticated pigs of the middle Neolithic and early Bronze Age periods from other sites in the region, suggestion that the pigs at Guanjia may not have been domesticated in the biological sense of the word. Other less securely identified taxa include Cyprinidae, *Phasianus*, and *Ursus*. Deer taxa were identified mainly based on antler and tooth morphology. Except for antlers and teeth, seven postcranial specimens were identified based on the completed articular surfaces of limb bone with distinct features. Limb bones with fewer identification points were classified as "small cervid", "medium cervid", "large cervid", or "cervid", depending on body size.

NISP (the Number of Identified Specimens) and MNI (Minimum Number of Individuals) were employed for counting frequencies of taxa. To detect the wear stages of *Sus scrofa* teeth, occlusal surfaces were gently brushed. Teeth eruption and wear stage were recorded following Grant (1982), and these observations were used to estimate the age at death (Bull and Payne 1982; Hongo and Meadow 1998; Magnell 2006; Lemoine et al. 2014). To increase the number of samples where age could be reliably determined, the epiphyseal fusion of postcranial skeletons was also applied to *Sus scrofa* age estimations (Silver 1969; Bull and Payne 1982; Zeder et al. 2015). *Sus scrofa* sex was decided by both the section shape and the development of the tooth root of the canine (Hillson 1992). The phenomenon of LEH (Linear Enamel Hypoplasia) reflects past physiological stress and can be found on the lingual or buccal surfaces of pig permanent molars (Dobney and Ervynck 1998). We observed both sides of 13 *Sus* tooth specimens, but no LEH was found.

Skeleton measurements were taken following the criteria of Von den Driesch (1976). To estimate *Sus* body sizes, the comparisons of permanent teeth, but not postcranial skeleton measurements were employed because most *Sus scrofa* long bones at Guanjia were not completely fused which might lead to less representative results. Usually, the size of M_3 is studied to observe morphological changes during pig domestication (Hongo and Meadow 1998; Ervynck et al. 2001; Rowley-Conwy et al. 2012). However, at Guanjia, M_2 was more suitable because in the samples analyzed M_3 was largely not totally erupted due to the relatively young age of the pigs at death and because M_2 was more representative due to less wear than dp_4, and M_1. For comparison, M_2 measurements published in zooarchaeological reports were also collected from Pleistocene *Sus lydekkeri* from Gongwangling (n=2), Lantian county, Shaanxi Province (Hu and Qi 1978:42), Huludong (n unknown), Nanjing city, Jiangsu Province (Dong 1999), Lingjing (n=1), Xuchang city, Henan Province (Dong and Li 2008), *Sus scrofa* from the early Holocene from Pupiao (n=2), Baoshan city, Yunnan Province (Zong and Huang 1985), and *Sus scrofa domesticus* from the middle Neolithic Yangshao period of Xipo (n=28), Lingbao city, Henan Province (Ma 2006:109,110), and the early Bronze Age period of Wangjinglou (n=20), Xinzheng city, Henan Province. Pig M_2 erupts at about one year old (12–13 mons) (Magnell 2006). After that, tooth length and width are affected by factors such as chewing and age. Throughout this process, width is less affected than length (Payne and Bull 1988; Zeder and Lemoine 2020). For secure comparison, we only selected *Sus scrofa domesticus* M_2 specimens from Xipo and Wangjinglou whose M_3 erupted as the same stage as Guanjia, to reduce potential length and width differences for each tooth specimen caused by age and abrasion factors.

Nevertheless, we mostly measured M_2 that had erupted and been worn down for about 6 to 12 months[2], potentially influencing the results further. It also needs to be pointed out that *Sus lydekkeri* from Gongwangling, Huludong, Lingjing, and *Sus scrofa* from Pupiao were all adult individuals and their M_2 were probably smaller than the sizes of just-erupted teeth due to the longer time of tooth wear.

Stable Carbon and Nitrogen Isotope Analysis

After zooarchaeological identification, samples were selected for isotope analysis and carbon dating. Bone collagen extraction from *Sus scrofa* and cervid remains was carried out at the Institute of Archaeology, Chinese Academy of Social Sciences, while stable carbon and nitrogen isotope ratios were analyzed using IsoPrime100 coupled with Vario EA at the Institute of Environment and Sustainable Development, Chinese Academy of Agricultural Science. Collagen was isolated from bones following the protocol proposed by Richards & Hedges (1999), with some modifications to include ultrafiltration prior to lyophilization (Brown et al. 1988). The prepared collagen was measured using an Isoprime 100 IRMS coupled with a Vario PYRO cube. The stable isotope results were analyzed comparing the ratio of the heavier isotope to the lighter isotope ($^{13}C/^{12}C$ or $^{15}N/^{14}N$) and reporting the results as "δ" in parts per 1,000 or per mil (‰) relative to internationally defined standards (McKinney et al. 1950) for carbon (Vienna Pee Dee Belemnite, VPDB) and nitrogen (Ambient Inhalable Reservoir, AIR). SA methoinine (in-house standard, $\delta^{13}C = -28.15\pm0.02$‰; $\delta^{15}N = -4.86\pm0.06$‰) and USGS 40 (L-glumatic acid, international standard) are used as reference materials. The measured values of USGS 40 are averaged -26.33 ± 0.05‰ for $\delta^{13}C$ and -4.54 ± 0.10‰ for $\delta^{15}N$, and are comparable with the certified values ($\delta^{13}C = -26.39\pm0.05$‰; $\delta^{15}N = -4.52\pm0.06$‰). After 5 ancient samples, both standards were inserted into the sample list for calibration and monitoring the stability. Details of samples including archaeological contexts, bone elements, collagen contents, as well as the resultant data are listed in Table S1.

Isotopic analysis is a useful tool for investigating changes in diets of humans and their domesticated animals. In particular, they allow for tracing the integration of C_4 millet into diets in Neolithic China. The natural ecosystem of central China is mainly dominated by C_3 plants with low $\delta^{13}C$ values (–28.5‰ to –24.4‰, mean –27.5‰) (Wang et al. 2003), whereas cereals cultivated during the Neolithic were primarily C_4 grasses, such as foxtail millet and broomcorn millet, with relative high $\delta^{13}C$ values close to -9.2 ± 0.5‰ (from –10.0‰ to –8.5‰, n=34) (Wang et al. 2022). If humans and their herds consumed certain amounts of millet over extended periods of time, the values of $\delta^{13}C$ in their collages would be higher than those of individuals (human or animal) relying exclusively on C_3 plants. In general, $\delta^{13}C$ cut of the value of –18% or greater can be an indication of C_4 plant consumption (Liu and Martin 2014; Hou et al. 2023). Although temperatures, precipitations, and canopy effect for example, can have some influences on the $\delta^{13}C$ and $\delta^{15}N$ values, previous studies have shown a substantial connection between the phenomenon of slight C_4 isotopic signals with $\delta^{13}C$ values around –18‰ and the possibility of millet-intake by *Sus* during the early Neolithic (Hu et al. 2008; Hou et al. 2023). For comparison, *Sus* (n=6), dog (n=4), and deer (n=6) data from the early Neolithic Cishan site (Hou et al. 2023), domesticated pig (n=70) data from the middle Neolithic Xipo site (Zhang et al. 2021), and human data (n=21) from the middle Neolithic Guanjia (Dong Yu et al. 2017) were included in this study. Comparisons of distributions

---

[2] Pig M_2 erupts at about one year old (12–13 months) (Magnell 2006). The baseline that we selected M_2 specimens from Guanjia, Xipo, and Wangjinglou is their M_3 were in the eruption stage and not fully erupted. This means that those pigs died between 1.5 to 2 years (18–24 months) (Bull and Payne 1982; Hongo and Meadow 1998; Magnell 2006). Our M_2 specimens were thus worn for about 6 to 12 months.

between two groups were made via the Mann-Whitney U test, and correlation analysis were conducted using the Pearson Correlation Coefficient.

Starch Grain and Phytolith Analysis

Thirty-two ceramic samples of starch grains and phytoliths were collected from the inner surface of pottery sherds. Two control samples were taken from the outer wall of the pottery. Each ceramic sample was first cleaned with a new toothbrush and distilled water to remove loose soil from the surface. Residues of microfossil material were then extracted by using an ultrasonic toothbrush and distilled water to clean the area in question for 3 minutes. The residue liquid from each sample was collected in a test tube. Sample processing involved two procedures: 1) EDTA (ethylenediaminetetraacetic acid; 0.1%) dispersion to release microparticles from small sediment micro aggregates; 2) SPT heavy liquid (sodium polytungstate, density 2.35) separation to extract microbotanical remains. Extracts were mounted in a 1:1 (vol: vol) solution of glycerol and distilled water on slides and scanned under a Zeiss Axio Scope A1 fitted with polarizing filters and differential interference contrast (DIC) optics, at 200× and 400× for starch grains, and phytoliths. Photographs were taken using a Zeiss Axiocam HRc3 digital camera and the Zeiss Axiovision software version 4.9. References for starch and phytolith identification used here include Zhao et al. (1998), Thomas and Atwell (1999), Piperno (2006), Robin and Huw (2006), Lu et al.(2009), and Liu et al (2014).

Results

Faunal Frequencies

Of a total of 1250 bone specimens, 102 are fish, 108 are birds, and 1040 are mammals. Due to poor preservation, the NISP of fish, birds, and mammals was only 203 and the MNI is 28 in total. Mammals accounted for approximately 60% while fishes and birds together accounted for around 40% (Table 1).

Table 1 Frequencies of fish, birds, and mammals by NISP and MNI

	NISP	% NISP		MNI	% MNI	
Cyprinidae	9	75	Fish, n=12, 5.9%	1	33.3	Fish, n=3, 10.7%
Silurus asotus	2	16.7		1	33.3	
Ctenopharyngodon idella	1	8.3		1	33.3	
Phasianus	71	100	Birds, n=71, 35%	7	100	Birds, n=7, 25%
Sus scrofa	41	34.2	Mammals, n=120, 59.1%	4	22.2	Mammals, n=18, 64.3%
Canis familiaris	2	1.7		1	5.6	
Ursus	1	0.8		1	5.6	
Rhizomys sinensis	4	3.3		1	5.6	
Muntiacus reeves	5	4.2		1	5.6	
Hydropotes inermis	2	1.7		1	5.6	
Capreolus pygargus	8	6.7		1	5.6	
Cervus nippon	13	10.8		2	11.1	
Elaphurus davidianus	1	0.8		1	5.6	
Small cervid	9	7.5		2	11.1	
Middle cervid	28	23.3		2	11.1	
Large cervid	6	5		1	5.6	

Total	203			28		

In mammals, *Sus scrofa* outnumbered all other mammals, accounting for a percentage of 34.2% of NISP and 22.2% of MNI. All deer, including the species-level identified deer and the small, middle, and large deer, made up about 60% of the mammals by NISP and MNI (Table 1).

Estimated Age at Death

There are five *Sus scrofa* mandibles (Table 2, No.135,102,20,22,23) and three *Sus scrofa* maxillae (Table 2, No.125,21,26) that could be identified into specific ranges of age at death. The right dp_4 (the third milk molar, No.135, **Fig. 3.c**) was kept with the middle wear stage (e), suggesting it died between 6–12 mons (Hongo and Meadow 1998; Lemoine et al. 2014); M_3 (the third molar) were all in the process of eruption in the other four mandibles (**Fig. 3.a** and **Fig. 3.b** for example), suggesting the individuals died between 1.5–2 years old (Bull and Payne 1982; Hongo and Meadow 1998; Magnell 2006). The three maxillae also reflect the ages at death were between 1.5–2-year-old (Bull and Payne 1982; Hongo and Meadow 1998) (Table 2).

Table 2 *Sus scrofa* teeth eruptions, wear, and estimated age at death of material from Guanjia. 'Max/Man' means maxillae or mandible, 'M/F' means male or female, 'L/R' means left or right, and '—' means unknown. Bull & Payne (1982) and Magnell (2006) were resources from wild pigs.

Lab No.	Pit	Max/ Man	Preserved portion (ratio)	M/F	L/R	Teeth eruption and wear				Age at death (mons)				Additional information
						dp4	M1	M2	M3	Bull & Payne (1982)	Magnell (2006)	Hongo & Meadow (1998)	Lemoine et al. (2014)	
135	H560	Man	dp4–M2 (1/4–1/2)	—	R	e	—	—	—	—	<14	6–12	6–12	
20	H254	Man	I–M3 (1/2–3/4)	F	L	—	e–f	b	0.5–1	19–23	19–24	18–24	18–30	Dentition distortion; M_2 length: 25.83mm, posterior width: 18.63mm; $\delta^{13}C$: –16.71‰, $\delta^{15}N$: 6.17‰
22	H254	Man	M1–M3 (1/4–1/2)	—	R	—	—	—	0–0.5	19–23	19–24	18–24	18–30	
23	H254	Man	L:C+P2P3+dp4–M3; R:C–P4; mandibular symphysis (1/2–3/4)	F	L+R	—	—	c	V/0.5	19–23	19–24	18–24	18–30	M_2 length: 25.95, posterior width: 17.35mm. Diet data failed to be extracted
102	H339	Man	M1–angle (1/4–1/2)	—	R	—	—	—	V	19–23	19–24	18–24	18–30	
27	H254	Man	C–P4 (＜1/4)	F	R	P4	—	—	—	＞12	＞14	＞12	＞12	
125	H236	Max	M2, M3 (＜1/4)	—	L	—	—	b	—	—	—	18–24	12–30	
21	H254	Max	dp4, M1, M2, M3 (＜1/4)	—	R	l	f	c	0.5	19–23	—	18–24	12–30	
26	H254	Max	M1, M2, M3 (＜1/4)	—	R	—	—	c	0–0.5	19–23	—	18–24	12–30	

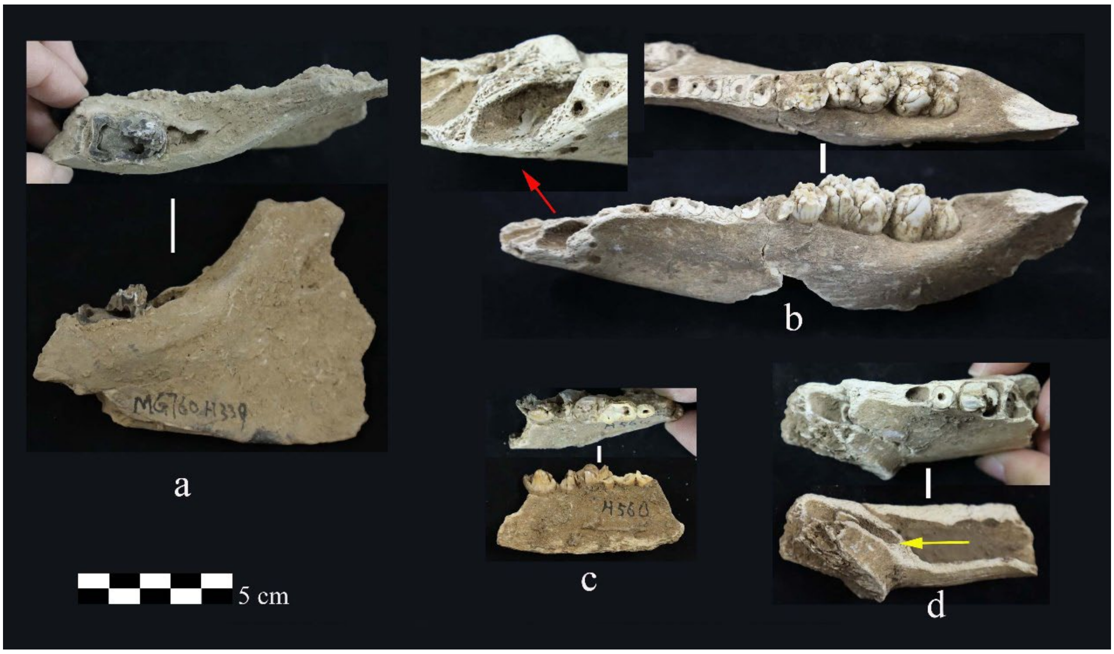

Fig. 3 *Sus scrofa* mandibles from Guanjia: a) Lab No.102, from pit H339, M_3 visible; b) Lab No.20, from pit H254; M_3 in eruption; the alignment of M_1 and M_2 were distorted; canine socket (magnified X2) had an oval shape, pointed out by the red arrow; c) Lab No.135, from pit H560, dp_4 kept; d) Lab No.27, from pit H254, the canine socket had an oval shape, closed root pointed out by the yellow arrow.

Based on postcranial epiphyseal fusion (n=14), the survivorship of pigs over 2 years were as low as 33.3% (19–23months range, n=3, Table S2), and none lived more than 4–5 years in the range of 48–60 months. *Sus scrofa* at Guanjia were thus mainly young individuals.

Sexes

For the three specimens (No.20, No.23, and No.27, Table 2) where sex could be securely determined, all the canine sockets were oval in shape (see **Fig. 3.b**, red arrow, and **Fig. 3.d** as examples), suggesting that they were female. Due to the loss of canine teeth, only observing socket morphology may affect our judgments. Thus, canine roots were carefully examined, and closed roots were observed (see **Fig. 3.d**, yellow arrow, as an example), another indicator that these were females (Hillson 1992).

Distorted alignment of teeth

The left lower molars M_1 and M_2 were not in a straight line, showing a distorted dentition phenomenon on the No.20 mandible (**Fig. 3.b**).

Dental Measurement Data

In no specimen were M3 completely erupted in the mandible or maxillae. Two metric data of the lower molar M_2 (No.20, length:25.83mm, posterior width:18.63mm; No.23, length: 25.95, posterior width:17.35mm; Table 2) will be employed below to investigate body sizes.

Stable C, N Isotope

Collagen was extracted successfully from seven of nine bone specimens for *Sus scrofa* while three of four for cervids (Table S1). Isotope values of cervids (δ^{13}C=−21.0±0.7‰, δ^{15}N =3.7±0.6‰, n=3) indicated their carbon isotopes are consistent with a diet based on C$_3$ plants. *Sus scrofa* (n=7) can be divided into two groups. The individual SIA01529 (δ^{13}C=–20.8‰, δ^{15}N =3.7‰) had isotopic values similar to the cervid, while the other six (SIA01505, SIA01506, SIA01508, SIA01510, SIA01524, SIA01527) display slightly higher δ^{13}C and δ^{15}N ratios (δ^{13}C=–17.4±0.8‰, δ^{15}N =5.5±0.7‰) than their counterparts.

Starch Grains and Phytoliths

Out of 32 pottery fragments in total, we successfully extracted 166 starch grains and 267 phytoliths from 26 samples. Panicoideae (**Fig. 4.a-b**) accounted for the largest number (n=52, 31.33%) and the highest presence rate (56.25%) of starch grains, which probably mainly consisted of broomcorn millet and foxtail millet. Based on the phytolith analysis, foxtail millet (n=14, **Fig. 4.c**) and broomcorn millet (n=29, **Fig. 4.d**) accounted for 10.86% and 5.24%, respectively, of a total of 267 phytoliths. These data suggest that millet crops made up part of the plants exploited by humans' at Guanjia. The appearance of millet remains is used to estimate the potential consumption in *Sus scrofa* diets in the discussion section.

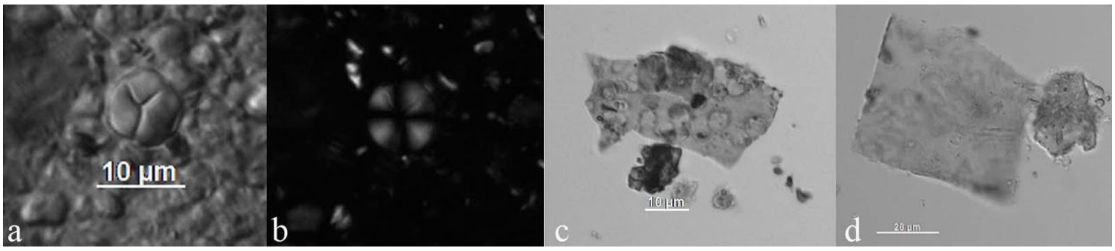

Fig. 4 Crop seeds at Guanjia. a. Strach grain, Panicoideae; b. Strach grain, polarized, Panicoideae; c. Phytolith, Ω-type, foxtail millet husk; d. Phytolith, η-type, broomcorn millet husk

Discussion

Early Neolithic sites and remains are not easy to find and are more likely to be destroyed by later disturbances, so the relatively limited sample size of *Sus scrofa* from Guanjia is already quite substantial in terms of research on this period. Although the sample size of Guanjia animals, plants, etc. is not large, our analyses still allow us to discuss questions about domestication and subsistence in conservative and cautious ways.

Early Pig Domestication

Archaeologists generally define pig domestication as a process of long-time gradual changes that go through the following stages: 1. wild animals unaffected or only marginally affected by humans; 2. animals managed by humans to various extents; 3. domesticated animals whose reproduction is controlled by humans. While most scholars agree on this general process of development, the specific terms they use to describe each of these stages differ between scholars (Hongo and Meadow 1998; Ervynck et al. 2001; Zeder 2006, 2012; Albarella et al. 2006; Vigne 2011; Price and Hongo 2020). At Guanjia, we found evidence for feeding and management via culling at specific ages and for specific sexes, suggesting early stage of pig domestication. The raising strategies are observed by frequencies, age structure, sex ratio, diet, body sizes, and pathological phenomena in the following.

(1) Frequency evidence. Although *Sus scrofa* at Guanjia only accounted for 34.2% of NISP and

22.2% of MNI in mammals, their percentage was much higher than that during the Paleolithic. For example, *Sus scrofa* made up only 0.2–0.3% of mammals by NISP at the late Middle Paleolithic site of Laonainaimiao in Henan Province (Qu et al. 2018). The potential domesticated species used for subsistence insurance may consist of a small number of meat resources in the initial domesticated stage (Redding and Rosenberg 1998), and this might explain the low *Sus scrofa* ratios at Guanjia.

(2) Demographic evidence. Though sample sizes for tooth eruption and wear (n=8, Table 2) and epiphyseal fusion (n=14, Table S2) are not very large, estimations for age at death based on the two methods together indicates that *Sus scrofa* were mainly young individuals less than 2 years old, suggesting selective kill-off by humans. Alternatively, intensive hunting may also lead to the young-dominated age structure of wild animals (Rowley-Conwy et al. 2012). However, two clues provide arguments against the hunting hypothesis for the case of Guanjia. First, among four mandibles from pit H254 (Table 2), the three specimens (No.20, 22, and 23) that could be attributed to accurate age ranges belonged to animals who died between 1.5–2 years old. Such concentrated age at death reflects the fact that *Sus scrofa* belonging to this age range was readily available to humans, probably by raising or controlling, but not by hunting, due to hunting being more uncertain in terms of acquiring animals with a particular age span. Second, Guanjia is not an isolated case of low-age pig slaughtering during early times: the majority of *Sus scrofa* at Jiahu (84.1%) , Dadiwan (89.5%), and Xipo (93.7%) were killed at less than 2 years old (**Fig. 5**). However, the ratio of subadults among the modern wild boar population (52.2%) was lower than that in the ancient samples (**Fig. 5**), reflecting a mortality pattern not affected by humans. Modern boars reach sexual maturity after 12–18 months (Ma 1986), and reach full growth at 2 years old (Albarella et al. 2011). After the age of 2, pigs will not gain more weight even if they ingest the same number of calories as before, meaning that it can be seen as economically more sound to not raise pigs beyond that age. This may explain the heavily selective harvesting of young individuals seen at Guanjia, Jiahu, Dadiwan, and Xipo. In sum, although we cannot completely rule out the possibility of intensive hunting, it is more likely that the slaughter of most herds under 2 years old was a common culling strategy for raising pigs during the Peiligang period.

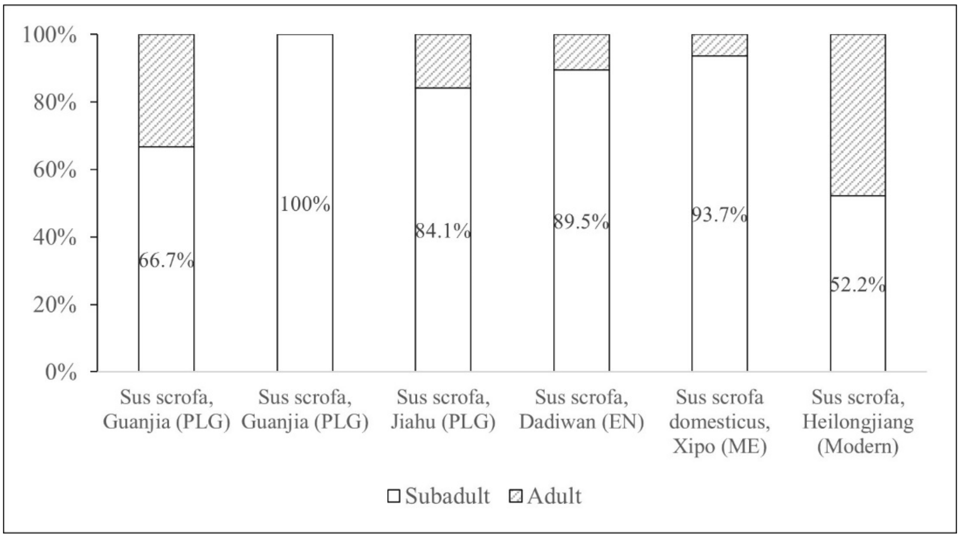

Fig. 5 *Sus* mortalities. The age of *Sus scrofa* (n=3) from Guanjia shown in the left column was estimated based on epiphyseal fusions and the age shown in the right column (n=5) was estimated based on tooth eruption and wear stages, ⩾2 years as “adults” (this study); *Sus scrofa* from Jiahu (n=58) (Luo and Zhang 2008), Dadiwan (n=19) (Qi et al. 2006), and Xipo (n=239) (Ma 2005) were determined by tooth eruption and wear stages, ⩾2 years as

"adults"; *Sus scrofa* from the Heilongjiang Province (n=73) (Ma 1986) not explain the criteria they used to distinguish between subadults and adults. PLG: Peiligang; EN: Early Neolithic; ME: Middle Neolithic.

(3) Dietary evidence. Both early Neolithic Guanjia and Cishan deer $\delta^{13}C$ values range from –21.82‰ to –20.63‰ (–21.11±0.4‰, n=9), and $\delta^{15}N$ values from 3.13‰ to 5.7‰ (4.29±0.7‰, n=9) (**Fig. 6**), providing the baselines for herbivores feeding in wild environments. Xipo pigs display C_4 -dominated diets ($\delta^{13}C$=–7.8±1.3‰, $\delta^{15}N$ =7.2‰±0.6‰, n=70) that were intensive-controlled by Yangshao-period humans who practiced intensive millet farming (Zhang et al. 2021). As mentioned above, Guanjia *Sus Scrofa* can be divided into two groups. The $\delta^{13}C$ value of the second group ($\delta^{13}C$=–17.4±0.8‰, n=6) is higher than –18‰, different from Guanjia and Cishan wild deer (Mann-Whitney U Test: p-value=0.0018), and different from Xipo domesticated pigs (Mann-Whitney U Test: p-value < 0.001). The reason for the low C_4 signals of the second group need to be investigated further. If the second group of *Sus scrofa* lived in an open environment, and the deer and SIA01529 lived in dense forests, the latter would likely be affected by the canopy effect leading to a lower $\delta^{13}C$ value among them than for the former. However, the gap caused by the canopy effect is approximately 2‰ (van der Merwe and Medina 1991), not as wide as the gap between the former ($\delta^{13}C$:–17.4±0.8‰) and the later (deer $\delta^{13}C$:–21.11±0.4‰; SIA01529 $\delta^{13}C$:–20.8‰). Moreover, an Ovis/Capra sample ($\delta^{13}C$: –19.6‰; $\delta^{15}N$:4.2‰) from the Yangshao Xipo site could provide the referenced $\delta^{13}C$ value of herbivores living in an open environment of this region (Zhang et al. 2021), whose value is about 2‰ higher than that of the deer and 2‰ lower than that of the second group of *Sus Scrofa*. Thus, the canopy effect is not a plausible explanation; it is more likely that *Sus Scrofa* consumed some C_4 plants which in turn caused the values we are seeing. However, the possibility of the canopy effect cannot be ruled out and the canopy effect in this region should be studied further in future.

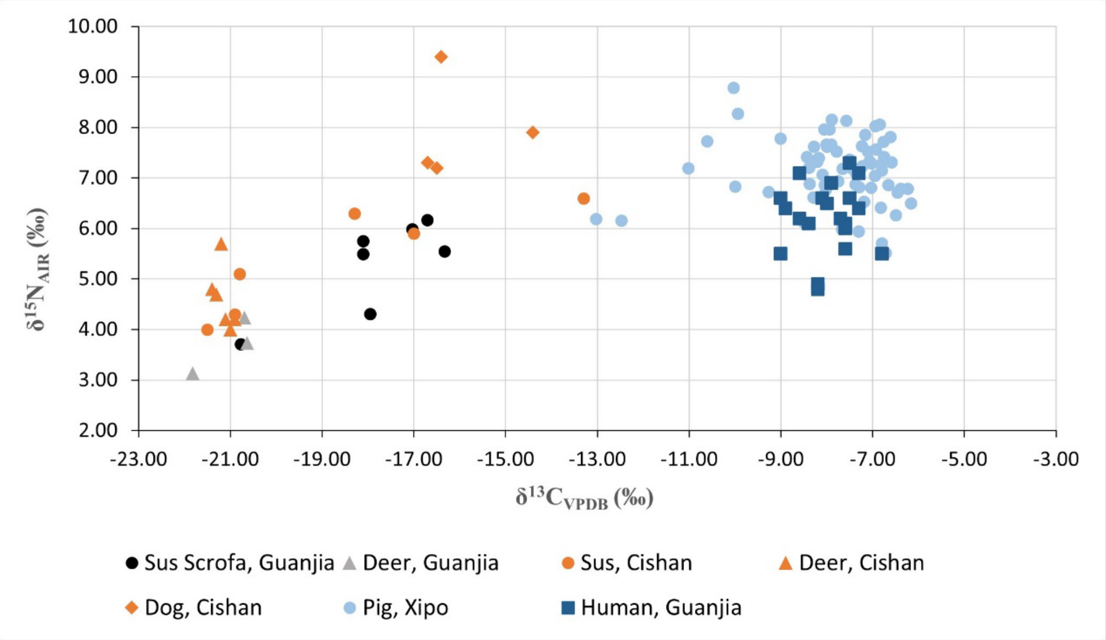

Fig. 6 Stable C, N isotope values of *Sus,* cervid, dog, and human samples from Guanjia, Cishan, and Xipo. Note that the animal bone samples of Guanjia (this study) and Cishan (Hou et al. 2023) date to the early Neolithic and the pig bones from Xipo (Zhang et al. 2021) and the human bones from Guanjia (Dong Yu et al. 2017).to the later Yangshao period.

Similarly, at Cishan like as Guanjia, the *Sus* fall into two distinct groups. The diets of group A

($\delta^{13}C$=–21.1±0.4‰, $\delta^{15}N$=4.5±0.6‰; n=3) are consistent with a diet based on C_3 plants**,** whereas group B ($\delta^{13}C$=–16.2±2.6‰, $\delta^{15}N$=6.3±0.4‰; n=3) consumed some amount of C_4 plants (Hou et al. 2023). Some *Sus* specimens from the second group of Guanjia and group B of Cishan overlap with the $\delta^{13}C$ values of Cishan domesticated dogs ($\delta^{13}C$=–16.0±1.1‰, $\delta^{15}N$ =8.0‰±1.0‰, n=4), whose diets could reflect the diets of early Neolithic humans to some extent (Hou et al. 2023).

Because the vegetation in the Central Plains is dominated by C_3 plants (Wang et al. 2003), the C_4 plants were cultivated millets and millet farming grasses, i.e. broomcorn millet, foxtail millet, green bristlegrass (*Setaria viridis*). Based on archaeobotanical investigations, broomcorn and foxtail millet were cultivated during Peiligang in the Central Plains (Wang et al. 2017; Zhao 2020). The millet starch and phytolith remains were collected from the insides of ceramics, showing that millets had been cultivated for consumption at Guanjia. Thus, the C_4 foods that *Sus scrofa* could access were likely millets or their by-products, either taken from farming fields by pigs running free or provided by farmers to pigs held in enclosures or at least gathered together on occasion. Namely, *Sus scrofa* were entering the human environments either of their free will or being forced to do so. Ethnological surveys in Italy and Greece suggest that it is common for farmers to provide some food, including crops, to free-range pigs to keep them under control or to support their survival in the summer when food is scarce (Albarella et al. 2011; Halstead and Isaakidou 2011). Considering the kill-off patterns, it is more plausible that humans actively fed or attracted pigs with crop food than wild boar around the site infiltrated human sites and "stole/raided" crops or kitchen waste. Furthermore, most of the *Sus scrofa* at Guanjia (57.1%, 4/7) showed slight C_4 signals higher than –18‰, while only one sample presented a pure C_3-plant diet, indicating that *Sus scrofa* access to millet or millet by-products quite often, which was more related to intentional care by humans.

The *Sus scrofa* $\delta^{15}N$ values also may reflect possible connections between *Sus scrofa* and humans. In **Fig.6**, when the $\delta^{13}C$ values of *Sus scrofa* becoming higher from the left (–20.77‰) to the right (–16.33‰), we can see their $\delta^{15}N$ values increase correspondingly from 3.71‰ to 6.17‰. This correlation is positive with statistical significance (Pearson Correlation Coefficient: r(7)= 0.81, p=0.03).. The high were not affected by suckling because they had been weaned for a while according to their ages at death (older than at least one year, Table S1), but suggest some proteins in wild, or food possibly related to humans were consumed. The combination of simultaneous increase of $\delta^{13}C$ and $\delta^{15}N$ values reveals *Sus scrofa* with higher values were probably consumed foods from human environments and shared more close relationships with humans.

(4) Animal body sizes based on M_2. As mentioned above, M_2 sizes of Pleistocene adult boars can be expected to be smaller than their original sizes due to age and wear, but they are clearly longer and/or wider than samples from Yangshao period domesticated pigs from Xipo (length mean: 20.74, width mean: 13.6; n=28) and early Bronze Age domesticated pigs from Wangjinglou (length mean: 20.75, width mean: 13.64; n=20)(Table S3), distributed on the upper right side of **Fig. 7**. Two Guanjia samples fall into the measurement range of teeth from wild boars (**Fig. 7**), differing clearly from Yangshao and early Bronze Age domesticated pigs, as well. This size difference between the Guanjia *Sus scrofa* and the Xipo and Wangjinglou pigs could not have been related to differences in sex, i.e. male pigs being usually larger and stronger than females, because the two samples of Guanjia were females (Table 2), relatively smaller than their counterparts. In sum, the size of Guanjia *Sus scrofa* teeth is closer to wild boars than domesticated pigs.

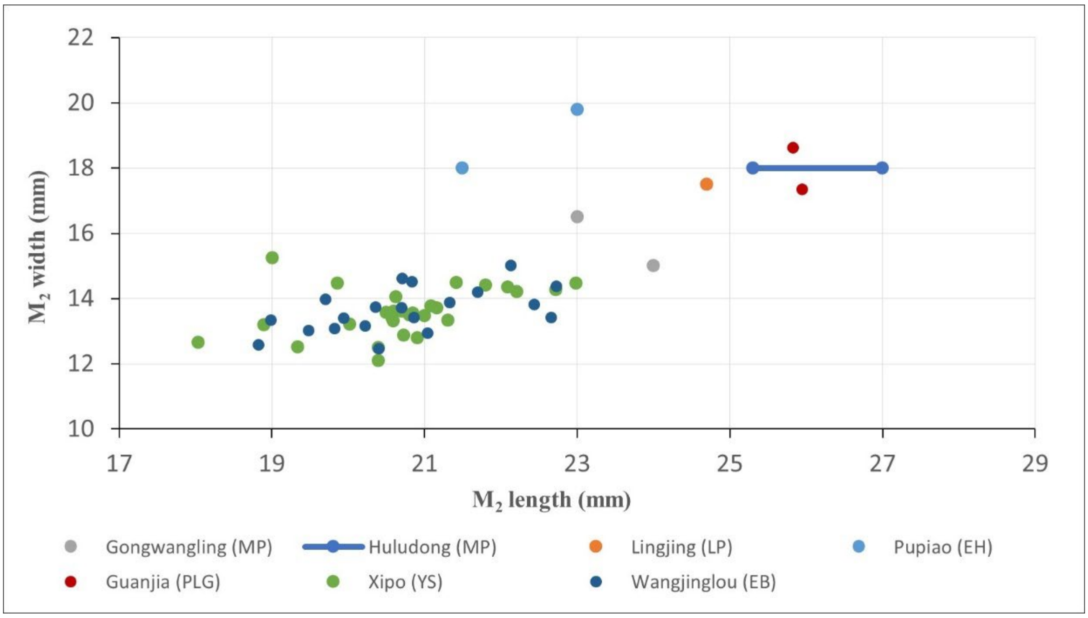

Fig. 7 The width and the length distributions of *Sus* M_2 from sites. Gongwangling (n=2) (Hu and Qi 1978:42), Huludong (unknow n; The blue line represents a range.) (Dong 1999), lingjing (n=1) (Dong and Li 2008), *Sus lydekkeri*, Pleistocene; Pupiao (n=2) (Zong and Huang 1985), *Sus scrofa*, Holocene; Guanjia (n=2) (this study), *Sus scrofa,* and Xipo (n=28) (Ma 2006:109,110), *Sus scrofa domestica*, Neolithic; Wangjinglou (n=20) (metric data from this study), *Sus scrofa domestica*, early Bronze. MP: Middle Pleistocene; LP: Late Pleistocene; EH: Early Holocene; PLG: Peiligang culture period (7000–5000 BC); YS: Yangshao culture period (5000–3000 BC); EB: Early Bronze Age (2000–1000 BC)

This interesting combination of human intervention reflected in age-at-death patterns and isotope data combined with the large tooth measurements at Guanjia can be explained with two different scenarios. The first scenario is a free-range keeping of pigs. Based on the isotope results of C_3-dominant diets, it was inferred that *Sus scrofa* at Guanjia were raised mainly free-ranging. The fact that none LEH phenomena were observed also suggests a less competitive living environment, further supporting the suggestion of free-range keeping of pigs. At Guanjia, even the left dentition of No.20 (**Fig. 3.b**, Table 2) was distorted, a sign of jaws beginning to be becoming shorter, probably because of access to human environments for food, but their teeth had not yet shrunken in size, or had changed but with a much slower speed than the jaws. Coincidentally, this specimen which showed dentition distortion belonged to an animal that ingested some C_4 plants and some proteins ($\delta^{13}C$: –16.71‰; $\delta^{15}N$: 6.17‰, Table S1), corresponding to accessing human environments for food as also inferred based on skeleton morphology. Thus, we conclude that some of the changes observed in the *Sus scrofa* population, such as distorted alignment of teeth were caused by humans, but their teeth sizes were not reduced, likely due to a free-range approach to pig rearing.

The second possible scenario is female breeding. It has been proposed for other regions that at the beginning of domestication, humans may control only female pigs instead of aggressive males to reduce raising costs but guarantee stable access to meat (Redding and Rosenberg 1998). In this scenario, females would breed with wild male boars that lived near the sites, thus, genes from wild populations were constantly imported into the next generations, leading to no obvious osteological size reduction. This phenomenon has been observed elsewhere for instance in the case of goat domestication (Zeder 2006, 2011; Zeder and Hesse 2007). At Guanjia, securely-sexed specimens are all females. The high ratio of females might indicate humans' preference for them and special control of females, but given the small number of specimens (n=3), this hypothesis has to be tested further, for instance via ancient DNA analysis, which we are currently working on.

It also must be noted that the discussions about body sizes are based entirely on M_2, some of which were different from their original sizes due to wear by chewing solid foods after weaning. Moreover, parts of the M_2 data compared in **Fig. 7** were gathered from published reports, rather than hand-measured by authors, so there may be inconsistencies in the error ranges between the different data. This does not mean that the other teeth share the same changing pattern (Albarella et al. 2006; Price and Hongo 2020), and larger sample sizes and more analysis are needed in the future to test these size estimates.

In sum, the *Sus scrofa* teeth from early Neolithic contexts at Guanjia were not as small as domesticated pigs from Yangshao and early Bronze Age sites, be it due to them being free range or due to female breeding or other reasons, meaning that we cannot recognize them as domesticated pigs morphologically. However, our analysis reveals that their numbers, mortalities, diets, and other characteristics were affected significantly by humans.

Subsistence

Our research suggests substantial reliance on wild animal resources at Guanjia. Guanjia was located near a river and net pendants and bone harpoons (**Fig. 2**) have been found at the site. Freshwater fish would thus have been an important meat resource. The current fish bone percentages of 5.9% by NISP and 10.7% by MNI (Table 1), much lower than that at Jiahu (62.08%–76.03% by NISP) (Luo et al. 2015), but they may have been underrepresented due to taphonomic factors such as the tiny size of these bones and the fact that no systematic screening was done during excavations at Guanjia. As small animals, *Phasianus* were also likely to undergo taphonomic bias, although they accounted for the largest number by NISP and MNI, suggesting how frequently humans hunted them in the past. Because fish and birds were much smaller than *Sus scrofa* and deer, their meat contributions were not as substantial. For mammals, human-raised animals, such as *Sus scrofa* and dogs, together accounted for 35.9% by NISP and 27.8% by MNI, and the rest was largely made up by wild animals. For example, deer made up about 60% of NISP and MNI (Table 1). It is thus obvious that even though humans began to raise domesticated herds, wild animals continued to serve as a major meat resource.

We are suggesting a greater reliance on wild plant resources than domesticated ones. The ratios of crops found at Guanjia were not very high according to starch grain results (Panicoideae, 31.33%) and phytolith results (broomcorn millet, 10.86%; foxtail millet, 5.24%), showing that farming was not highly developed, which confirms previous research on that time period and region (Liu 2014; Wang et al. 2017; Zhang et al. 2018; Bestel et al. 2018; Zhao 2020). This might be an important reason why the Guanjia *Sus scrofa* isotopic results suggest that pigs only consumed a very tiny number of millet crops or crop byproducts. In contrast, during the Yangshao period when agriculture was more developed (Zhao 2020), pigs were fed plenty of crops or crop byproducts as reflected by their C_4 plant-dominated diets (**Fig. 6**) (Liu and Martin 2014; Zhang et al. 2021).

Based on the specific data of teeth eruption and wear stages, *Sus scrofa* at Guanjia were killed at 0.5–1 years old (n=1) or 1.5–2 years old (n=4) (Table 2). This could be a sign of seasonal killing. Most wild boars give birth once a year (Ma 1986; Albarella et al. 2011), and the time is probably in spring (Wang et al. 2013). Thus, Guanjia *Sus scrofa* probably were killed in autumn and winter, the seasons when the least amount of fresh plant food was available. Furthermore, pigs are fatter after the summer, the time when plenty of food is available. In cold and dry climates, people also tend to take advantage of the cold winter months for meat preservation (Albarella et al. 2011). These points may be the reason why humans concentrated on slaughter in autumn and winter. However, we cannot infer Guanjia was a seasonally occupied site only from the faunal analysis alone. Further research is needed to test this preliminary hypothesis.

Conclusion

This case study provides a tentative picture of how Peiligang humans raised pigs in the early stages of domestication. We evaluated early Neolithic human subsistence by combining zooarchaeological, palaeobotanical, and dietary approaches. Morphologically, the teeth sizes of *Sus scrofa* at Guanjia were not as small as domesticated pigs of the Yangshao and early Bronze Age periods, thus we do not find evidence for size reduction during the early phases of pig domestication. However, the large teeth might be the result of human raising strategies: free range and female breeding. We do see some evidence of distorted alignment of teeth that may indicate mandible sizes were beginning to decrease. Furthermore, our understanding of the connections between humans and *Sus scrofa* were strengthened by our analysis of frequencies, age and sex structures, and isotopic data, reflecting the facts that Guanjia humans consciously raised pigs.

Humans at Guanjia primarily relied on a hunting-gathering economy while animal husbandry and plant farming just contributed a small part of their food resources. Although millet farming was not yet fully developed, most *Sus scrofa* consumed some amount of C_4 plants, probably from millet provided by humans. This kind of C_4-feeding strategy continued to develop gradually for the next two thousand years, resulting in the thriving pig husbandry of the following Yangshao period.

References

Albarella U, Dobney K, Rowley-Conwy P (2006) The domestication of the pig (Sus Scrofa): New challenges and approaches. In: Documenting Domestication: New Genetic and Archaeological Paradigms. University of California Press, Berkeley, pp 209–227

Albarella U, Manconi F, Trentacoste A (2011) A week on the plateau: pig husbandry, mobility and resource exploitation in central Sardinia. In: Ethnozooarchaeology:The present and past of human-animal relationships. Oxbow Books, Oxford, pp 143–159

Bestel S, Bao Y, Zhong H, et al (2018) Wild plant use and multi-cropping at the early Neolithic Zhuzhai site in the middle Yellow River region, China. The Holocene 28:195–207. https://doi.org/10.1177/0959683617721328

Brown TA, Nelson DE, Southon JR, Vogel JS (1988) Improved Collagen Extraction by Modified Longin Method. Radiocarbon 30:171–177. https://doi.org/10.1017/S0033822200044118

Bull G, Payne S (1982) Tooth eruption and epiphysial fusion in pigs and wild boar. In: Ageing and sexing animal bones from archaeological sites. British Archaeological Reports, Oxford, pp 55–171

Carden RF, Hayden TJ (2008) Epiphyseal fusion in the postcranial skeleton as an indicator of age at death of European Fallow Deer (Dama dama dama, Linnaeus, 1758). In: Recent advances in ageing and sexing animal bones. Oxbow Books, Oxford, pp 227–236

Cohen A, Serjeantson D (2015) A manual for the identification of bird bones from archaeological sites, Revised. Archetype Publications Ltd, London

Cucchi T, Hulme-Beaman A, Yuan J, Dobney K (2011) Early Neolithic pig domestication at Jiahu, Henan Province, China: clues from molar shape analyses using geometric morphometric approaches. Journal of Archaeological Science 38:11–22. https://doi.org/10.1016/j.jas.2010.07.024

Dobney K, Ervynck A (1998) A protocol for recording linear enamel hypoplasia on archaeological pig teeth. International Journal of Osteoarchaeology 8:263–273

Dong N, Yuan J (2020) Rethinking pig domestication in China: regional trajectories in central China and the Lower Yangtze Valley. Antiquity 94:864–879. https://doi.org/10.15184/aqy.2020.122

Dong W 董为 (1999) Yu Nanjing Tangshan Zhiliren Bansheng De Outilei Jiqi Guhuanjing Qianxi 与南京汤山直立人伴生的偶蹄类及其古环境浅析 [The artiodactyla from Hulu cave, Tangshan, Nanjing and the enviroment of Nanjing man]. Renleixue Xuebao 人类学学报 [Acta Archaeologica Sinica] 18:270–281

Dong W 董为, Li ZY 李占扬 (2008) Henan Xuchang Lingjing Yizhi De Wangengxinshi Outilei 河南许昌灵井遗址的晚更新世偶蹄类 [Late Pleistocene artiodactyla (Mammalia) from the Lingjing site, Xuchang, Henan province (China)]. Gujizhui Dongwu Xuebao 古脊椎动物学报[Vertebrata Palasiatica] 46:31–50

Dong Yu, Morgan Chelsea, Chinenov Yurii, et al (2017) Shifting diets and the rise of male-biased inequality on the Central Plains of China during Eastern Zhou. Proceedings of the National Academy of Sciences 114:932–937. https://doi.org/10.1073/pnas.1611742114

Ervynck A, Dobney K, Hongo H, Meadow R (2001) Born Free? New Evidence for the Status of “Sus scrofa” at Neolithic Çayönü Tepesi (Southeastern Anatolia, Turkey). Paléorient 27:47–73

Fan WQ 樊温泉, Qin CY 秦存誉 (2022) Henan Mianchixian Guanjia Yizhi Peiligang Wenhua Yicun Fajue Jianbao 河南渑池县关家遗址裴李岗文化遗存发掘简报 [Brief report on the excavation of Peiligang cultural remains at the Guanjia site in Mianchi County, Henan]. Kaogu 考古 [Archaeology] 653:22–36

France DL (2009) Human and nonhuman bone identification: A color atlas. CRC Press, Boca Raton

Grant A (1982) The use of tooth wear as a guide to the domestic animals. In: Ageing and sexing animal bones from archaeological sites. British Archaeological Reports, Oxford, pp 91–108

Halstead P, Isaakidou V (2011) A pig fed by hand is worth two in the bush: Ethnoarchaeology of pig husbandry in Greece and its archaeological implications. In: Albarella U, Trentacoste A (eds) Ethnozooarchaeology: The present and past of human-animal relationships. Oxbow Books, pp 160–174

Hillson S (1992) Mammal Bones and Teeth: An Introductory Guide to Methods of Identification, The first edition. Left Coast Press, London

Hongo H, Kikuchi H, Nasu H (2021) Beginning of pig management in Neolithic China: comparison of domestication processes between northern and southern regions. Animal Frontiers 11:30–42. https://doi.org/10.1093/af/vfab021

Hongo H, Meadow R (1998) Pig exploitation at Neolithic Çayönü Tepesi (southeastern Anatolia)

Hou LL 侯亮亮, Li WY 李文艳, Wang LP 王路平, et al (2023) Hebeisheng Wu'an Cishan Yizhi Dongwu Guge De Wending Tongweisu Fenxi 河北省武安磁山遗址动物骨骼的稳定同位素分析 [Stable isotopic analysis of faunal remains from the Cishan site in Wuan, Hebei]. Nanfang Wenwu 南方文物[Cultural Relics in Southern China] 142–149

Hu CK 胡长康, Qi T 齐陶 (1978) Shanxi Lantian Gongwangling Gengxinshi Buru Dongwuqun 陕西蓝田公王岭更新世哺乳动物群[GongWangLing Pleistocene mammalian fauna of Lantian, Shaanxi]. Kexue Chubanshe 科学出版社, Beijing

Hu Y, Wang S, Luan F, et al (2008) Stable isotope analysis of humans from Xiaojingshan site: implications for understanding the origin of millet agriculture in China. Journal of Archaeological Science 35:2960–2965

Larson G, Dobney K, Albarella U, et al (2005) Worldwide phylogeography of wild boar reveals multiple centers of pig domestication. Science 307:1618–1621. https://doi.org/10.1126/science.1106927

Larson G, Liu R, Zhao X, et al (2010) Patterns of East Asian pig domestication, migration, and turnover revealed by modern and ancient DNA. Proc Natl Acad Sci USA 107:7686–7691. https://doi.org/10.1073/pnas.0912264107

Lemoine X, Zeder MA, Bishop KJ, Rufolo SJ (2014) A new system for computing dentition-based age profiles in Sus scrofa. Journal of Archaeological Science 47:179–193

Liu L (2014) Peiligang: Agriculture and domestication. In: Smith C (ed) Encyclopedia of global archaeology. Springer, New York, NY, pp 5855–5858

Liu L, Ma S, Cui J (2014) Identification of starch granules using a two-step identification method. Journal of Archaeological Science 52:421–427. https://doi.org/10.1016/j.jas.2014.09.008

Liu X, Martin J (2014) Under one roof: People, crops and animals in Neolithic North China. In: Living in the landscape: Essays in honour of Graeme Barker. McDonald Institute for Archaeological Research, Cambridge, pp 227–234

Lu H, Zhang J, Wu N, et al (2009) Phytoliths Analysis for the Discrimination of Foxtail Millet (Setaria italica) and Common Millet (Panicum miliaceum). PLoS ONE 4:e4448. https://doi.org/10.1371/journal.pone.0004448

Luo YB 罗运兵, Yuan J 袁靖, Yang MF 杨梦菲(2015) Dongwu Yanjiu 动物研究. In: Wuyang Jiahu II 舞阳贾湖（二）. Kexue Chubanshe 科学出版社, Beijing, pp 333–371

Luo YB 罗运兵, Zhang JZ 张居中(2008) Henan Wuyangxian Jiahu Yizhi Chutu Zhugu De Zaiyanjiu 河南舞阳县贾湖遗址出土猪骨的再研究[Restudy of the pigs' bones from the Jiahua Site in Wuyang County, Henan]. Kaogu 考古 [Archaeology] 484:90–96

Ma X (2005) Emergent social complexity in the Yangshao culture: Analyses of settlement patterns and faunal remains from Lingbao, Western Henan, China. British Archaeological Reports, Oxford

Ma Y (1986) Heilongjiang Sheng Shoulei Zhi. Heilongjiang Kexue Jishu Chubanshe, Haerbin

Magnell O (2006) Tooth Wear in Wild Boar (Sus scrofa). In: Ruscillo D (ed) Recent advances in ageing and sexing animal bones. Oxbow Books, pp 189–203

McGovern PE, Zhang J, Tang J, et al (2004) Fermented beverages of pre- and proto-historic China. Proceedings of the National Academy of Sciences 101:17593–17598. https://doi.org/10.1073/pnas.0407921102

McKinney CR, McCrea JM, Epstein S, et al (1950) Improvements in mass spectrometers for the measurement of small differences in isotope abundance ratios. Rev Sci Instrum 21:724–730. https://doi.org/10.1063/1.1745698

Payne S, Bull G (1988) Components of variation in measurements of pig bones and teeth, and the use of measurements to distinguish wild from domestic pig remains. Archaeozoologia 2:27–66

Piperno DR (2006) Phytoliths: A comprehensive guide for archaeologists and paeoecologists. Altamira Press, Lanham

Price M, Hongo H (2020) The archaeology of pig domestication in Eurasia. J Archaeol Res 28:557–615. https://doi.org/10.1007/s10814-019-09142-9

Qi GQ 祁国琴, Lin ZY 林钟雨, An JY 安家瑗 (2006) Dadiwan Yizhi Dongwu Yicun Jianding Baogao 大地湾遗址动物遗存鉴定报告. In: Qin'an Dadiwan 秦安大地湾 [Dadiwan in Qin'an: Report on excavations at a Neolithic site]. Wenwu Chubanshe 文物出版社 [Cultural Relics Press], pp 861–910

Qu T, Chen Y, Bar-Yosef O, Wang Y (2018) Late middle Palaeolithic subsistence in the Central Plain of China: A zooarchaeological view from the Laonainaimiao site, Henan Province. Asian Perspectives 57:210–221

Redding RW, Rosenberg M (1998) Ancestral pigs: A new (Guinea) model for pig domestication in the Middle East. In: Ancestors for the pigs: pigs in prehistory, MASCA Research Papers in Science and Archaeology 15. Museum Applied Science Center for Archaeology, University of Pennsylvania Museum of Archaeology and Anthropology, Philadelphia, pp 65–76

Richards MP, Hedges REM (1999) Stable Isotope Evidence for Similarities in the Types of Marine Foods Used by Late Mesolithic Humans at Sites Along the Atlantic Coast of Europe. Journal of Archaeological Science 26:717–722. https://doi.org/10.1006/jasc.1998.0387

Robin T, Huw B (2006) Ancient Starch Research. Left Coast Press, Walnut Creek

Rowley-Conwy P, Albarella U, Dobney K (2012) Distinguishing wild boar from domestic pigs in prehistory: A review of approaches and recent results. J World Prehist 25:1–44. https://doi.org/10.1007/s10963-012-9055-0

Silver I (1969) The ageing of domestic animals. In: Science in Archaeology: A survey of progress and research. Thames and Hudson, London, pp 283–302

Thomas DJ, Atwell WA (1999) Starches. Eagan Press, St. Paul

van der Merwe NJ, Medina E (1991) The canopy effect, carbon isotope ratios and foodwebs in amazonia. Journal of Archaeological Science 18:249–259. https://doi.org/10.1016/0305-4403(91)90064-V

Vigne J-D (2011) The origins of animal domestication and husbandry: A major change in the history of humanity and the biosphere. Comptes Rendus Biologies 334:171–181. https://doi.org/10.1016/j.crvi.2010.12.009

Von den Driesch A (1976) A guide to the measurement of animal bone from archaeological sites. Peabody Museum Press, Harvard

Wang C, Lu H, Gu W, et al (2017) The spatial pattern of farming and factors influencing it during the Peiligang culture period in the middle Yellow River valley, China. Science Bulletin 62:1565–1568. https://doi.org/10.1016/j.scib.2017.10.003

Wang G, Han J, Liu D (2003) The carbon isotope composition of C3 herbaceous plants in loess area of northern China. Science in China Series D: Earth Sciences 10:1069–1076

Wang H 王华, Wang WL 王炜林, Hu SM 胡松梅, Martin L (2013) Weishui Liuyu Xinshiqishidai Jiazhu De Xunhua Yu Siyang Celue 渭水流域新石器时代家猪的驯化与饲养策略[The domestication and husbandry strategies of the pigs in the Wei river valley during the

Neolithic age].Kaogu 考古 [Archaeology] 552:87–98

Wang X, Zhao Z, Zhong H, et al (2022) Manuring and land exploitation in the Central Plains of late Longshan (2200–1900 BCE) China: Implications of stable isotopes of archaeobotanical remains. Journal of Archaeological Science 148:105691. https://doi.org/10.1016/j.jas.2022.105691

Yuan J, Flad RK (2002) Pig domestication in ancient China. Antiquity 76:724–732. https://doi.org/10.1017/S0003598X00091171

Zeder MA (2011) The origins of agriculture in the Near East. Current Anthropology 52:S221–S235. https://doi.org/10.1086/659307

Zeder MA (2012) The domestication of animals. Journal of Anthropological Research 68:161–190. https://doi.org/10.3998/jar.0521004.0068.201

Zeder MA (2006) Central questions in the domestication of plants and animals. Evolutionary Anthropology: Issues, News, and Reviews 15:105–117. https://doi.org/10.1002/evan.20101

Zeder MA, Hesse B (2007) The initial domestication of goats (Capra hircus) in the Zagros Mountains 10,000 years ago. Science 2254–2257

Zeder MA, Lemoine X (2020) Factors affecting molar size in Sus scrofa. Journal of Archaeological Science 124:105266. https://doi.org/10.1016/j.jas.2020.105266

Zeder MA, Lemoine X, Payne S (2015) A new system for computing long-bone fusion age profiles in Sus scrofa. Journal of Archaeological Science 55:135–150

Zhang J, Cheng Z, Lan W, et al (2018) The new progresses of the paleoethnobotanical studies of the Jiahu site in Wuyang, Henan. Archaeology 607:100–110

Zhang J, Lu H, Gu W, et al (2012) Early Mixed Farming of Millet and Rice 7800 Years Ago in the Middle Yellow River Region, China. PLOS ONE 7:e52146. https://doi.org/10.1371/journal.pone.0052146

Zhang M, Liu Y, Li Z, et al (2022) Ancient DNA reveals the maternal genetic history of East Asian domestic pigs. Journal of Genetics and Genomics 49:537–546. https://doi.org/10.1016/j.jgg.2021.11.014

Zhang Q, Hou Y, Li X, et al (2021) Stable isotopes reveal intensive pig husbandry practices in the middle Yellow River region by the Yangshao period (7000-5000 BP). PLoS One 16:e0257524. https://doi.org/10.1371/journal.pone.0257524

Zhao ZJ 赵志军 (2020) Xinshiqi Shidai Zhiwu Kaogu Yu Nongye Qiyuan Yanjiu 新石器时代植物考古与农业起源研究[Origin of agriculture and archaeobotanical works in China]. Zhongguo Nongshi 中国农史[Agricultural History of China] 3–13

Zhao Z, Pearsall DM, Benfer RA, Piperno DR (1998) Distinguishing rice (Oryza sativa poaceae) from wildOryza species through phytolith analysis, II Finalized method. Economic Botany 52:134–145

Zong GF 宗冠福, Huang XS 黄学诗(1985) Yunan Baoshan Pupiao Quanxinshi Zaoqi Wenhua Yiwu Ji Buru Dongwu De Yicun 云南保山蒲缥全新世早期文化遗物及哺乳动物的遗存. Shiqian Yanjiu 史前研究 46–50