SCIENCE CHINA
Earth Sciences

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June 2024 Vol.67 No.6: 1910–1921
https://doi.org/10.1007/s11430-023-1330-6

Wood use and forest management by Neolithic millet farmers at the Xinglong site, northern China

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Received November 10, 2023; revised April 10, 2024; accepted April 25, 2024; published online May 11, 2024

Abstract The origin and development of agriculture and its relationship with climate change are hotly debated topics among environmental archaeologists. In this study, we analyzed wood charcoal materials from the Neolithic Xinglong site in northern China in order to understand the woody vegetation around the site and how early millet farmers shaped local woodlands. Our results suggest that the area around the Xinglong sites during 8700–7000 yr BP was primarily woodlands, including *Prunus sibirica* shrubs, *Ulmus* and *Acer* forests, and *Populus* stands near waterways. From 8000 to 7000 yr BP, the warm and humid climate probably contributed to the expansion of *Acer*, *Rhamnus*, and *Juniperus*, and may have facilitated the development of early millet agriculture. Among these ancient wood fragments that we studied, the high percent of *Prunus* charcoal appears to indicate an abundance of fruit trees, which might have constituted the main component of local vegetation. Meanwhile, the wood taxa illustrate the existence of a variety of ecological habitats, and it is logical to assume that people made full use of the locally available wood resources. Notably, *Populus* and *Ulmus* were the dominant sources of fuel. The results of tree-ring curvature analyses indicate that people mainly collected trunks or large branches of *Ulmus*, *Populus*, *Acer*, and *Juniperus* timbers. We interpret the increasing use of *Prunus* twigs and the declining percentage of *Prunus* charcoal in the period between 8000–7000 yr BP as indicating that people started to protect and manage wild fruit trees. They may have started pruning to acquire more food resources as part of the cultural responses and adaptation strategies employed by these early millet cultivators.

Keywords Xinglong site, Wood charcoal, Wood use, Woodland management

Citation: Shen H, Qiu Z, Zhao K, Zhou X, Li X. 2024. Wood use and forest management by Neolithic millet farmers at the Xinglong site, northern China. Science China Earth Sciences, 67(6): 1910–1921, https://doi.org/10.1007/s11430-023-1330-6

1. Introduction

Human activity and its impact on global ecosystems, especially relating to the beginnings of agriculture, have been prominent scientific topics among paleoclimatologists and environmental archaeologists for more than a century (deMenocal, 2001; Weiss and Bradley, 2001; Ruddiman, 2003, 2008; Zong et al., 2007; Dong et al., 2020, 2022). During the shift from the last deglaciation to the early and middle Holocene, a few restricted populations of humans, notably in southwest Asia and East Asia, gradually transferred from hunting-gathering economies to cereal cultivation and animal husbandry (Bellwood, 2005; Crawford, 2006). By the transition to the late Holocene agricultural production became the main subsistence economy for humans around the world. With the development of agriculture came sharp demographic expansions further driving large-scale reshaping of terrestrial ecosystems (Zong et al., 2007; Yerkes et al., 2012; Innes et al., 2013; Cheng et al., 2018; Zheng et al., 2021).

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Increasingly studies are showing that slash-and-burn agriculture has exerted considerable impact on global vegetation for millennia, like in some regions resulting the disappearance of forests (Zong et al., 2007; Atahan et al., 2008; Kaplan et al., 2009; Neumann et al., 2012). On the other hand, people have developed a series of cultural strategies to adapt to their surroundings, such as the conscious management of woodlands to encourage the expansion of fruit- and nut-bearing trees, which was widely recognized across East and southwest Asia (Fall et al., 2002; Janick, 2005; Miller and Gross, 2011; Asouti and Kabukcu, 2014). Therefore, reconstructing the patterns of interaction between agricultural communities and their regional environment will help answer questions related to ecological impacts and adaptations in the past, and assessing the adaptive strategies of human societies in the context of future climate change.

The Yellow River and West Liaohe River basins of northern China are located in the center of the origin for broomcorn (*Panicum miliaceum*) and foxtail millet (*Setaria italica*) agriculture. Currently, approximately 30 archaeological sites have been discovered to possess archaeobotanical remains of early millets, including Donghulin (Yang et al., 2012; Zhao et al., 2020), Nanzhuangtou (Yang et al., 2012), Xinglonggou Locality 1 (Zhao, 2004), Cishan (Lu et al., 2009), Shangzhai (Yang et al., 2009), Yuezhuang (Crawford et al., 2013, 2006), Dadiwan (Liu et al., 2004; Li, 2018), and Baijia (Yang et al., 2016). Recently in the Bashang region of Hebei province, millet seeds were recovered from the Xinglong and Sitai sites, which displayed morphological features with a relatively small size, a long shape, and a slightly flat back (Zhao et al., 2023; Qiu et al., 2023). These features are characteristics of an early stage of domestication, suggesting that the practice of millet cultivation occurred widely across northern China. At present, there are only direct dates on millets from six of these sites, and the earliest AMS^{14}C date on broomcorn millet comes from Dadiwan, falling in the period of 7872–7663 yr BP (Li, 2018). The other directly dated remains have proven to be roughly contemporaneous, notably from Xinglong, Yuezhuang, Zhuzhai, Baijia (Zhao, 2004; Yang et al., 2016; Qiu et al., 2023; Bestel et al., 2018). These data point to an early onset of cultivation behaviors around 8000–7500 yr BP, with a rapid spread of millet agriculture across northern China.

Currently, research into the effects of early millet farming on regional environment has been based on sedimentary micro-charcoal and pollen and sedimentary micro-charcoal analysis. Studies of micro-charcoal records from the Guanzhong Basin (Li et al., 2009), Longdong Loess Plateau (Tan et al.,2008), Horqin dunefield (Mu et al., 2016), and Daihai Lake (Wang et al., 2013) all show a rapid increase in charcoal content starting around 8000 yr BP, implying that early agricultural activities such as forest clearing to increase farmland might have led to considerably frequent fire occurrences. Pollen records from Jijitan in the Nihewan Basin indicate that a phase of deforestation occurred during the period of 6600–6000 yr BP, which possibly reflects the influence of agricultural activities (Lu et al., 2018). By contrast, the pollen record from Gonghai Lake in Shanxi only shows possible evidence for anthropogenic activities after 1600 yr BP (Xu et al., 2017). Meanwhile, there have been few studies on archaeological wood charcoal from these early millet-cultivating sites. As a direct index of human collection and usage of woody plants (Li et al., 2011; Asouti and Kabukcu, 2014; Asouti et al., 2015; Knapp et al., 2015; Shen et al., 2018), wood charcoal remains also record information on the composition of local woodlands (Asouti and Austin, 2005; Sun et al., 2013; Shen et al., 2018, 2021; Wang, 2022). Thus, the analysis of wood charcoal burded at these sites can provide important clues to understanding the environmental background and mechanism of the early millet agricultural system.

The Xinglong site was recently discovered in the Bashang region of northern China, and is one of the most important sites relating to the early stage of millet agriculture (Qiu et al., 2023). The flotation results from this site revealed an abundance of wood charcoal fragments, fruit stones, weeds, and millet seeds. A direct radiocarbon date based on broomcorn millet was traced back to 7682–7570 yr BP (Qiu et al., 2023). Except for plant remains, a large number of houses, hearths, and cemeteries, spanning a period from 8700–5200 yr BP, were also discovered during the 2018–2019 excavations (National Museum of China et al., 2021). In this study, we conducted a systematic analysis of wood charcoal fragments from the Xinglong sites. We identified wood taxon and measured tree-ring curvature. In doing so, we sought to reconstruct local woodland vegetation communities and explore how early agricultural groups adapted to and impacted on their surrounding environments.

2. Xinglong site and its environment

The Xinglong site (42°5′22″N, 114°36′49″E, 1410 masl), located to the southeast of the modern Xinglong village in Kangbao County of Hebe Province, was discovered and a test pit was excavated during an archaeological survey of the Kangbao and Zhangbei counties by a joint team from National Museum of China and Hebei Provincial Institute of Cultural Relics and Archaeology in 2016 and 2017 (National Museum of China et al., 2021, Figure 1a).The excavation area during 2018–2019 reached around 1,025 m^2, revealing a a variety of archaeological remains. The occupation covered three phases, including the transition from the Paleolithic to the Neolithic, the Neolithic proper, and the Liao and Jin dynasties. The transition period (ca. 13500–10000 yr BP) is featured by only a few stone tools, including microblades,

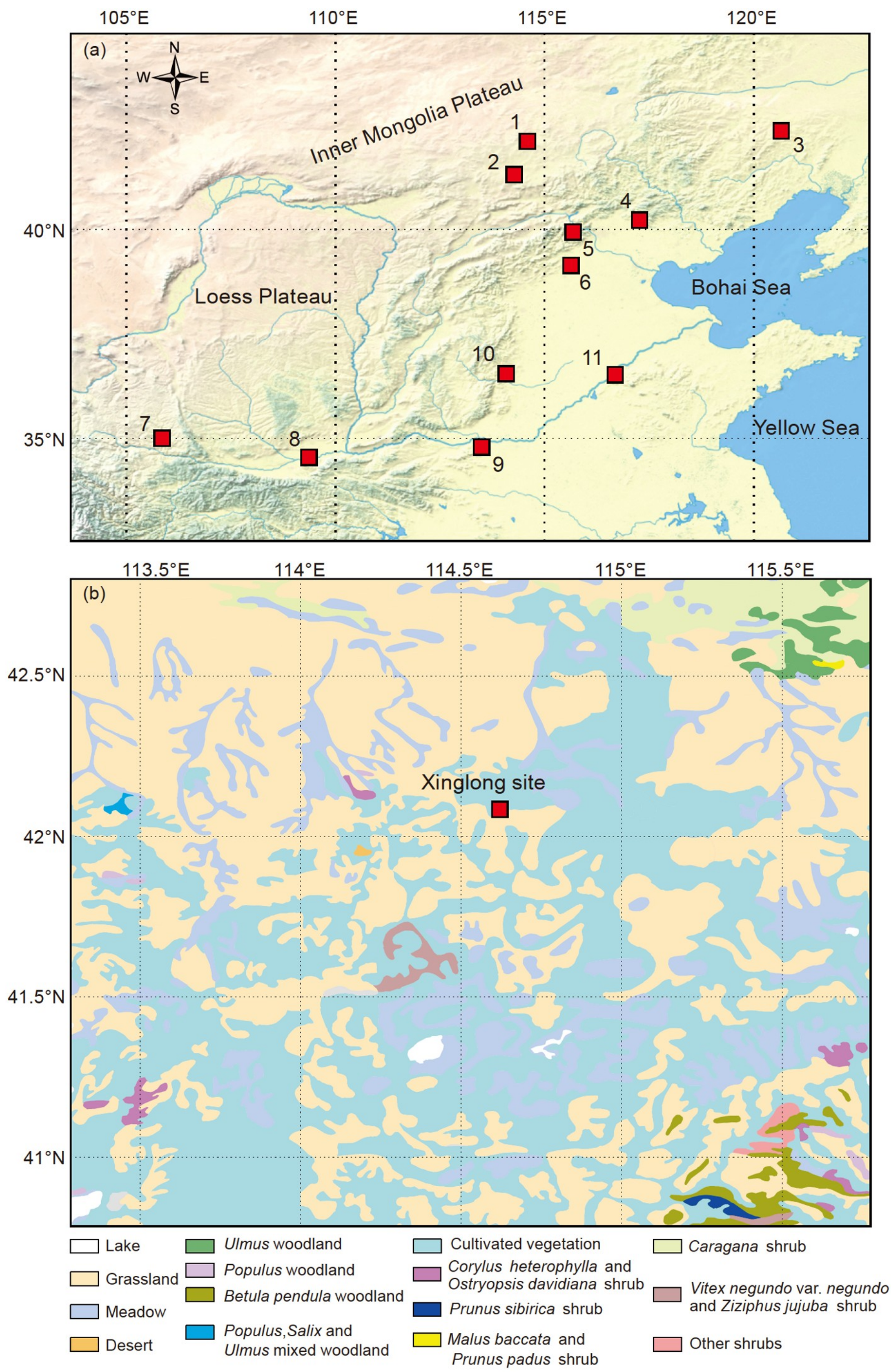

Figure 1 Location of Xinglong and the other sites mentioned in this study with the surrounding vegetation. (a) 1, Xinglong; 2, Sitai; 3, Xinglonggou; 4, Shaizhai; 5, Donghulin; 6, Nanzhuangtou; 7, Dadiwan; 8, Baijia; 9, Zhuzhai; 10, Cishan; 11, Yuezhuang. The base map is from https://www.naturalearthdata.com/. (b) The vegetation type is referenced from the Editorial Committee of Vegetation Map of China, Chinese Academy of Sciences (2001).

microblade cores, and blades (National Museum of China et al., 2021). The Neolithic remains are dominated by houses and cemeteries, comprising five phases, which were constructed through a radiocarbon dating campaign, as well as a close study of the material culture. Phase I (8700–8100 yr BP) share similarities in remains to those found at the Yumin site in Inner Mongolia. Phase II (8000–7600 yr BP) and Phase III (7450–7000 yr BP) show a close relationship with the Xinglongwa Culture. Phase IV (7000–6000 yr BP) belongs to the Hougang I Culture and Phase V (5800–5200 yr BP) is mainly composed of stone hearths, microflakes, and circular pit graves (National Museum of China et al., 2021; Qiu et al., 2023) (Table 1). The cultural deposits of the Liao and Jin dynasties are super-

Table 1 AMS ^{14}C dating results from Xinglong [a)]

Phase	Context	Lab. No.	Material	AMS ^{14}C date (yr BP)	Calibrated age (2δ, yr BP)
Phase I	F16①	Beta-647835	*Prunus* charcoal	7700±30	8546–8411 (95.4%)
	F8①	BA190807	*Prunus sibirica* stone	7410±35	8343–8170 (93.6%) 8073–8055 (1.8%)
Phase II	F17-HDM1	BA190801	*Prunus sibirica* stone	6975±30	7924–7898 (9.9%) 7866–7704 (85.6%)
	F17③C	Beta-647834	*Prunus* charcoal	7000±30	7877–7742 (72.0%) 7932–7890 (23.4%)
	F17③B	BA190800	*Prunus sibirica* stone	6790±30	7676–7582 (95.4%)
	F20-K2	BA190802	*Prunus sibirica* stone	7075±35	7970–7835 (94.2%) 7806–7799 (1.3%)
	F15HDM1	BA190797	Broomcorn millet	6770±45	7682–7570 (93.8%) 7529–7520 (1.7%)
Phase III	F3-H2	BA190798	*Panicum miliaceum*	6340±30	7324–7238 (62.6%) 7220–7166 (32.9%)
	F6-Z1	BA190799	*Panicum miliaceum*	6165±30	7161–6962 (95.4%)

a) dates of F16① and F17③C are from this study and the other dates are from Qiu et al. (2023), calibrated by IntCal20 using OxCal version 4.4

imposed on the top of the Neolithic remains.

This site is situated on the southern margin of the Mongolia Plateau and has a temperate continental monsoon climate, with high summer temperatures alongside precipitation. The mean annual temperature is about 2.0 °C. The highest temperature is around 18.8 °C, usually occurring in July, and the temperature in January is the lowest, at about –17.5 °C. The mean annual precipitation is about 348.5 mm, changing from 170.1 mm to 570.1 mm (Liu et al., 2022). The current vegetation is dominated by temperate grasslands, and the main plants are represented by *Stipa orientalis*, *S. grandis*, *S. tianschanica*, *Artemisia frigida*, *A. desertorum*, and *Bothriochloa ischaemum* (Figure 1b). There is also a large area of meadow vegetation, which mainly consists of *Sanguisorba officinalis*, *Artemisia Tanacetifolia*, *Carex* spp, *Calamagrostis epigeios*, and *Suaeda glauca*. The shrubs include *Caragana liouana*, *C. microphylla*, and *Spiraea salicifolia*. Shrubs of *Prunus sibirica*, *Corylus heterophylla*, *Ostryopsis davidiana*, and *Ziziphus jujuba* only cover a limited area. Woodlands are usually dominated by *Ulmus macrocarpa*, *U. pumila*, *Populus tremula*, *P. nigra*, and *Betula pendula* subsp. *mandshurica* (Editorial Committee of Vegetation Map of China, Chinese Academy of Sciences, 2001).

Seed remains recovered from flotation at Xinglong show that people used a variety of plant resources, including cereals (*Panicum miliaceum*, *Setaria italica*, *Hordeum vulgare*, *Triticum aestivum*), weeds (*Setaria viridis*, *Polygonum aviculare*) and other wild edible plants (mainly Chenopodiaceae, *Artemisia*, and *Prunus sibirica*) (Qiu et al., 2023). The number of broomcorn millet grains recovered from Neolithic sediments was considerably higher than that of foxtail millets. Wheat, barley, and buckwheat start to occur in small quantities during the Liao and Jin dynasties. From Neolithic Phase I to the Liao and Jin dynasties, the percentage of cereals increased quickly, whereas other plants gradually decreased, suggesting that, proportionally, cereals became more significant in the diet. At the same time, the absolute number of other wild edible plants per unit volume of flotation soil (density ratios) shows an increasing trend, implying people continued to widely use wild plants. Other than plant remains, a larger number of animal bones were identified, including fish and mammals, such as *Lepus tolai*, *Bos primigenius*, and *Capreolus* (Qiu et al., 2023). Most animals are wild, indicating that the subsistence economy of Xinglong people was largely based on hunting and gathering, accompanied by limited agricultural production.

3. Materials and methods

Plant remains were recovered from soil samples using a simple bucket flotation method, with a sieve aperture of 80 mesh (0.18 mm). The soil samples are collected from 135 contexts, including houses, hearths, pits, and deposit layers (Table 2). To explore the strategies of fuelwood collection by Xinglong people, soil samples from hearths were intensively collected, including slate, shallow-pit, and stone standing hearths (Figure 2). A total of 2,908.5 L of soil was processed, covering Phases I–III, Phase V, and the Liao and Jin dynasties. Considering that there were few cultural remains found in Phase IV and its cultural context is not clear, we did not conduct further analysis on the samples from this phase. The plant remains recovered from flotation were dried and

Table 2 The contexts of flotation samples in Xinglong during 2018–2019 (referenced from Qiu et al., 2023)

Phase	Context							Total
	House deposit	Hearth	House floor	Ash pit deposit	Ash heap	Trench deposit	Deposit layer	
Liao and Jin dynasties				2		1	3	6
Phase V (5800–5200 yr BP)	3	1			17		3	24
Phase III (7450–7000 yr BP)	25	6	16	8	2		3	60
Phase II (8000–7600 yr BP)	11	8	10	2				31
Phase I (8700–8100 yr BP)	5	2	2		1	2	2	14
Total	44	17	28	12	20	3	11	135

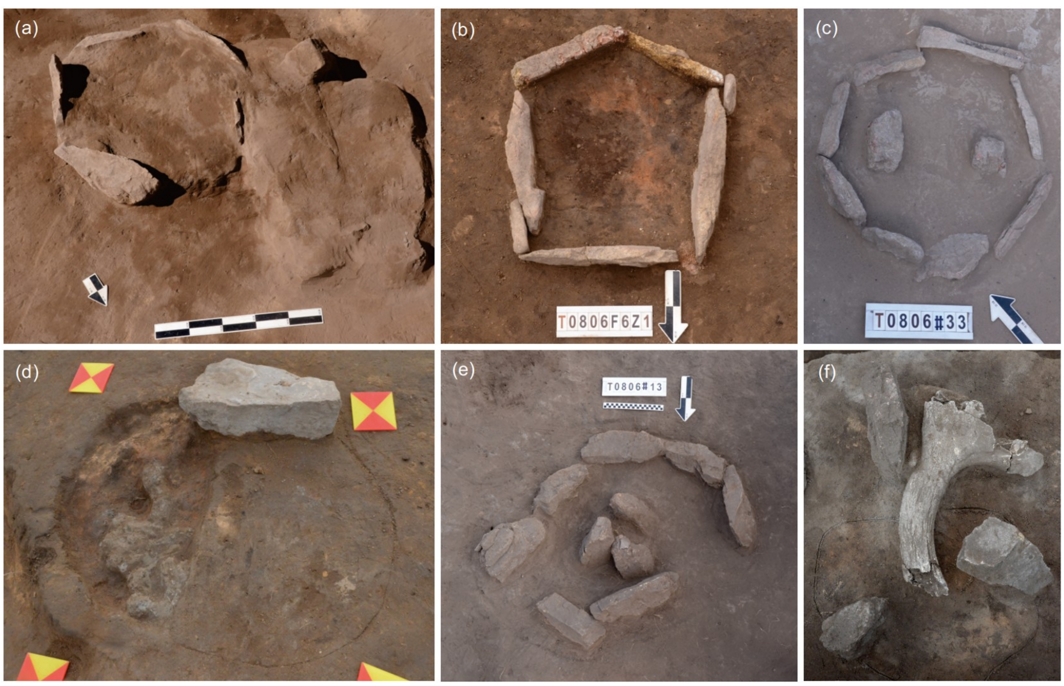

Figure 2 Different types of hearths at Xinglong. (a)–(c) Slate hearth; (d) shallow-pit hearth; (e)–(f) stone standing hearth.

then classified into wood charcoal and seeds under microscopy for the following identification.

Wood charcoal fragments were identified in the following steps: (1) classify wood charcoal into different types under microscopy according to the anatomical features from transverse, tangential, and radial sections; (2) apply gold coating to three sections of each wood charcoal type; (3) using a scanning electron microscope (ZEISS EVO25) to photograph the wood anatomy under different magnifications (50–1000 X); and (4) identifying each wood charcoal type with reference to modern wood anatomy (Cheng et al., 1992; Jiang et al., 2010).

We also conducted systemic measurements of the tree-ring curvature for each wood charcoal fragment. Due to seasonal differences in climatic conditions, the appearance of tree rings is common in temperate regions. A complete tree ring consists of earlywood (quick growth period with large pores or tracheids) and latewood (slow growth period with small pores or tracheids). In the transverse section of the wood stem, within the unit area, the closer to the heartwood position, the greater the curvature of the annual rings; conversely, the closer to the sapwood, the smaller the curvature of the growth rings. Therefore, we can use the pattern of tree-ring curvature to identify which part of the plant the ancient people collected. Generally, a high percent of strongly curved rings indicates that people largely used twigs or small branches as fuel, while the abundance of weakly curved rings suggests that trunks or large branches were widely collected (Marguerie and Hunot, 2007). Referring to the method proposed by Marguerie and Hunot (2007), a transparent test card was placed under constant magnification when the measurements were taken, and the annual rings were divided into three types according to their curvature: weakly curved, moderately curved, and strongly curved (Figure 3).

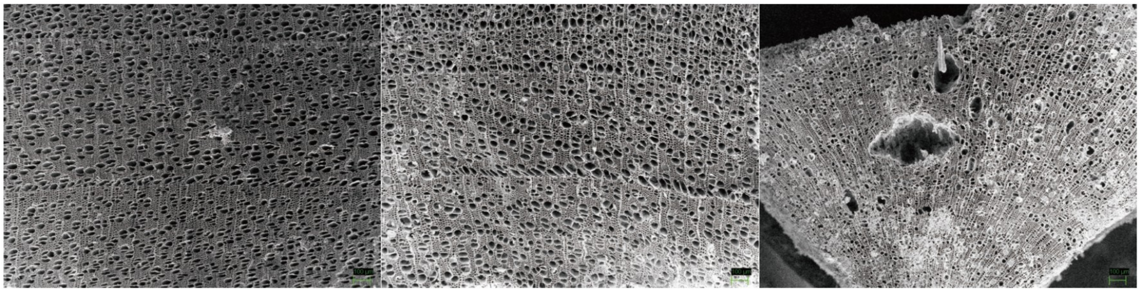

Figure 3 Three types of tree-ring curvature.

4. Results

A total of 3,367 wood charcoal fragments were analyzed in this study. Since the number of charcoal fragments from either Phase V and the Liao and Jin dynasties is too small to meet the statistical requirements, so we mainly discuss the results from Phase I–III. According to our identifications, the wood taxa primarily include *Prunus*, *Populus*, *Ulmus*, *Acer*, *Rhamnus*, *Tamarix*, and the coniferous wood *Juniperus* (Figure 4) (Appendix Table 1, https://link.springer.com). *Ulmus* was the most abundant wood fragment type, and the average percent reached more than 30% of the total charcoal fragments, followed by *Populus*, with an average of 28.66% (Figure 5a). The fruit wood charcoal, *Prunus*, occurred with an average of 16.47%, and *Juniperus* was relatively limited, only covering 12.63% of the total charcoal. The percentages of other wood taxa, such as *Acer* and *Rhamnus*, comprise less than 5%, respectively.

A total of 72 wood charcoal fragments were analyzed from sediments dated to Phase I (8700–8100 yr BP), and only *Prunus*, *Populus*, and *Ulmus* were found. *Ulmus* and *Prunus* were abundant, with an average of 62.5% and 33.33%, respectively. *Populus* occurred at a low abundance, with only 4.17% (Figure 5a). The tree-ring curvature shows that *Prunus* charcoal was weakly or moderately curved, representing 17.14% and 15.71% of the total charcoal fragments, respectively (Figure 5b). *Ulmus* charcoal is also mainly weakly curved, covering 50%, followed by moderately curved rings, and only few charcoal fragments had strongly curved rings. The percentage of weakly curved *Populus* charcoal was close to that of moderately curved, about 2%, and no strongly curved ring specimens were noted.

In Phase II (8000–7600 yr BP), *Ulmus*, *Prunus*, *Acer*, *Rhamnus*, and *Juniperus* were identified from 2,471 charcoal fragments. Compared with Phase I, the content of *Ulmus* decreased significantly, from 62.5% to 25.17%, and *Prunus* also declined from 33.33% to 16.51% (Figure 5a). However, *Populus* charcoal increased sharply from 4.17% to 32.01%, and became the most abundant wood taxa during this phase. Meanwhile, roughly 13% of the wood was from *Juniperus* in Phase II. *Acer*, *Rhamnus*, and *Tamarix* also begin to emerge at this stage, but all of them with abundance of less than 5%. Tree-ring curvature shows that weakly or moderately curved *Prunus* charcoal decreased rapidly to less than 5%, while the strongly curved charcoal starts to appear and reaches 8% (Figure 5b). The percentage of the weakly and moderately curved *Ulmus* fragments also shows a quick decline, with no evident change in the content of strongly curved charcoal. Notably, the proportion of weakly curved *Populus* charcoal fragments increased sharply, from 2.86% to 25.03%. The number of *Acer* and *Juniperus* charcoal fragments is relatively small, mainly with weakly curved rings.

In Phase III (7450–7000 yr BP), we identified 814 charcoal fragments, and the wood taxa were similar to those of Phase II, except for the absence of *Tamarix* (Figure 5a). The content of *Ulmus* charcoal increased rapidly from 25.17% in Phase II to 49.39% in Phase III. *Populus* declined slightly, but its abundance still remains above 20%. The percentage of *Prunus* charcoal continued to decrease, from 33.33% in Phase I to 14.86% in this phase. *Juniperus* remained at about 13%, and *Acer* and *Rhamnus* charcoal fragments were still less than 5% each. For the tree-ring curvature, weakly curved *Ulmus* charcoal increased considerably, from 17.41% in Phase II to 38.63% in this phase, and the moderately and strongly curved charcoal were 8.67% and 3.79%, respectively (Figure 5b). The proportions of different tree-ring curvatures in *Prunus* charcoal were similar, at around 5% for each of the three types. *Populus*, *Acer*, and *Juniperus* during this phase were dominated by weakly curved growth rings.

In addition, the charcoal assemblage from hearths shows marked spatiotemporal differences (Figure 6). Only *Ulmus* (66.67%) and *Prunus* (33.33%) were identified in the F16 shallow-pit hearth of Phase I. In the hearth remains from Phase II, the difference between the F9 shallow-pit hearth and the F19 slate hearth was significant. In the hearth of F9, a large number of small twigs were found, comprising more than 80% of the total charcoal fragments, followed by *Populus* (7.54%). *Ulmus*, *Prunus*, and *Rhamnus* were at about 4% each. The wood taxa in the F19 slate hearth were rich in diversity, including all identifiable plant types in this study.

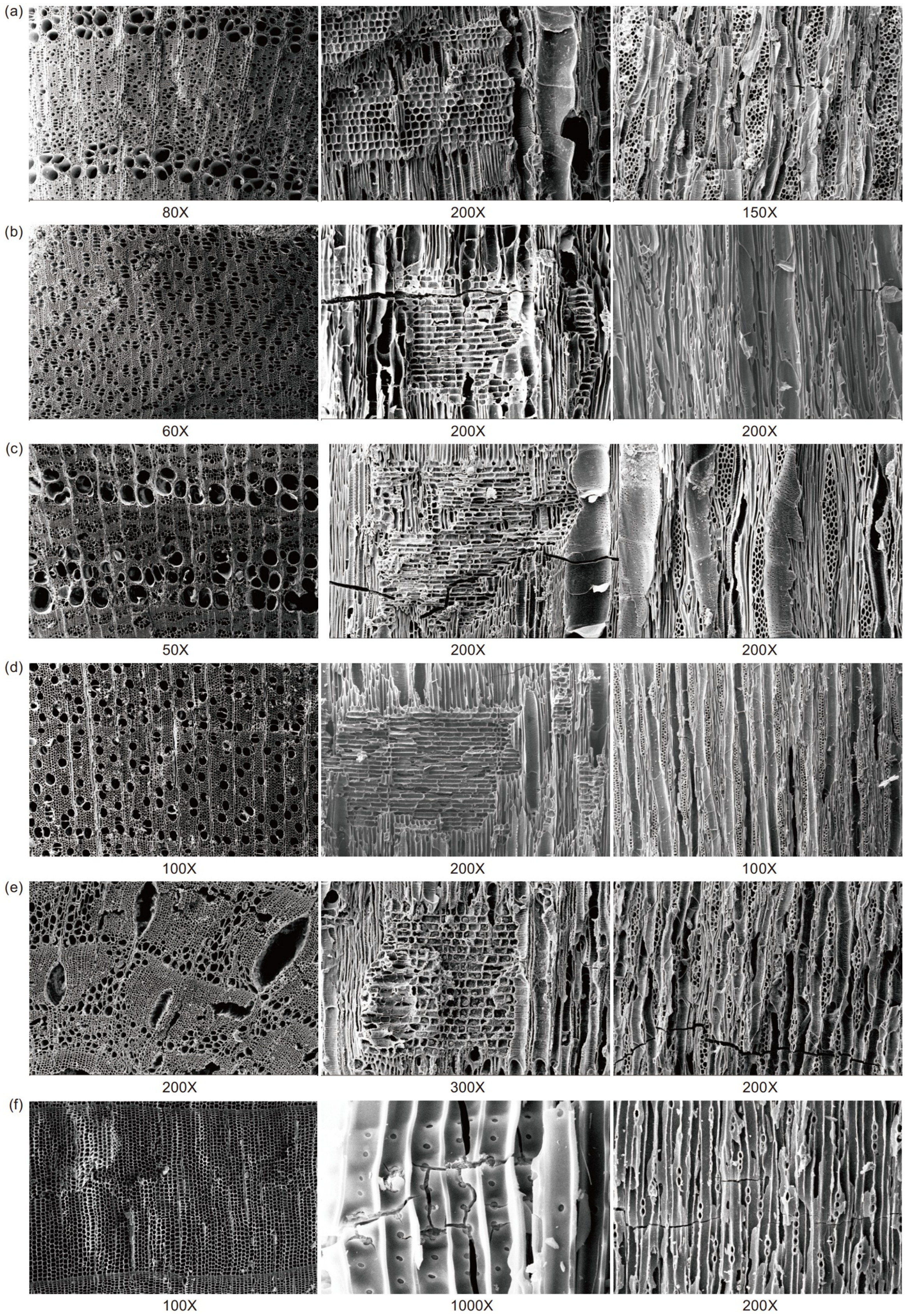

Figure 4 Anatomical features of the main wood taxa at Xinglong. (a) *Prunus*; (b) *Populus*; (c) *Ulmus*; (d) *Acer*; (e) *Rhamnus*; (f) *Juniperus*. The left, middle, and right images represent transverse, tangential, and radial sections, respectively.

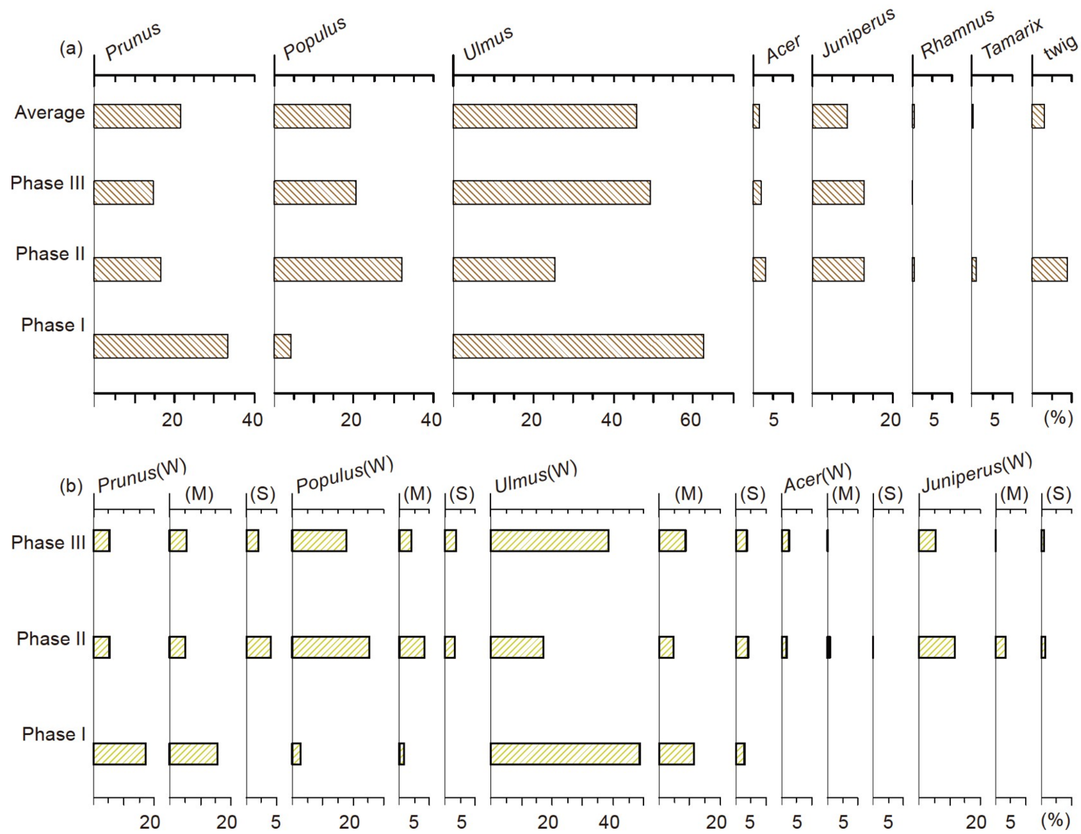

Figure 5 Changes in the charcoal assemblage and tree-ring curvature in Phase I (8700–8000 yr BP), Phase II (8000–7600 yr BP), and Phase III (7450–7000 yr BP) (a) percentages of the woody plants; (b) tree-ring curvature of main woods; (W), (M), and (S) represent weakly, moderately, and strongly curved rings.

Among the wood taxa, *Juniperus* was the most common plant, accounting for 38.1%, followed by *Ulmus* (28.57%). Other plants, such as *Populus* and *Prunus*, were found in small quantities, both with less than 10%. During Phase III, wood taxa found in the F3 shallow-pit hearth and the F4 slate hearth were the same, whereas the percentage of charcoal types varied considerably. *Ulmus* dominated the shallow-pit hearth in F3, with an abundance of 70%, followed by *Populus* (16.78%). In the F4 slate hearth, *Ulmus*, *Populus*, and *Prunus* were abundant, both at greater than 30%. A small number of *Juniperus* and *Acer* wood fragments were also found in this hearth, while both were recovered at less than 5%.

5. Discussion

5.1 Woodland types in the Bashang region

Paleoclimatic studies suggest that, during the early stage of millet agriculture in northern China, the climate was warmer and wetter than present time, with deciduous broadleaved forest and coniferous and broadleaved mixed forest dominating the landscape (Xiao et al., 2004; Xu et al., 2010, 2017; Chen et al., 2015; Xie et al., 2019; Zhao et al., 2023; Qi et al., 2018). These studies also show that early Holocene grasslands gradually transformed into mixed forest grasslands. For example, pollen results from Daihai demonstrate that vegetation was dominated by coniferous and broadleaved mixed forests during the mid-Holocene (Li et al., 2004; Xiao et al., 2004). Precipitation was 100–200 mm per annum greater than it is today (Xu et al., 2010), and the lake level was at least 40 m above the current level (Hou et al., 2023). Pollen records from Gonghai suggest that the concentrations of deciduous broadleaved trees reached its highest during 7800–5300 yr BP (Chen et al., 2015). Coniferous and broadleaved mixed forests prevailed (Xu et al., 2017), and the lake level was high (Cao et al., 2021). Climatic conditions revealed by pollen data from Anguli-Nuur were optimum around 8000 yr BP, and the sparse woody grassland was replaced by a mixed forest grassland (Qi et al., 2018). Whereas, there is still limited information about the microenvironmental dynamics of millet agricultural settlements, especially the compositions of local woodlands.

We have identified a range of woody plants in sediments from the Xinglong site, including *Prunus*, *Populus*, *Ulmus*, *Acer*, *Juniperus*, *Rhamnus*, and *Tamarix*. Nowadays, *Populus nigra* stands are still distributed in a small area around the Xinglong site, but the other plants are no longer common in

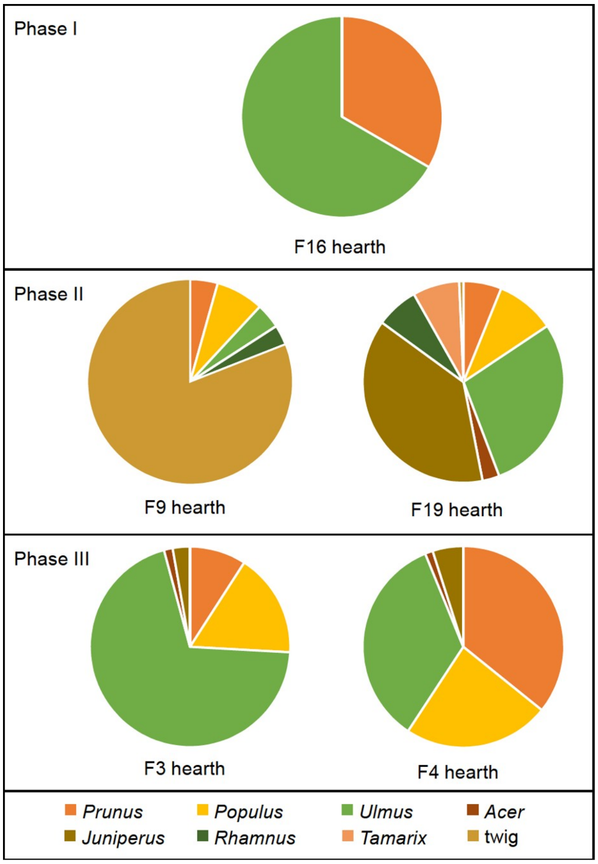

Figure 6 Wood charcoal assemblage in different hearths during Phase I (8700–8000 yr BP), Phase II (8000–7600 yr BP), and Phase III (7450–7000 yr BP).

this area. The dominant vegetation in this region is mainly composed of temperate grasslands. *Prunus sibirica* shrubs are currently restricted to the Yanshan Mountains, southeast of the site (Editorial Committee of Flora of Hebei, 1986, 1989; Editorial Committee of Vegetation Map of China, Chinese Academy of Sciences, 2001). *Ulmus* and *Tamarix* have a wide geographical distribution, and *Ulmus macrocarpa* can currently be found on the eastern edge of Hunshandake Sandy Land, northwest of the site. *Acer* mainly grows in the southern foothills of the Yanshan Mountains. There are two species of *Juniperus* distributed in Hebei Province, namely *J. chinensis* and *J. rigida*, which are found in the Xiaowutai Mountains. *Rhamnus* are currently concentrated in the Xiaowutai and Yanshan mountains.

Based on modern habitat information of different woods, the charcoal analysis of the Xinglong site shows that this area was once distributed with rich woody vegetation, including *Populous*, *Ulmus*, *Juniperus*, and *Acer* woodlands, as well as *Prunus sibirica*, *Rhamnus*, and *Tamarix* shrubs. During 8000–7000 yr BP, the woody plants were much more diverse, with the appearance of *Acer*, *Rhamnus*, *Tamarix*, and *Juniperus*, which corresponds to paleoclimatic records, illustrating that this period in the Bashang region was warmer and more humid than it is today. These climatic conditions might have contributed to the wide distribution of woody plants and provide optimal conditions for the rapid development and dispersal of early millet agriculture in northern China (Dong et al., 2016; Zhao et al., 2023).

Among the woods identified in Xinglong, *Prunus* and *Ulmus* plants are edible, and the *Prunus* genus contains many fruits of economic importance, such as peaches, apricots, plums, and cherries. The young fruits and leaves of *Ulmus* can also be used as food. In Phase I, *Prunus* and *Ulmus* charcoal appeared in great abundance, and their percentages reached more than 95% of the total charcoal. During Phase II and III, the percentages of *Ulmus* and *Prunus* charcoal declined, while they still remained high around 42%–64%. Combined with the large number of apricot fruit stones found in Xinglong, we could reasonably conclude that there were large areas of apricot woodlands around the Xinglong site, and these fruits provided an important food source for the early millet farmers. At other early millet-cultivation sites in northern China fruit remains are also abundant, including *Vitis* sp., *Juglans* sp., and *Quercus* sp. found in Donghulin (Liu et al., 2010; Zhao et al., 2020), and *Quercus* sp., *Juglans mandshurica*, *Zizyphus jujuba*, and *Vitis* sp. in Zhuzhai (Bestel et al., 2018; Wang et al., 2018). The starch grains from grinding stones at Shangzhai are dominated by *Quercus* seeds, followed by starch from *Setaria italica* (Yang et al., 2009). The edible plants found in Xinglong are mainly composed by *Prunus sibirica* (Qiu et al., 2023). The abundance of fruit remains seems to suggest that during the early stage of millet agriculture, people still relied heavily on gathering and hunting, and fruiting trees composed an important part of local vegetation.

5.2 Impact on and adaptation to environment by early millet cultivators

The collection and use of wood resources comprised a significant part of the daily practices of ancient people. At the Xinglong site, *Ulmus*, *Populus*, and *Prunus* fragments are relatively abundant, with more than 15% on average for each of the three types. The abundance of *Juniperus* is about 13%, while *Acer*, *Rhamnus*, and *Tamarix* are less prominent, with each representing less than 3% of the assemblage. The habitats of *Ulmus*, *Prunus*, and *Rhamnus* are primarily distributed on sunny slopes; *Populus* and *Tamarix* mainly grow along rivers and are typical riparian plants. *Juniperus* is concentrated in mountainous areas, and *Acer* is primarily found on shady slopes or mountain valleys within an altitude of 400–1500 masl (Editorial Committee of Flora of Hebei, 1986, 1989). Drawing on the charcoal assemblages from Xinglong, we argue that people made full use of the locally available wood resources, including riverbanks, sunny slopes, and mountain valleys.

In addition, wood charcoal assemblages changed over time. During Phase I, people mainly collected *Ulmus* and *Prunus* woods from sunny slopes. The appearance of *Acer*, *Juniperus*, *Rhamnus*, and *Tamarix* in Phase II and III suggests that the wood collection catchment of the Xinglong groups expanded considerably. Meanwhile, *Populus* increased from less than 5% in Phase I to ca. 30% in Phase II, indicating that more plants from riparian woodlands were harvested. Pollen results from the Sitai section and the Anguli-Nuur core, near the Xinglong site, reveal that trees significantly increased and forested grasslands appeared during 8000–7000 yr BP, which is consistent with the abundance of woody plants in sediment at Xinglong (Qi et al., 2018; Zhao et al., 2023). These forest expansions were likely the result of a climate that was warmer and more humid than the present. The climatic conditions might also have contributed to the expansion of riparian woodlands and the increased collection of widely distributed *Populus* plant. On the contrary, *Prunus* charcoal continually declined, from 33% in Phase I to 17% in Phase II. When it came to Phase III, *Prunus* accounted for 15% of the total charcoal fragments. However, the other wood types show fluctuating changes, with no sustained increase or decrease. The palynological data from the Sitai section and the Anguli-Nuur core also suggests there was no clear signal of human activities on regional vegetation (Qi et al.,2018; Zhao et al., 2023), implying a limited effect of early millet agriculture on the environment.

Hearth structure also shows obvious changes over time, whereas shallow-pit hearths prevailed in Phase I, while Phases II and III were dominated by slate hearths (National Museum of China et al., 2021). Qiu et al. (2023) suggest that seed types are correlated to the types of hearths, like the slate hearths of Phase III mainly contained Chenopodiaceae, *Artemisia*, and millets. While in this study, we show that there is no clear relation between the types of hearth structure and wood charcoal taxa, but with obvious differences in the wood charcoal assemblages from individual hearth. For example, the F16 shallow-pit hearth in Phase I was dominated by *Ulmus* and *Prunus*, while in the F9 shallow-pit hearth in Phase II, *Populus* was the most abundant taxon, followed by *Prunus* and *Ulmus*. In the F3 shallow-pit hearth from Phase III, *Ulmus* was largely used, with a small number of *Populus*, *Prunus*, *Juniperus*, and *Acer*. Among the slate hearths, wood charcoal found in the F19 hearth of Phase II was mainly composed of *Ulmus*, while the F14 hearth of Phase III shows an abundance of *Prunus*. The significant differences in the charcoal assemblages from hearths probably indicate that there was no conscious selection or preference for the fuelwoods.

According to the analysis of tree-ring curvature, *Ulmus*, *Populus*, *Acer*, and *Juniperus* are all dominated by weakly curved rings, followed by moderately curved rings, implying that people mainly collected trunks or large branches of these plants. Notably, there are obvious changes in the percentage of the *Prunus* charcoal. In Phase I, *Prunus* charcoal was dominant and the tree rings were mainly weakly curved, with a small number of moderately curved rings and no strongly curved rings, showing that people largely collected *Prunus* trunks or large branches at this time. Subsequently, *Prunus* charcoal continued to decrease, and the proportion of strongly curved rings increased sharply, suggesting that the utilization of *Prunus* woods was reduced and collection transferred from trunks and large branches to small branches and twigs. Nevertheless, the number of *Prunus sibirica* stones at this site increased significantly, from 49 in Phase I to 1,121 in Phase III (Qiu et al., 2023). The percentage of *Prunus sibirica* stones of total seeds also increased over time, with the lowest percent in Phase I and considerably higher percentages in Phases II and III.

Combining the analysis of *Prunus* charcoal and stones, we could infer that Xinglong people might have started to protect and manage *Prunus* shrubs during 8000–7000 yr BP. The practices of reducing the collection of *Prunus* woods and pruning by cutting off small branches and twigs probably promoted the expansion of *Prunus* plants, demonstrating the ability of early millet agricultural groups to shape and adapt to their environment. A series of studies from early agricultural sites in West Asia also suggest the presence of similar woodland management. In the Irano-Anatolian region, the establishment and spread of deciduous *Quercus* is thought to be related to anthropogenic protection, including the controlling of competing arboreal vegetation through selective cutting, coppicing, pollarding, and shredding (Asouti and Kabukcu, 2014). In the southern Levant, the expansion of woodlands was likely the result of intensive management of *Pistacia* woodlands for food, fuel, and pasture (Asouti et al., 2015).

In summary, with the transition to a sedentary agricultural way of life, people gradually increased their exploitation of local animal and plant resources. Likewise, wild fruit trees might have attracted great attention from early farmers. To acquire a more abundant food supply, people would have mastered various methods of woodland management, such as pruning fruit trees and the selective cutting of other non-economic trees to encourage the growth and expansion of fruit woodlands. The management of *Prunus* trees around the Xinglong site appears to have provided an important example of the active interaction between early agricultural groups and their environments. More analysis of wood charcoal remains and evidence from other proxies is still needed to comprehensively understand the cultural responses and adaptive strategies of early agricultural populations.

6. Conclusion

Wood charcoal identification at Xinglong revealed a variety of woody plants, including *Prunus*, *Populus*, *Ulmus*, *Acer*, *Juniperus*, *Rhamnus*, and *Tamarix*, showing the presence of large-scale woodland distributions around the site. The abundance of *Prunus* wood likely correlates with an importance of fleshy fruits at ancient Xinglong. On the basis of the habitats of identified plants, Xinglong people appears to have made full use of available wood resources, including riparian woodlands, shrubs on sunny slopes, and sparse forests in mountain valleys. *Populus* and *Ulmus* were the main sources of fuel. During 8000–7000 yr BP, the warm and humid climate promoted the emergence of *Acer*, *Juniper*, *Tamarix*, and *Rhamnus* plants, and the expansion of riparian *Populus* woodland, contributing to the increased harvesting of poplar woods. The measurement of tree-ring curvature indicates that people mainly collected trunks or large branches of *Ulmus*, *Populus*, *Acer*, and *Juniperus* plants. Meanwhile, Xinglong people probably had mastered the knowledge of how to protect and manage *Prunus* woodlands via pruning and increasing the cutting of nonfruit trees to increase food supply, demonstrating the active response and adaptation of early millet cultivators to their environments.

Acknowledgements *We sincerely thank Dr. Wenhui Liu for his help in wood charcoal collection, and Drs. Peter Jia and Robert Spengler and two reviewers for their valuable suggestions on this manuscript. This work was supported by the National Natural Science Foundation of China (Grant Nos. T2192952, 42002202, 42107470) and the Youth Innovation Promotion Association of Chinese Academy of Sciences (Grant No. 2022071).*

Conflict of interest The authors declare that there are no conflicts of interest.

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(Editorial handling: Huayu LU)