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Holocene fluctuations in vegetation and human population demonstrate social resilience in the prehistory of the Central Plains of China

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Abstract

Archaeologists and palaeoclimatologists have focused on the impact of climate on the prehistoric civilizations around the world; however, social resilience in the face of the climate change remains unclear, especially during the Neolithic and Bronze Age in the Central Plains of China (CPC). In this paper, we present palynological results from the Dahecun Core, Henan Province, China. Our pollen data indicate a warm and wet climate condition from 9200 to 4000 cal BP, which then switches to a cool and dry climatic condition during the Neolithic-Bronze Age transition (∼4000–3600 cal BP). We analyze ^{14}C dates from archaeological sites to demonstrate four episodes of population increase and present vegetation dynamics, determined from available pollen data, to provide evidence for the synchronous shifts in vegetation and human population during the Neolithic. Our results indicate that the aridification in the early Bronze Age did not cause population collapse, highlighting the importance of social resilience to climate change. The pollen, radiocarbon dates and archaeobotanical records from the CPC provides new evidence that supports the claim that the development of agriculture and complex societies, under the stress of a dry climate, set the stage for the dramatic increase of human population around 3800–3400 cal BP.

1. Introduction

Current research has linked the rise and fall of prehistoric complex societies to climate change, implying that climate change determined the success or failure of prehistoric civilizations (Weiss *et al* 1993, DeMenocal 2001, Kaniewski *et al* 2019, Sinha *et al* 2019). However, interactions between prehistoric societies and climate change are much more complex than this deterministic narrative (Munoz *et al* 2010, Endfield 2012, Armit *et al* 2014, Contreras 2017, Haldon *et al* 2018, Xu *et al* 2019). Numerous cases around the world show during similar shifts in climate, some complex societies collapsed while others flourished (Wang 2004, Butzer and Endfield 2012, Dunning *et al* 2012, Dong *et al* 2017). Moreover, when these climatic events occur, different socieites respond using a diverse set of adaptation strategies (Rosen and Rivera-Collazo 2012, Chen *et al* 2015a, Flohr *et al* 2016). Archaeological research has revealed that prehistoric societies are quite resilient and flexible to changing environmental and climatic regimes

(Marcus 1998, Butzer et al 2012, Li et al 2020). Therefore, it is necessary for the environmental sciences to explain the complexity and diversity of adaptation strategies to periods of climate change in prehistory.

Climate change is often argued to have a direct influence on demographic fluctuations (Li et al 2015, Tallavaara et al 2015, Bevan et al 2017, Xu et al 2019). Previous research has used the summed probability distribution (SPD) of large radiocarbon databases to develop a relative population growth curve that can be matched with paleoclimatic records, examples of this type of research are found in Europe (Shennan et al 2013, Bevan et al 2017, Roberts et al 2019), America (Munoz et al 2010, Riris and Arroyo-Kalin 2019), Australia (Williams 2013) and East Asia (Wang et al 2014, Li et al 2015, Dong et al 2019, Xu et al 2019). However, in the Chinese case, the long-term human responses to environmental change in the Central Plains of China (CPC) are still poorly understood, mainly due to the lack of high-resolution climate records and quantitative proxies of human activity. Here, we report two sets of independent proxies: one is a pollen record from the Dahecun Core in the CPC that ranges from ca. 10000 to 2000 cal BP (figure 1); and the other is a dataset of radiocarbon dates from CPC, which is a proxy of demographic fluctuations and human activity. We compare these two datasets to develop a deeper understanding of the relationship between climate change and human responses.

2. Regional setting

The CPC has been regarded as the ‘Cradle of Chinese Civilization’ (Yan 1987, Zhao 2000), making it an ideal region to examine the relationship between past climate change and human populations growth and decline. The first two decades of the 21st century have seen an enormous upsurge in archaeological work in this region. Enormous quantities of new data, including ^{14}C dates from various landforms across the CPC have been generated from archaeological excavations as a result of China’s fast pace of economic development (Wang et al 2014, Liu et al 2019a).

Regional vegetation is characterized by coniferous-deciduous forests and shrubs found in mountainous areas, including *Pinus tabulaeformis, Pinus bungeana, Abies chensiensis*, and *Betula albo-sinensis*. At lower elevations, broad-leaved deciduous forests are common, including *Ulmus pumila, Populus tomentosa, Salix matsudana* and *Robinia pseudoacacia. Eleocharis acicularis, Salix sinopurpurea* and *Typha* spp. are common in wetlands (Wang et al 1989, Zhang et al 2018a, Ren et al 2019).

The CPC has experienced six major Neolithic and Bronze Age archaeological cultures dating from ca. 9000 to 3000 cal BP: Peiligang (ca. 9000–7000 cal BP), Yangshao (ca. 7000–5000 cal BP), Longshan (ca. 5000–3900 cal BP), Erlitou (ca. 3900–3500 cal BP), Early Shang (Erligang, ca. 3600–3300 cal BP) and Late Shang (Yinxu, ca. 3300–3000 cal BP) (Liu and Chen 2012). Regional archaeological surveys have shown fluctuations in population size and settlement patterns during the Holocene (Liu et al 2019a). Compared to the Yangshao culture, there are many more Longshan archaeological sites, suggesting a significant increase in population size (Liu 2004). The Erlitou culture is characterized by its large elite palaces, numerus turquoise and bronze artifacts, and is widely recognized as the first state-level society in China (IACASS 2014, Zhang et al 2019). Current evidence of craft production at the Erlitou site indicates that it was inhabited by a socially and economically diverse population that likely fulfilled a variety of specialized services for wider society during the early Bronze Age (Liu and Chen 2012).

3. Materials and methods

3.1. Sampling strategy and stratigraphy

In the spring of 2008, our team drilled a core at Dahecun, an archaeological site located to the northeast of Zhengzhou. The Zhengzhou region is on the boundary of the Loess Plateau and North China Plain. It is surrounded by the Yellow River to the north, the Songshan Mountains to the southwest, and the North China Plain to the east. The annual precipitation is about 650 mm, and the annual mean temperature is 14.4 °C (Zhengzhou Committee of Chorography 1999).

Dahecun is located on the west edge of the North China Plain. Originating from the southwestern hilly area, the Jialu River flows to the northeast of Dahecun. The Dahecun core is situated on the floodplain of the Jialu River. Geological survey has found that the strata of this area are composed of alluvial or paleochannel deposits that formed during the early Holocene. During the middle Holocene, lacustrine or swamp deposits formed throughout the area before these deposits were buried by alluvial deposits during the late Holocene (Liu 1992, Yu et al 2016, Li et al 2019b). The ancient lake around Dahecun is estimated to be 61 km^2 large during the mid-Holocene (Yu et al 2016). The location of the Dahecun core was selected to avoid direct inflow, ensuring continuous deposition of the sediments. The core is 334 cm long and the lower 296 cm was sampled at 2 cm intervals for pollen analysis. The sediments are mainly dark grey silt and fine silty sand, interpreted as a lacustrine or swamp deposit.

Lithologic layers:

(a) 334–324 cm, coarse sand layer, containing some root pores and small pieces of charcoal.
(b) 324–262 cm, grey yellowish clayey silt layer, mixed with sand and organics. The lower part

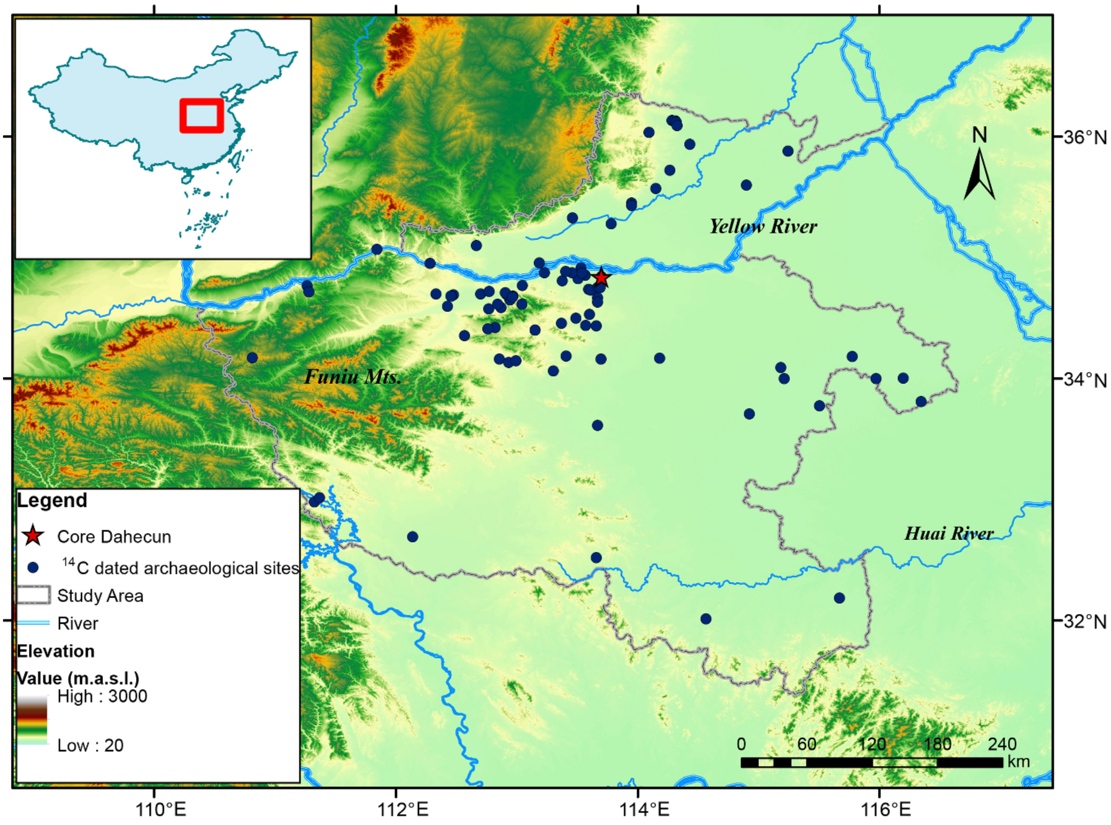

Figure 1. Topographical map showing the locations of the Dahecun Core (red star) and radiocarbon dates from Neolithic and Bronze Age archaeological sites in Central Plains of China. The data set of the background map is provided by International Scientific & Technical Data Mirror Site, Computer Network Information Center, Chinese Academy of Sciences (www.gscloud.cn).

of this layer is a dark sediment that contains carbonate nodules.

(c) 262–124 cm, mottled silt layer with fragments of coarse sand, containing pieces of charcoal.
(d) 124–78 cm, dark grey silty clay layer.
(e) 78–38 cm, complex of grey yellowish clayey silt and black clay, containing burned earth.
(f) 38–0 cm, yellowish to mottled (black specks) fine sand, containing the cultural remains including pieces of pottery that stylistically date to the Han dynasty (202 BCE–220 CE) and burned earth.

3.2. Radiocarbon dating and Pollen analysis

We collected five samples for accelerator mass spectrometry (AMS) radiocarbon dating. They were dated at the Xi'an AMS Center, China.

A total of 149 sediment samples from the Dahecun Core were selected for pollen analysis. All samples were treated with HCl, KOH, HF and acetolysis (Fægri and Iversen 1989, Moore *et al* 1991). To calculate pollen concentration, we added one *Lycopodium* spore tablet to each sample to serve as a marker. We excluded four samples which contained less than 100 pollen grains. Approximately 150 pollen and spore grains were counted for the remaining 145 samples. Pollen percentage diagrams were constructed using the TILIA (www.tiliait.com/, version 2.6.1, published in 2019) software.

The pollen and spores recovered from these sediments were transported by air, rainout, and surface runoff, with contributions from inflows of Jialu River. As previous research has pointed out, pollen preserved in lacustrine-alluvial sediments can come from both local vegetation and upstream sources (Zhu *et al* 2003, Brown *et al* 2007), therefore we consider that the Dahecun pollen signals reflect both local and regional vegetation.

3.3. Radiocarbon dates from archaeological sites in Central Plains of China

The uncalibrated ^{14}C dates were screened using the criteria described by Wang *et al* (2014). We eliminated the following dates: (a) dates with high error bars (1σ standard deviation of the ^{14}C ages >400 years); (b) dates derived from soils, shells, other unknown materials, or materials unsuitable for dating; (c) dates that had weak associations with human occupation or settlements such as temples, pagodas or canoes. If the dates were derived from different materials in the same context at a site, we selected the most reliable dating material. The ^{14}C database of the CPC contains 754 dates from 89 sites (figure 1). Most dates were derived from the ^{14}C database for China ($N = 4656$)

(Wang *et al* 2014). The 754 dates from CPC (∼0.167 million km^2) exceed Williams' (2012) suggested minimum sample size of 500 in a much larger region (∼7.69 million km^2), and thus the dataset we used can mitigate site- and period-level biases (Gamble *et al* 2005, Shennan and Edinborough 2007, Williams 2012). Therefore, we conclude that these dates reliably reflect changes in human activity and population dynamics in CPC.

The linkage between the SPD of large radiocarbon databases and human population is based on the proposition that the production and deposition of carbonized cultural material increases as population size increases, thus producing more material for radiocarbon dating (Munoz *et al* 2010, Bevan *et al* 2017, Xu *et al* 2019). The core assumption of this technique (more people → more datable samples → more radiocarbon dates) has been critically discussed, from the taphonomic loss of samples to the false signals linked to small sample sizes (e.g. Surovell *et al* 2009, Williams 2012, Contreras and Meadows 2014). Some of these problems can be solved by means of a hypothesis testing method introduced in Shennan *et al* (2013), and Timpson *et al* (2014). Their approach developed a statistical testing framework, where the observed SPDs are compared against a statistical confidence envelope of a fitted model (Crema *et al* 2016, Crema 2019). We use R package rcarbon to generate SPD of radiocarbon dates and to test observed SPDs against theoretical models (Bevan and Crema 2021, R Core Team 2019). A detailed description of these methods can be found in Shennan *et al* (2013) Timpson *et al* (2014), Crema *et al* (2016), Bevan *et al* (2017), Crema and Bevan (2021).

4. Results

4.1. Chronology and pollen assemblages

The Dahecun Core yielded five radiocarbon dates (table 1). Based on the relative dating of the pottery sherds (202 BCE–220 CE) excavated from depth 38 to 20 cm in layer f, the age of the boundary of cultural layer (layer f) and alluvial deposit (layer e) was estimated to ca. 2000 BP. An age-depth model was established through a Bayesian age model of these five AMS dates and one estimated date (figure 2). The age-depth model fit well with lithostratigraphic correlation with the adjacent cores (Liu 1992, Yu *et al* 2016, Wang *et al* 2019).

The pollen record from Dahecun Core is illustrated in figure 3. From ca. 10000 to 4000 cal BP, the regional vegetation was dominated by various trees, including *Pinus, Betula, Abies, Tsuga, Alnus, Quercus*, and *Juglans*. According to the recovered pollen assemblages and the cluster analysis, there are three major vegetation zones:

Zone 1 (334–270 cm, ca. 10000–9200 cal BP). This zone is dominated by conifer (e.g. *Pinus, Tsuga, Alnus*) and broadleaved trees (e.g. *Betula, Juglans, Quercus*). There is an increase of *Betula* and *Juglans* at the expense of *Tsuga* and *Alnus* at ca. 9530 cal BP. The high percentage of *Pinus, Betula* indicate cool and wet climate conditions.

Zone 2 (270–75 cm, ca. 9200–4000 cal BP). While *Pinus* still comprises more than 50% of the pollen percentage, this zone is marked by a rapid decrease in *Betula* pollen. The percentage of *Tsuga* and *Polypodium* exhibit an increasing trend compared with Zone 1, indicating a warm and humid conditions. The relatively high percentage of the Pteridophytes taxa shows that the lake level was stable at this stage.

Zone 3 (75–38 cm, ca. 4000–2000 cal BP). This zone is marked by the increasing trend of *Artemisia* and *Chenopodiaceae* at the expense of trees, such as *Pinus, Alnus, Tsuga*, and *Quercus*. The percentage of *Pinus* decreases in the lower part and increases in the upper part again. The decrease of various trees and increase of drought-tolerant taxa such as *Artemisia* and *Chenopodiaceae* imply a fluctuating cool and arid environment.

4.2. Demographic history

The SPD curve for the CPC exhibits several episodes of demographic fluctuations, with four peaks (8100–7600, 5600–5000, 4200–4000, 3800–3400 cal BP), and four declines (7500–6500, 5000–4500, 4000–3900, 3400–3000 cal BP) (figure 4). When incorporating the demographic fluctuations with cultural changes, it is notable that population increases when the archaeological cultures flourish. The first demographic peak (ca. 8100–7600 cal BP) corresponds with the rise of the Peiligang Culture and the formation of early millet-based agriculture (Zhao 2014, Ren *et al* 2016, He *et al* 2017). The second peak was the late Yangshao (ca. 5600–5000 cal BP), when the number of settlements quickly increased (Liu 2004). The third peak was the late Longshan (4200–4000 cal BP), characterized by the emergence of a complex chiefdom organization (Liu *et al* 2019a). The fourth peak was the Erlitou and early Erligang period (3800–3400 cal BP), marking the emergence of the earliest states in China (Liu and Chen 2012).

The four episodes of population decline indicate periods of cultural transition. The first was during the late Peiligang to the early Yangshao transition (ca. 7500–6500 cal BP), and the second was during the early Longshan period ca. 5000–4500 cal BP. The third population decrease around 4000–3900 cal BP corresponds with the transition from the late Longshan to Erlitou Culture. The fourth decline from ca. 3400 to 3000 cal BP can be interpreted in two ways. One interpretation is that the political center moved to Anyang Yinxu in northern Henan during the second half of the Shang dynasty, resulting in a large scale migration of people from central Henan to Anyang and its surrounding area (Liu and Chen 2012). The other interpretation of this

Table 1. Result of AMS-radiocarbon dating from the Dahecun Core, calibrated using CalPal (www.calpal-online.de).

				$\delta^{13}C$ (‰)		^{14}C age (a BP)		
Lab. no.	Field no.	Depth (cm)	Dating material	$\delta^{13}C$	Error (1σ)	^{14}C age	Error (1σ)	Calibrated age (cal BP)
XA3327	Z2 53	106	Soil OM	−16.76	0.61	4989	29	5714 ± 39
XA3328	Z2 86	172	Charcoal	−15.84	0.2	6137	27	7062 ± 75
XA3326	DHC04	220	Soil OM	−20.66	0.45	6736	32	7608 ± 23
XA3338	Z2 135	270	Soil OM	−18.04	0.18	8252	30	9224 ± 63
XA3331	Z2 153	306	Soil OM	−22.67	1.16	8470	61	9484 ± 38

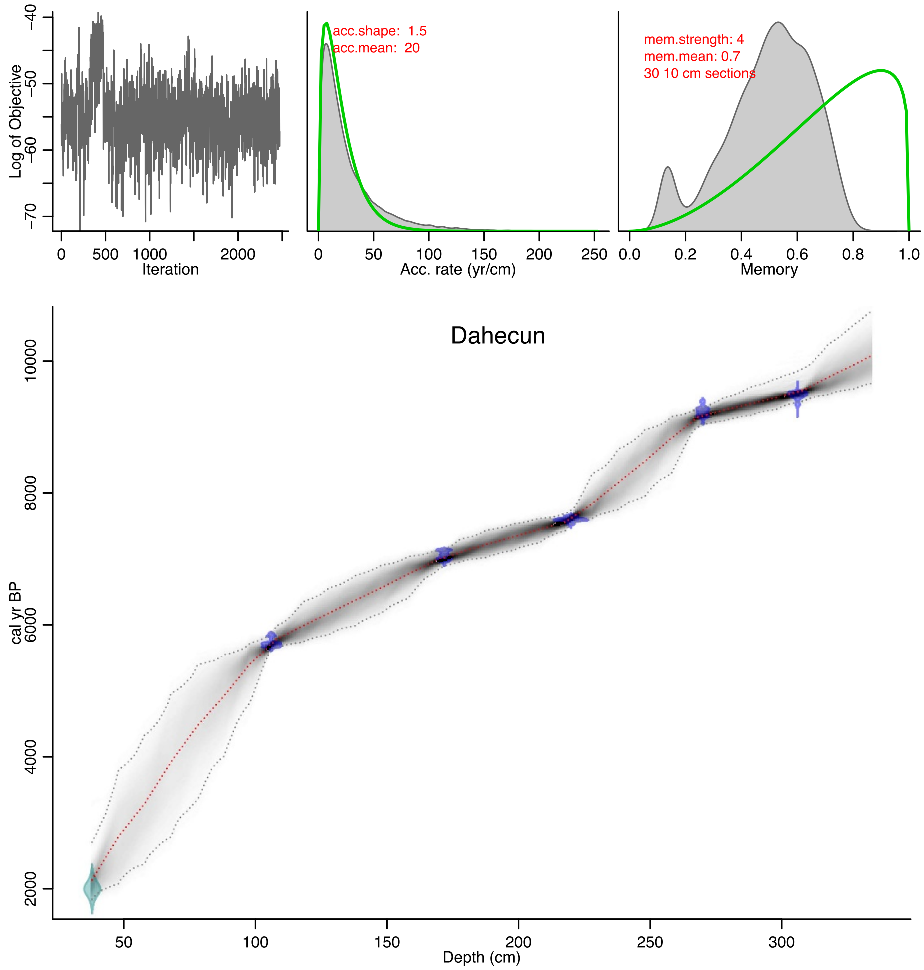

Figure 2. Age-depth relationship of the Dahecun Core based on Bayesian age model obtained by Bacon 2.3 (Blaauw and Christen 2011), using the IntCal13 atmospheric curve (Reimer *et al* 2013).

shift is that more archaeological sites are dated by ceramic typologies and historical documents instead of radiocarbon dates in late Bronze and Iron Age, which are reflected in the decline of the SPD for the younger ages after 3400 cal BP. The decline of the SPD in late Bronze Age can also be seen on the Chinese Loess Plateau (Li *et al* 2015).

Our results fit well with known fluctuations in settlement patterns in the Yiluo region of the CPC, reflected in changes in site number and AMS dates analyzed using the SPD method. The full-coverage regional survey by Liu *et al* (2019a) has shown the population peaks in the late Yangshao, late Longshan, and Erlitou period (Liu *et al* 2019a). However, this trend is different from the population estimation based on the numbers of archaeological sites of the whole China, which indicates a population decrease during the Erlitou period (Hosner *et al* 2016 see figure 5, Leipe *et al* 2019 see figure 3). This difference might be due to regional variability. Additionally, the mean size of archaeological sites during the Erlitou period is larger than the Longshan period,

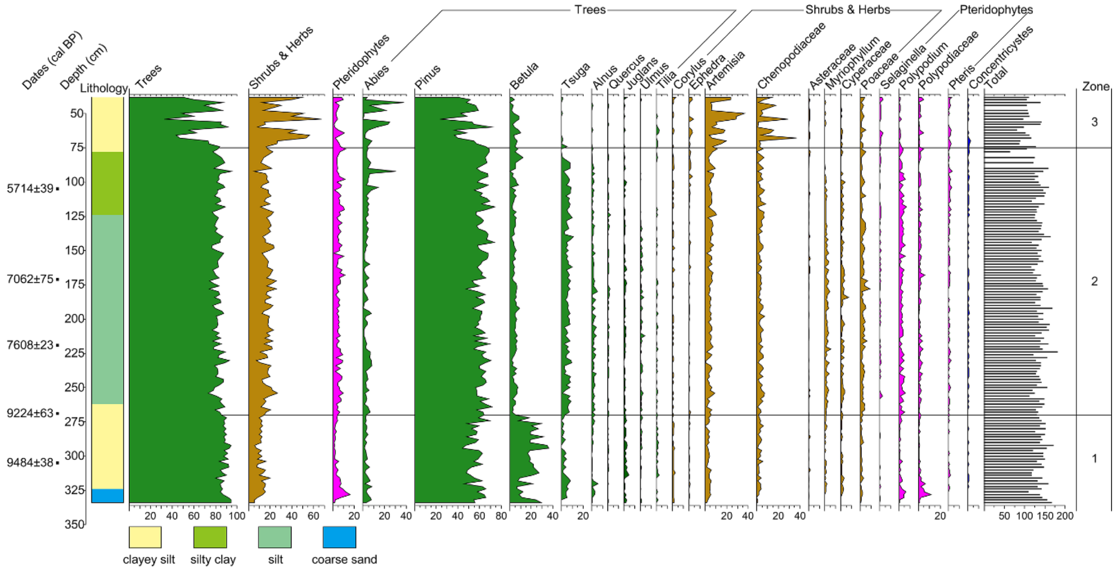

Figure 3. Pollen diagram of major pollen types for the Dahecun Core. The green, brown and purplish red represent trees, shrubs and herbs, and pteridophytes, respectively.

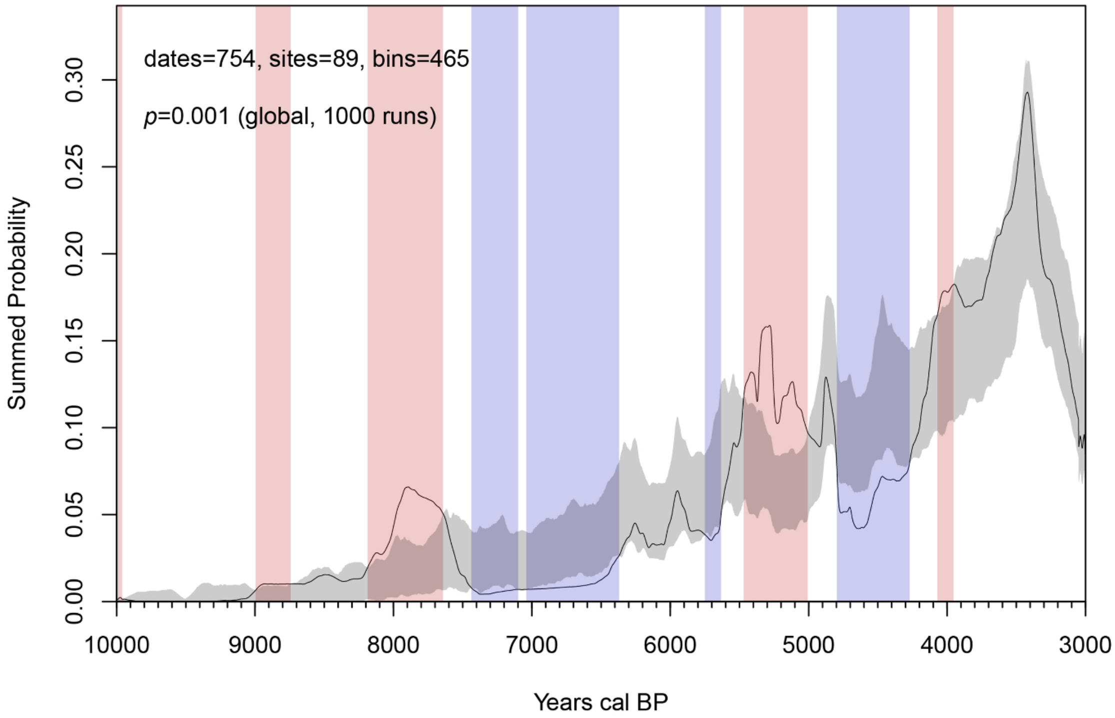

Figure 4. A summed probability distribution (SPD) of radiocarbon dates in Central Plains of China (solid black line) compared with Monte-Carlo envelope of equivalent random samples drawn from a fitted logistic growth model of population growth (the grey band). Red and blue bands represent areas where the observed SPD significantly deviates from the logistic model (red bands are those where population exceeds the expectations of the logistic model, blue bands are those where population is beneath expectations).

which also should reflect changes in the estimated population size (Liu *et al* 2019a).

5. Discussion

5.1. Vegetation dynamics, climate change and demographic fluctuations

Vegetation dynamics, demographic fluctuations and climate change over the course of the Holocene are illustrated in figure 5. Pollen records reveal that the changing ecosystems of the region are associated with demographic fluctuations. A major climatic shift around 9200 BP changed the temperature and moisture availability, and led to the expansion of *Tsuga* (figure 3). Precipitation reconstruction from Gonghai Lake, located in Shanxi Province, also indicates a more humid climatic condition from ca. 9000 cal BP (figure 5(d), Chen *et al* 2015b). The

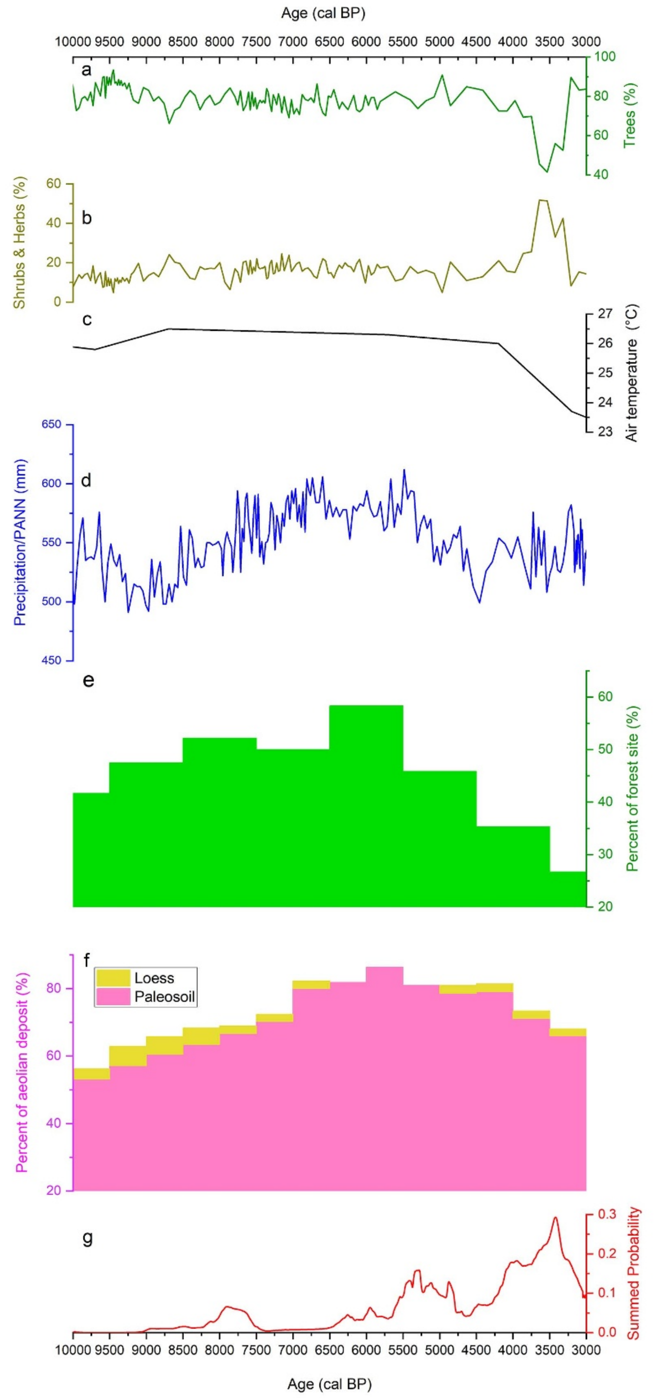

Figure 5. Comparison of the reconstructed vegetation dynamics, air temperature, annual precipitation and demographic fluctuations in Central Plains of China (CPC) with other large-scale vegetation history and regional paleoclimatic records. (a) Percentage of tree pollen (%) from Dahecun Core. (b) Percentage of shrub and herb pollen (%) from Dahecun Core. (c) Air temperature reconstructed based on GDGTs from the Mangshan loess plateau (Peterse *et al* 2011). (d) Pollen-based annual precipitation (PANN) reconstructed from Gonghai Lake (Chen *et al* 2015b). (e) Percentage of forest type in north-central China (Li *et al* 2019a). (f) Moisture index synthesis reconstructed from the sedimentary facies of aeolian deposits in the East Sandy Land in northern China (Li *et al* 2014). (g) A summed probability distribution (SPD) of radiocarbon dates in CPC as proxy for demographic fluctuations.

first two visible increases in population size, from ca. 8100–7600 to 5600–5000 cal BP, correspond with tree dominated vegetation cover, which indicates a warm and humid climate during the mid-Holocene. The environment during the mid-Holocene was characterized by an increase in moisture availability, with high values of *Tsuga* and *Alnus*, and increases of some taxa prefer to wet habitats, such as *Myriophyllum* and *Polypodium. Tsuga* decreased abruptly around 4500 cal BP, while the pollen percentage of herbacous plants (*Artemisia, Chenopodiaceae*) increased (figure 3). A climate shift at ca.

4500–4000 cal BP is also seen across other parts in north-central China (Chen *et al* 2015b, Zhang *et al* 2018b).

Several cultural and demographic changes correspond with major shifts in climate and ecosystems. The rise of the Peiligang culture at ca. 9000 BP coincides with the replacement of the cold-tolerant taxa (*Betula*) with the thermophilous and hygrophilous taxa such as *Tsuga* and *Alnus*. There is a clear signal for the precipitation decline around the 5000 cal BP climate event (Feng *et al* 2006, Chen *et al* 2015b, Xu *et al* 2017), when the pollen abundance of trees rapidly decreases (figure 5(a)). This may have caused a food shortage and resulted in the Yangshao–Longshan transition and the subsequent population decline during the early Longshan period (5000–4800 cal BP). The population decrease in early-late Longshan cultural transition time (ca. 4500 cal BP) coincides with more serious aridity and a sharp decrease in *Tsuga* (figure 3). A decline in trees and an increase in various other herb taxa (e.g. *Artemisia, Chenopodiaceae*) at ca. 4000 cal BP occurred at the same time as the transition from Longshan culture to Erlitou culture and the third population decline (4000–3900 cal BP). Demographic changes occur at each environmental-cultural transition, suggesting that the vegetation dynamics, climate change, cultural transitions and demographic fluctuations are closely linked.

Overall woodland species are relatively stable at around 70%–90% throughout the early Holocene up to ca. 9000–3900 cal BP, but then herb taxa increase approximately coincident with the increase in archaeological radiocarbon at the start of the Early Bronze Age. The amount of non-arboreal taxa doubles at the start of the Bronze Age, from ca. 25% to 50% of the pollen abundance, at the expense of arboral taxa, like *Tsuga, Pinus*, and *Alnus*. There is a synchronous non-arboreal taxa and radiocarbon-inferred population peak at ca. 3500 cal BP. Non-arboreal taxa appears to decrease rapidly, followed by a period between 3200 and 3000 cal BP when vegetation remains stable. The air temperature reconstruction based on branched glycerol dialkyl glycerol tetraethers (GDGTs) from Mangshan loess plateau in CPC indicates a cooling climate condition after 4000 cal BP (figure 5(c), Peterse *et al* 2011). Independent moisture index synthesis reconstructed from the sedimentary facies of aeolian deposits in the East Sandy Land of northern China (figure 5(f), Li *et al* 2014) shows that summer monsoon intensity decreased after 4000 cal BP, which may have had a significant role in increasing aridity and subsequent forest decline. This can be supported by a large-scale palaeovegetation reconstruction which suggested that forest vegetation flourished during 9000–4000 cal BP but decreased thereafter in north-central China (figure 5(e), Li *et al* 2019a). Population increases, however, should have accelerated the trajectory of forest degradation from the early Bronze Age onwards (figure 5). Thus, deforestation between ca. 3800 and 3500 cal BP was due to the combination of increasing aridity and human activities, which was initiated by decreased monsoon intensity beginning in the late Neolithic (Zhao *et al* 2009, Ren *et al* 2019).

5.2. Evidence of social resilience to past climate change

The comparison of the pollen, paleoclimate and archeological data shows that population size rapidly increased from 3800 to 3400 cal BP, during a cold and arid period. This period is defined by the transition from millet-based agriculture to a multiple crop system, which would have facilitated demographic growth by increasing food resources (Lee and Bestel 2007, Lee *et al* 2007, Zhao 2007, Liu *et al* 2019b).

Flotation results summarized in figure 6 show the development of agriculture on the CPC. Archaeobotanical research has revealed a transition from a hunting and gathering dominated subsistence strategy to an subsistence economy dominated by sedentary agriculture during the mid-late Yangshao period (6000–5000 BP) (Zhao 2014), which should be one factor driving the distinct peak in human population around 5600–5000 cal BP. During the late Longshan period (4500–3900 cal BP), the crop mainly cultivated is foxtail millet (*Setaria italica*), supplemented with broomcorn millet (*Panicum miliaceum*), rice (*Oryza sativa*), and soybean (*Glycine*) (Zhang *et al* 2014, He *et al* 2017). During the Erlitou period (3900–3500 cal BP), wheat (*Triticum aestivum*) was introduced into the CPC, but its proportion in the main crops remained low (see figure 6, Zhao 2007, Zhang *et al* 2014, Long *et al* 2018, Liu *et al* 2019b). From 3900 to 3500 cal BP, the abundance ratio of rice from the flotation results also steadily increased, especially at the Erlitou site (Lee and Bestel 2007, Zhao 2007, Zhang *et al* 2014). This may indicate an advancement in water management technologies. During Erligang period (3600–3300 cal BP), the proportion of wheat visibly increase, showing its more and more significant role in food resource (Lee *et al* 2007, Zhao 2007, Zhang *et al* 2014). The higher yield per unit area of wheat and rice compared with millets and the increasingly diverse agricultural system contributed to the growing resilience towards instable climatic conditions after 3900 cal BP. Similar strategies were found in the northeastern Tibetan Plateau of China, where farmers used a risk reduction strategy based on crop diversification which included cultivating cold-tolerant wheat and barley faced with the 4000 cal BP climatic cooling (d'Alpoim Guedes and Bocinsky 2018).

Another aspect that can explain the dramatic demographic growth from 3800 to 3400 cal BP is the rise of state-level complex societies in the CPC

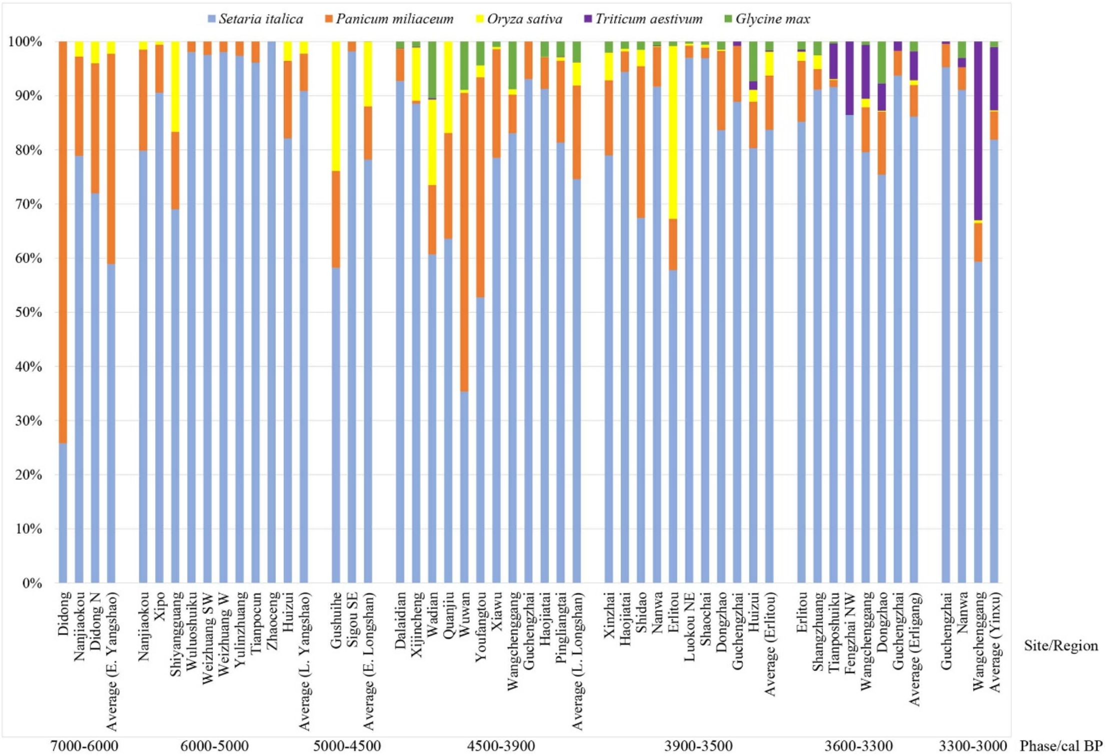

Figure 6. Abundance ratio of crops from the flotation results in Central Plains of China: Didong and Didong N (Wei 2014), Nanjiaokou (Qin 2009), Xipo (Zhao 2011), Shiyangguan (Fuller and Zhang 2007), Wuluoshuiku, Weizhuang SW, Weizhuang W, Yulinzhuang, Tianpocun and Zhaoceng (Lee *et al* 2007), Huizui (Lee and Bestel 2007, Zhang *et al* 2014), Gushuihe (Fuller and Zhang 2007), Sigou SE (Lee *et al* 2007), Dalaidian (Wu 2016), Xijincheng (Chen *et al* 2010), Wadian (Liu *et al* 2018), Quanjiu (Wei 2014), Wuwan, Youfangtou, Xiawu and Shidao (Fuller and Zhang 2007), Wangchenggang (Zhao and Fang 2007), Guchengzhai (Chen *et al* 2012), Haojiatai and Pingliangtai (Deng and Qin 2017), Xinzhai (Zhong *et al* 2016), Dongzhao (Yang *et al* 2017), Nanwa (Wu *et al* 2014), Erlitou (Zhao 2007), Luokou NE, Shaochai, Shangzhuang and Fengzhai NW (Lee *et al* 2007).

during the Erlitou and Erligang period. The capitals of Erlitou culture and Shang dynasties are all located on the CPC and facilitated population nucleation (Liu and Chen 2012). The size of the largest site expanded from 70 ha in late Longshan period to 300 ha during the Erlitou period (Liu *et al* 2019a), also mirrors the SPD graph of AMS dates.

6. Conclusion

Climate fluctuations have played significant roles in the population dynamics during the early and middle Holocene (ca. 10000–3900 cal BP). However, social resilience to external challenges, especially the diverse agricultural system and development of the complex societies to a highly centralized dynastic heartland in Chinese civilization, ultimately determined the trajectories of demographic fluctuations in the late Holocene (3800–3000 cal BP).

Confronted with the fluctuation and limitation of resources caused by episodes of climatic aridification, like food shortages for example, people in the CPC had two ways to survive. Firstly, the number of cultivated plants expanded to include foxtail millet, broomcorn millet, wheat, soybean and rice, which reduced the risk of food production. Secondly, population nucleation as a result of the first dynastic states in China also benefited the protection of the existing resources. In sum, the development of agriculture and the formation of earliest dynastic states in China has greatly contributed to the dramatic increase in population during the early Bronze Age.

Data availability

The data that support the findings of this study are available upon reasonable request from the authors.

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References

Armit I, Swindles G T, Becker K, Plunkett G and Blaauw M 2014 Rapid climate change did not cause population collapse at the end of the European Bronze Age *Proc. Natl Acad. Sci.* **111** 17045–9

Bevan A, Colledge S, Fuller D, Fyfe R, Shennan S and Stevens C 2017 Holocene fluctuations in human population demonstrate repeated links to food production and climate *Proc. Natl Acad. Sci.* **114** E10524–31

Bevan A and Crema E 2021 Rcarbon: calibration and analysis of radiocarbon dates. R package version 1.4.2 (15 March 2021) (available at: https://cran.r-project.org/web/packages/rcarbon/index.html)

Blaauw M and Christen J A 2011 Flexible paleoclimate age-depth models using an autoregressive gamma process *Bayesian Anal.* **6** 457–74

Brown A G, Carpenter R G and Walling D E 2007 Monitoring fluvial pollen transport, its relationship to catchment vegetation and implications for palaeoenvironmental studies *Rev. Palaeobot. Palynol.* **147** 60–76

Butzer K W 2012 Collapse, environment and society *Proc. Natl Acad. Sci.* **109** 3632–9

Butzer K W and Endfield G H 2012 Critical perspectives on historical collapse *Proc. Natl Acad. Sci.* **109** 3628–31

Chen F H *et al* 2015a Agriculture facilitated permanent human occupation of the Tibetan Plateau after 3600 B.P *Science* **347** 248–50

Chen F H *et al* 2015b East Asian summer monsoon precipitation variability since the last deglaciation *Sci. Rep.* **5** 11186

Chen W W, Zhang J Z and Cai Q F 2012 Analysis of plant remains excavated from Guchengzhai walled city in Xinmi, Henan Province *Huaxia Archaeol.* **1** 54–62 (in Chinese with English abstract)

Chen X X, Wang L Z and Wang Q 2010 Analysis of the flotation results from the Xijincheng site in Boai County, Henan Province (year 2006–2007) *Huaxia Archaeol.* **3** 67–76 (https://cnki.com.cn/Article/CJFDTOTAL-HXKG-201003011.htm) (in Chinese with English abstract)

Contreras D A 2017 Correlation is not enough: building better arguments in the archaeology of human-environment interactions *The Archaeology of Human-Environment Interactions* ed D A Contreras (New York: Routledge) pp 3–22

Contreras D A and Meadows J 2014 Summed radiocarbon calibrations as a population proxy: a critical evaluation using a realistic simulation approach *J. Archaeol Sci.* **52** 591–608

Crema E R 2019 Analysing large collection of radiocarbon dates using R *Big Data in Archaeology: R Workshop* (University of Cambridge)

Crema E R and Bevan A 2021 Inference from large sets of radiocarbon dates: software and methods *Radiocarbon* **63** 23–39

Crema E R, Habu J, Kobayashi K and Madella M 2016 Summed probability distribution of ^{14}C dates suggests regional divergences in the population dynamics of the Jomon period in eastern Japan *PLoS One* **11** e0154809

d'Alpoim Guedes J and Bocinsky R K 2018 Climate change stimulated agricultural innovation and exchange across Asia *Sci. Adv.* **4** eaar4491

DeMenocal P B 2001 Cultural responses to climate change during the late Holocene *Science* **292** 667–73

Deng Z H and Qin L 2017 Comparative research of crop structure in Central China during Longshan period *Huaxia Archaeol.* **3** 98–108 (in Chinese with English abstract)

Dong G H, Li R, Lu M X, Zhang D J and James N 2019 Evolution of human–environmental interactions in China from the late Paleolithic to the Bronze Age *Prog. Phys. Geogr. Earth Environ.* **26** 0309133319876802

Dong G H, Liu F W and Chen F H 2017 Environmental and technological effects on ancient social evolution at different spatial scales *Sci. China Earth Sci.* **60** 2067–77

Dunning N P, Beach T P and Luzzadder-Beach S 2012 Kax and kol: collapse and resilience in lowland Maya civilization *Proc. Natl Acad. Sci.* **109** 3652–7

Endfield G H 2012 The resilience and adaptive capacity of social-environmental systems in colonial Mexico *Proc. Natl Acad. Sci.* **109** 3676–81

Fægri K and Iversen J 1989 *Textbook of Pollen Analysis* 4th edn (Chichester: Wiley)

Feng Z D, An C B and Wang H B 2006 Holocene climatic and environmental changes in the arid and semi-arid areas of China: a review *Holocene* **16** 119–30

Flohr P, Fleitmann D, Matthews R, Matthews W and Black S 2016 Evidence of resilience to past climate change in Southwest Asia: early farming communities and the 9.2 and 8.2 ka events *Quat. Sci. Rev.* **136** 23–39

Fuller D Q and Zhang H 2007 A preliminary report of the survey archaeobotany of the upper Ying Valley (Henan Province) *Archaeological Discovery and Research at the Wangchenggang Site in Dengfeng (2002–2005)* ed School of Archaeology and Museology of Peking University and Henan Provincial Institute of Cultural Relics and Archaeology (Zhengzhou: Great Elephant) pp 916–58

Gamble C, Davies W, Pettitt P, Hazelwood L and Richards M 2005 The archaeological and genetic foundations of the European population during the late glacial: implications for 'agricultural thinking' *Camb. Archaeol. J.* **15** 193–223

Haldon J, Mordechai L, Newfield T P, Chase A F, Izdebski A, Guzowski P, Labuhn I and Roberts N 2018 History meets palaeoscience: consilience and collaboration in studying past societal responses to environmental change *Proc. Natl Acad. Sci.* **115** 3210–8

He K Y, Lu H Y, Zhang J P, Wang C and Huan X J 2017 Prehistoric evolution of the dualistic structure mixed rice and millet farming in China *Holocene* **27** 1885–98

Hosner D, Wagner M, Tarasov P E, Chen X and Leipe C 2016 Spatiotemporal distribution patterns of archaeological sites in China during the Neolithic and Bronze age: an overview *Holocene* **26** 1576–93

IACASS (Institute of Archaeology, Chinese Academy of Social Sciences) 2014 *Erlitou: 1999–2006* (Beijing: Cultural Relics Publishing House) (in Chinese)

Kaniewski D, Marriner N, Cheddadi R, Morhange C, Bretschneider J, Jans G, Otto T, Luce F and Van Campo E 2019 Cold and dry outbreaks in the eastern Mediterranean 3200 years ago *Geology* **47** 933–7

Lee G A and Bestel S 2007 Contextual analysis of plant remains at the Erlitou-period Huizui site, Henan, China *Bull. Indo Pac. Prehistory Assoc.* **27** 49–60

Lee G A, Crawford G W, Liu L and Chen X C 2007 Plants and people from the Early Neolithic to Shang periods in North China *Proc. Natl Acad. Sci.* **104** 1087–92

Leipe C, Long T, Sergusheva E A, Wagner M and Tarasov P E 2019 Discontinuous spread of millet agriculture in eastern Asia and prehistoric population dynamics *Sci. Adv.* **5** eaax6225

Li H, An C B, Fan W J, Dong W M, Zhao Y T and Wang H P 2015 Population history and its relationship with climate change on the Chinese Loess Plateau during the past 10,000 years *Holocene* **25** 1144–52

Li Q, Wu H B, Yu Y Y, Sun A Z and Luo Y L 2019a Large-scale vegetation history in China and its response to climate change since the Last Glacial Maximum *Quat. Int.* **500** 108–19

Li Q, Wu H B, Yu Y Y, Sun A Z, Markovic S B and Guo Z T 2014 Reconstructed moisture evolution of the deserts in northern China since the Last Glacial Maximum and its implications for the East Asian Summer Monsoon *Glob. Planet. Change* **121** 101–12

Li X, Zhang S J, Lu M X, Qiu M H, Wen S Q and Ma M M 2020 Dietary shift and social hierarchy from the Proto-Shang to Zhou Dynasty in the Central Plains of China *Environ. Res. Lett.* **15** 035002

Li Y F, Shen H D, Yu G, Li C H and Hu S Y 2019b A study of lacustrine and palustrine sediments and environmental changes in Zhengzhou regions during the past 20000 years *J. Stratigr.* **43** 364–75 (in Chinese with English abstract)

Liu C, Zhao Z J and Fang Y M 2018 Analysis of the flotation results from Wadian site in Yuzhou, Henan Province (year 2007, 2009) *Huaxia Archaeol.* **1** 95–102 (in Chinese with English abstract)

Liu J S 1992 Preliminary study of the Holocene stratigraphy in Zhengzhou *J. Stratigr.* **16** 111–9 (in Chinese with English abstract)

Liu L 2004 *The Chinese Neolithic: Trajectories to Early States* (Cambridge: Cambridge University Press)

Liu L and Chen X C 2012 *The Archaeology of China: From the Late Paleolithic to the Early Bronze Age* (Cambridge: Cambridge University Press)

Liu L, Chen X C, Wright H, Xu H, Li Y, Chen G L, Zhao H, Kim H and Lee G A 2019a Rise and fall of complex societies in the Yiluo region, North China: the spatial and temporal changes *Quat. Int.* **521** 4–15

Liu X Y, Jones P J, Matuzeviciute G M, Hunt H V, Lister D L, An T, Przelomska N, Kneale C J, Zhao Z J and Jones M K 2019b From ecological opportunism to multi-cropping: mapping food globalisation in prehistory *Quat. Sci. Rev.* **206** 21–8

Long T W, Leipe C, Jin G Y, Wagner M, Guo R Z, Schröder O and Tarasov P E 2018 The early history of wheat in China from ^{14}C dating and Bayesian chronological modelling *Nat. Plants* **4** 272–9

Marcus J 1998 The peaks and valleys of ancient states: an extension of the dynamic model *Archaic States* ed G M Feinman and J Marcus (Santa Fe, CA: SAR Press) pp 59–94

Moore P D, Webb J A and Collinson M E 1991 *Pollen Analysis* (Oxford: Blackwell Scientific Publications)

Munoz S E, Gajewski K and Peros M C 2010 Synchronous environmental and cultural change in the prehistory of the northeastern United States *Proc. Natl Acad. Sci.* **107** 22008–13

Peterse F, Prins M A, Beets C J, Troelstra S R, Zheng H, Gu Z, Schouten S and Damsté J S S 2011 Decoupled warming and monsoon precipitation in East Asia over the last deglaciation *Earth Planet. Sci. Lett.* **301** 256–64

Qin L 2009 Plant remains excavated from early-middle Yangshao layers at the Nanjiaokou site *Nanjiaokou in Sanmenxia* (Beijing: Science Press) pp 427–35 (in Chinese)

R Core Team 2019 *R: A Language and Environment for Statistical Computing* (Vienna: R Foundation for Statistical Computing)

Reimer P J *et al* 2013 IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP *Radiocarbon* **55** 1869–87

Ren X L, Lemoine X, Mo D W, Kidder T R, Guo Y Y, Qin Z and Liu X Y 2016 Foothills and intermountain basins: does China's Fertile Arc have 'Hilly Flanks'? *Quat. Int.* **426** 86–96

Ren X L, Mo D W, Storozum M J, Lemoine X, Yu Y Y, Gu W F, Lei X S, Zhang J Q, Lü J Q and Kidder T R 2019 Early urban impact on vegetation dynamics: palaeoecological reconstruction from pollen records at the Dongzhao site, Henan Province, China *Quat. Int.* **521** 66–74

Riris P and Arroyo-Kalin M 2019 Widespread population decline in South America correlates with mid-Holocene climate change *Sci. Rep.* **9** 6850

Roberts C N, Woodbridge J, Palmisano A, Bevan A, Fyfe R and Shennan S 2019 Mediterranean landscape change during the Holocene: synthesis, comparison and regional trends in population, land cover and climate *Holocene* **29** 923–37

Rosen A M and Rivera-Collazo I 2012 Climate change, adaptive cycles, and the persistence of foraging economies during the late Pleistocene/Holocene transition in the Levant *Proc. Natl Acad. Sci.* **109** 3640–5

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

Shennan S and Edinborough K 2007 Prehistoric population history: from the late glacial to the late Neolithic in central and northern Europe *J. Archaeol Sci.* **34** 1339–45

Sinha A *et al* 2019 Role of climate in the rise and fall of the Neo-Assyrian Empire *Sci. Adv.* **5** eaax6656

Surovell T A, Finley J B, Smith G M, Brantingham P J and Kelly R 2009 Correcting temporal frequency distributions for taphonomic bias *J. Archaeol Sci.* **36** 1715–24

Tallavaara M, Luoto M, Korhonen N, Järvinen H and Seppä H 2015 Human population dynamics in Europe over the Last Glacial Maximum *Proc. Natl Acad. Sci.* **112** 8232–7

Timpson A, Colledge S, Crema E, Edinborough K, Kerig T, Manning K, Thomas M G and Shennan S 2014 Reconstructing regional population fluctuations in the European Neolithic using radiocarbon dates: a new case-study using an improved method *J. Archaeol Sci.* **52** 549–57

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

Wang L S, Hu S Y, Yu G, Wang X H, Wang Q, Zhang Z H, Ma M M, Cui B L and Liu X B 2019 Multiproxy studies of lake sediments during mid-Holocene in Zhengzhou region of the Henan Province, central China, and the implications for reconstructing the paleoenvironments *Quat. Int.* **521** 104–10

Wang S Y, Wang Y Z, Wang Z Y, Wang Q and Jia L J 1989 Characteristics of the vegetation in Henan Province *Acta Agric. Univ. Henanensis* **23** 386–92 (in Chinese with English abstract)

Wang W 2004 A study of the causes of cultural changes in a vast territory of China around 2000 BC *Archaeology* **1** 67–77 (in Chinese with English abstract)

Wei X T 2014 The discoveries and preliminary research of plant remains in the region of the Western Henan and the Southwestern Shanxi in the Neolithic Age *Dongfang Archaeology* vol 11 (Beijing: Science Press) pp 343–64 (in Chinese)

Weiss H, Courty M A, Wetterstrom W, Guichard F, Senior L, Meadow R and Curnow A 1993 The genesis and collapse of third millennium north Mesopotamian civilization *Science* **261** 995–1004

Williams A N 2012 The use of summed radiocarbon probability distributions in archaeology: a review of methods *J. Archaeol Sci.* **39** 578–89

Williams A N 2013 A new population curve for prehistoric Australia *Proc. R. Soc.* B **280** 20130486

Wu W W, Zhang J H and Jin G Y 2014 Archaeobotanical evidence for agriculture of settlement at Nanwa site in Dengfeng, Henan Province from Erlitou period to Han dynasty *Zhongyuan Relics* **1** 109–17 (in Chinese)

Wu X 2016 The research of plant remains in longshan period from Dalaidian Site in Henan MSc Thesis Shandong University (in Chinese with English abstract)

Xu D K, Lu H Y, Chu G Q, Liu L, Shen C M, Li F J, Wang C and Wu N Q 2019 Synchronous 500 year oscillations of monsoon climate and human activity in Northeast Asia *Nat. Commun.* **10** 4105

Xu Q H, Chen F H, Zhang S R, Cao X Y, Li J Y, Li Y C, Li M Y, Chen J H, Liu J B and Wang Z L 2017 Vegetation succession and East Asian Summer Monsoon Changes since the last deglaciation inferred from high-resolution pollen record in Gonghai Lake, Shanxi Province, China *Holocene* **27** 835–46

Yan W M 1987 The unity and diversity of prehistoric cultures in China *Cult. Relics* **3** 38–50 (in Chinese)

Yang Y Z, Yuan Z J, Zhang J Q, Cheng Z J, Xuan H L, Fang F, Zhang J Z and Gu W F 2017 Characteristics and development of agriculture during Xia and Shang dynasties based on carbonized plant analysis at the Dongzhao Site, Central China *Acta Anthropol Sin.* **36** 119–30 (in Chinese with English abstract)

Yu G *et al* 2016 *Sedimentology of Lake-River Systems and Environmental Evolutions in Zhengzhou Regions* (Beijing: Science Press) (in Chinese)

Zhang C, Pollard A M, Rawson J, Huan L, Liu R and Tang X 2019 China's major Late Neolithic centres and the rise of Erlitou *Antiquity* **93** 588–603

Zhang J N *et al* 2018a Early–middle Holocene ecological change and its influence on human subsistence strategies in the Luoyang Basin, north-central China *Quat. Res.* **89** 446–58

Zhang J N, Xia Z K and Zhang X H 2014 Research on charred plant remains from the Neolithic to the Bronze Age in Luoyang Basin *Chin. Sci. Bull.* **59** 3388–97 (in Chinese with English abstract)

Zhang N, Yang Y, Cheng H, Zhao J, Yang X, Liang S, Nie X, Zhang Y and Edwards R L 2018b Timing and duration of the East Asian summer monsoon maximum during the Holocene based on stalagmite data from North China *Holocene* **28** 1631–41

Zhao H 2000 The historical process toward the centricity of Central Plains *Cult. Relics* **1** 41–7 (in Chinese with English abstract)

Zhao Y, Yu Z C, Chen F H, Zhang J W and Yang B 2009 Vegetation response to Holocene climate change in monsoon-influenced region of China *Earth Sci. Rev.* **97** 242–56

Zhao Z J 2011 Characteristics of agricultural economy during the formation of ancient Chinese civilization *J. Natl Museum China* **90** 19–31 (in Chinese with English abstract)

Zhao Z J 2014 The process of origin of agriculture in China: archaeological evidence from flotation results *Quat. Sci.* **34** 73–84 (in Chinese with English abstract)

Zhao Z J and Fang Y M 2007 Flotation results and analysis of Wangchenggang site in Dengfeng *Huaxia Archaeol.* **2** 78–89 (in Chinese with English abstract)

Zhao Z J 2007 Research into the agricultural economy in the Central Plains, 2500–1500 BC *Archaeological Science* vol 2 ed Institute of Archaeology, Chinese Academy of Social Sciences (Beijing: Science Press) pp 1–11 (in Chinese)

Zhengzhou Committee of Chorography 1999 *The Chorography of Zhengzhou City* (Zhengzhou: Zhongzhou Classical Press)

Zhong H, Zhao C Q, Wei J Y and Zhao Z J 2016 Analysis of flotation results from Xinzhai site in Xinmi, Henan Province (year 2014) *Agric. Archaeol.* **1** 21–9 (in Chinese)

Zhu Y, Xie Y, Cheng B, Chen F and Zhang J 2003 Pollen transport in the Shiyang River drainage, arid China *Chin. Sci. Bull.* **48** 1499–506