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Seeing the wood for the trees: active human–environmental interactions in arid northwestern China

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Abstract. Due largely to demographic growth, agricultural populations during the Holocene became increasingly more impactful ecosystem engineers. Multidisciplinary research has revealed a deep history of human–environmental dynamics; however, these pre-modern anthropogenic ecosystem transformations and cultural adaptions are still poorly understood. Here, we synthesis anthracological data to explore the complex array of human–environmental interactions in the regions of the prehistoric Silk Road. Our results suggest that these ancient humans were not passively impacted by environmental change; rather, they culturally adapted to, and in turn altered, arid ecosystems. Underpinned by the establishment of complex agricultural systems on the western Loess Plateau, people may have started to manage chestnut trees, likely through conservation of economically significant species, as early as 4600 BP. Since ca. 3500 BP, with the appearance of high-yielding wheat and barley farming in Xinjiang and the Hexi Corridor, people appear to have been cultivating *Prunus* and *Morus* trees. We also argue that people were transporting preferred coniferous woods over long distances to meet the need for fuel and timber. After 2500 BP, people in our study area were making conscious selections between wood types for craft production and were also clearly cultivating a wide range of long-generation perennials, showing a remarkable traditional knowledge tied into the arid environment. At the same time, the data suggest that there was significant deforestation throughout the chronology of occupation, including a rapid decline of slow-growing spruce forests and riparian woodlands across northwestern China. The wood charcoal dataset is publicly available at https://doi.org/10.5281/zenodo.8158277 (Shen et al., 2023).

1 Introduction

The extent of long-term interaction between humans and their environment, especially relating to the ways early agricultural groups reshaped and adapted to terrestrial ecosystems, has been the subject of ongoing debate (Ruddiman, 2003; Zong et al., 2007; Zalasiewicz et al., 2017; ArchaeoGLOBE Project, 2019; Renn, 2020; Dong et al., 2020a, 2022a; Cowie et al., 2022). While humans have undoubtedly been interacting with their environment since before the Holocene, the magnitude and complexity of this interaction following the adoption of agricultural economies increased immensely. During this process, people shifted their subsistence system from hunting–gathering to cereal cultivation and animal husbandry, and they increasingly gained the ability to alter and adapt their ecological surroundings (Bellwood, 2005; Zeder, 2008; Zohary et al., 2012). Around 5000 BP, agricultural populations across Europe and Asia first came into contact via diffusion of crops, contributing to food globalization in prehistory (Sherratt, 2006; Jones et al., 2011; Dong et al., 2017, 2022b; Boivin et al., 2016; Liu et al., 2019; Zhou et al., 2020). The intermingling of millets, adapted for arid and short-season grasslands in northern China, with cereals, adapted for rainy season growth in arid southwestern Asia, eventually facilitated a greater intensification of farming systems (Spengler, 2019; Miller et al., 2016).

Mounting evidence shows that the development of intensive farming systems was accompanied by a series of ecological and social changes (Bellwood, 2005; Weisdorf, 2005; Atahan et al., 2008; Kaplan et al., 2009; Bocquet-Appel, 2011; D. Q. Fuller et al., 2011; Asouti et al., 2015; Ruddiman, 2013). For instance, the dispersal and expansion of agriculture largely altered the natural geographic distributions of anthropophilic plants (crops and weeds) and directly influenced vegetation communities worldwide (Vigne et al., 2012; D. Fuller et al., 2011; Crowther et al., 2016; Boivin et al., 2017; Spengler et al., 2021). Forest clearing, either to increase the surface area of arable land or to acquire wood for construction or fuel, has caused large-scale deforestation and created a more open landscape (Zong et al., 2007; Atahan et al., 2008; Kaplan et al., 2009; Innes et al., 2013; Zheng et al., 2021). Meanwhile, human-mediated management of local woodlands to encourage the growth of fruit- and nut-bearing trees, shifting land-use strategies from an emphasis on short-term returns of annual cereals to long-term investment with delayed-return crops, has been widely recognized (Fall et al., 2002; Janick, 2005; Miller and Gross, 2011; Miller, 2013; Asouti and Kabukcu, 2014; Asouti et al., 2015). Today, essentially all ecosystems on the planet are anthropogenic constructs, recognized through the increasingly prominent use of the term Anthropocene (Crutzen, 2002; Ruddiman, 2003, 2013; Monastersky, 2015).

Northwestern China, the focus region of this paper. It is of particular interest because it is located at the core of the ancient trade routes that are colloquially referred to as the Silk Road, and farmers in the region were the first to experiment with agricultural crops from both West and East Asia (Wang et al., 2017; Dong et al., 2017, 2018, 2022b; Zhou et al., 2020; Li, 2021). Specifically, evidence from the Dadiwan site has revealed that broomcorn millet cultivation began as early as 7800 BP (Liu et al., 2004; Li, 2018), and the gradual diffusion of broomcorn millet reached farmers in the mountains of Central Asia by 4500 BP (Spengler et al., 2014; Yatoo et al., 2020). The remains of barley (*Hordeum vulgare* var. *nudum*) and wheat (*Triticum aestivum*) found at the Tongtian Cave site have been dated to around 5200 BP, representing the earliest known southwestern Asian cereals found in East Asia (Zhou et al., 2020). In addition to long-distance diffusion of cereals and knowledge of their cultivation, this area also fostered the transcontinental dispersals of sheep, goat, bronze-smelting technology, mudbrick-manufacturing techniques, and a variety of other cultural attributes (Mei and Shell, 1991; Dodson et al., 2009; Li et al., 2011; Yang et al., 2017; Dong et al., 2017; Chen et al., 2018; Ren et al., 2022). Additionally, most of this region is characterized by a hyper-arid desert and fragile oasis ecosystem, which is especially vulnerable to human activity, making it a prime zone for studying the interaction between early agricultural societies and the environment.

Archeologists and geologists working in this region have mainly focused their attention on the relationship between climate change and Neolithic cultural development, as well as anthropogenic impacts on regional ecosystems. These scholars have argued that enhanced precipitation during the late-Yangshao (5500–5000 BP), Majiayao-type (5300–4800 BP), and Qijia (4200–3800 BP) periods played an important role in the expansion of these early farmers (An et al., 2004, 2005, 2006; Hou et al., 2009; Liu et al., 2010; Dong et al., 2012; Dong, 2013, 2016, 2020a). A reduction in the number of archeological sites during the gap between the early and middle Majiayao (4800–4400 BP) and the decline of the Qijia culture are thought to be a response to increasing aridity (Dong et al., 2012; Dong, 2013). Concurrent with these changes, people were actively engaged in reshaping the landscape. For instance, a wood charcoal study from the Hexi Corridor has suggested that prehistoric wood collection led to a rapid reduction in local woodlands and a decline in woody-plant diversity (Shen et al., 2018). However, relatively less attention has been paid to the cultural responses and adaption strategies employed by early farmers in these arid environments. Meanwhile, scientific records are geographically uneven, with regions such as the Hexi Corridor attracting considerable attention, whereas few studies have targeted the vast area of Xinjiang, leading to an incomplete picture of prehistoric human–environmental interactions along the ancient Silk Road.

In this study, we present a comprehensive synthesis of wood charcoal records from northwestern China. Since the first charcoal analysis, beginning in the 1940s (Salysbury and Jane, 1940), the application of reflected-light microscopy has allowed for the rapid identification of charcoal, making it widely used in the (1) reconstruction of firewood collection strategies (Asouti and Austin, 2005; Marguerie and Hunot, 2007; Li et al., 2016; Shen et al., 2018; Kabukcu, 2017; Mas et al., 2021), (2) elucidation of the impacts that woodcutting had on local forests (Li et al., 2011; Asouti et al., 2015; Knapp et al., 2015; Shen et al., 2018), (3) identification of woody communities' compositions (Wang et al., 2014; Asouti et al., 2015; Allué and Zaidner, 2022; Mas et al., 2022), and (4) determination of fruit and/or nut tree management (Miller, 2013; Asouti and Kabukcu, 2014; Shen and Li, 2021). Here, we seek to identify patterns within wood charcoal assemblages recovered from seven archeological sites in Xinjiang, which we contrast with more than 30 other published regional records. We aim to explore multiple perspectives on the complexities of human–environmental interactions within the agricultural background, including the influence of farming and woodcutting on woody-vegetation change, as well as the strategies applied in response to climatic aridification.

2 Study area

2.1 Regional setting

Our study focuses on the provinces of Xinjiang and Gansu, due to the important roles people in this region played in exchange along the ancient Silk Road. This region is characterized by montane ecoclines, including those of the Tianshan, Altai, Altun, and Qilian mountains (Fig. 1). Due to glacial snowmelt, alluvial plains are widely distributed across the lowland basins, and fine-grained nutrients and water brought by the runoff nourish a network of oases, especially within the Hexi Corridor and Tarim Basin (Zheng et al., 2015). Climatically, mean annual precipitation (MAP) is geographically uneven, due to differences in prevailing air masses. For the western Loess Plateau, which is under the control of the Asian monsoons, the MAP usually exceeds 400 mm (https://data.cma.cn/, last access: 19 May 2024). Water vapor carried by the westerlies mainly concentrates in the Ili or Irtysh valleys and Junggar Basin, and the MAP can sometimes reach more than 500 mm (Xiao et al., 2006; Zheng et al., 2015). In the Tarim Basin and the Hexi Corridor, the MAP is usually less than 200 mm (https://data.cma.cn/, last access: 19 May 2024). Temperatures are also spatially and seasonally unevenly distributed; likewise, the mean annual temperature in the Kunlun, Tianshan, and Altai mountains is below 0°C, while that of the Turpan Basin is around 14°C (Chen, 2010).

Due to the arid climate, vegetation types here are characterized by expansive deserts (Xinjiang Integrated Expedition Team and Institute of Botany, 1978). Along the rivers in the lowland basins, riparian woodlands are mainly composed of *Populus*, *Elaeagnus*, *Ulmus*, and *Salix* (Chen, 2010). Within the montane belt, vegetation usually changes across the following banded ecoclines from lowest to highest elevation: grassland (dominated by *Stipa*), coniferous forest (mainly *Picea* and *Larix*), subalpine steppe (mainly *Stipa*), alpine meadows (including *Stipa*, *Carex*, and *Artemisia*), and alpine cushion vegetation (represented by *Androsace*, *Stellaria media*, and *Geranium wilfordii*) (Chen, 2010; Zheng et al., 2015; Xinjiang Integrated Expedition Team and Institute of Botany, 1978). Wild fruit and nut woodlands are distributed throughout the Tianshan Mountains, especially in the Ili Valley, and the main wild fruit trees include *Malus* sp., *Juglans regia*, and *Prunus* spp. (Chen, 2009; Abudureheman et al., 2016).

2.2 Prehistoric cultures and agriculture

As an important cultural bridge connecting East and West Asia, northwestern China has fostered a variety of cultural communities. The early Neolithic cultures included the Dadiwan and Yangshao, mainly distributed in southern Gansu (Institute of Cultural Relics and Archaeology of Gansu, 2006). Later, people with material culture ascribed to the Majiayao expanded quickly into the Hexi Corridor around 4800 BP (Xie, 2002; Dong et al., 2020b). From 4000 to 3000 BP, the main archeological cultures in Gansu consisted of the Xichengyi, Qijia, Siba, and Dongjiatai (Li et al., 2010), and the Shanma and Shajing cultures gradually developed after 3000 BP (Li, 2009; Gansu Provincial Institute of Cultural Relics and Archaeology et al., 2015). In Xinjiang, the prehistoric peoples before 4000 BP were represented by material culture categorized as the Afanasievo and Chemurchek (Shao, 2018). From 4000 to 3500 BP, the Andronovo culture expanded into western Xinjiang, and the Tianshanbeilu and Xiaohe cultures occupied the eastern Tianshan and the Tarim Basin, respectively (Mei and Shell, 1999; Ruan, 2014; Jia et al., 2017; Shao and Zhang, 2019; Xinjiang Institute of Cultural Relics and Archaeology, 2004, 2014). Since 3500 BP, cultural communities have continually diversified, with more localized groups forming, like the Subeixi culture in the Turpan Basin (Chen, 2002).

Archeobotanical evidence shows that millet cultivation was already practiced by ca. 7800–7350 BP (Liu et al., 2004; Li, 2018). By at least 5500 BP, people were engaging in an intensive intermixed crop–livestock system by integrating pig maintenance with millet cultivation (Yang et al., 2022). From 5000 to 4000 BP, both East Asian millets diffused into the Hexi Corridor, while agricultural practices in Xinjiang were restricted to limited microenvironmental pockets (Zhou et al., 2016; Dong et al., 2017, 2018, 2020b; Li, 2021). From 4000 BP, mixed agricultural systems composed of both East and southwestern Asian crops became more prominent, although barley and wheat had reached northwestern China about a millennium prior (Flad et al., 2010; Zhao et al., 2013; Yang et al., 2014; Zhang et al., 2017; Zhou et al., 2016, 2020; Jiang et al., 2017a, b; Tian et al., 2021). Stable carbon isotope

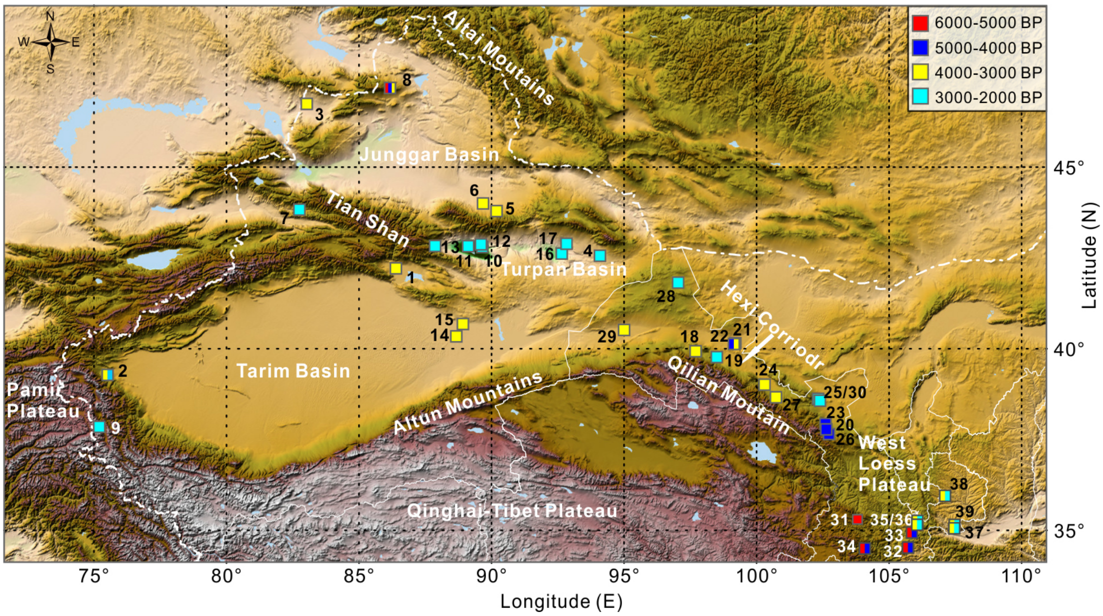

Figure 1. The location of archeological sites mentioned in this study: (1) Xintala, (2) Wupaer, (3) Xiakalangguer, (4) Shirenzigou, (5) Sidaogou, (6) Xicaozi, (7) Qiongkeke, (8) Tongtian Cave, (9) Jirzankal, (10) Yanghai, (11) Jiayi, (12) Shengjindian, (13) Yuergou, (14) Xiaohe, (15) Gumugou, (16) South Aisikexiaer Cemetery, (17) Wupu, (18) Xihetan, (19) Zhaojiashuimo, (20) Huoshaogou, (21) Huoshiliang, (22) Ganggangwa, (23) Lifuzhai, (24) Xichengyi, (25) Sanjiao, (26) Mozuizi, (27) Donghuishan, (28) Jingbaoer, (29) Yingwoshu, (30) Sanjiaocheng, (31) Majiayao, (32) Xishanping, (33) Dadiwan, (34) Shannashuzha, (35) Daping, (36) Gaozhuang, (37) Jiangjiazui, (38) Laohuzui, and (39) Qiaocun. The base map was obtained from https://www.ncei.noaa.gov/maps/grid-extract/ (last access: 22 November 2023).

data also suggest that the consumption of both C_3 and C_4 plants was widely practiced after 4000 BP (Liu et al., 2014; Zhang et al., 2015; An et al., 2017; Wang et al., 2016, 2017; Ma et al., 2016; Qu et al., 2018). Around 3700–3300 BP, wheat and barley gradually replaced the millets, becoming the dominant crops within the Hexi Corridor (Zhou et al., 2016). From 3300 to 2200 BP, agriculture in Xinjiang gradually developed into something more complex and spread to larger areas and more diverse ecozones, as evidenced by the diversification of crops and the appearance of irrigation technology and various types of farming tools (Li, 2021). Meanwhile, secondary crops, such as *Vitis vinifera* and *Ziziphus jujuba*, appeared more widely after ca. 2500 BP, indicating a strong concept of land tenure associated with the development of agriculture (Jiang et al., 2009, 2013; Li, 2021)

3 Archeobotanical data and chronology

3.1 Chronology of the archeological sites

In this study, we present data from seven archeological sites and have developed a chronology based on accelerator mass spectrometry (AMS) ^{14}C dating through the Beta Analytic Testing Laboratory and Australian Nuclear Science and Technology Organisation. For dating, we focused on wheat seeds and wood charcoal, and the calibrated ages were generated using OxCal v4.4 with IntCal20 (Table 1, Fig. 2; Reimer et al., 2020). The dating results show that the seven archeological sites cover a time span between 3900 and 2000 BP, and the oldest dates come from Xintala (at ca. 3900–3500 BP). The Xiakalangguer, Sidagou, Xicaozi, and Qiongkeke sites fall into the period of 3500–3000 BP. The chronology for Shirenzigou covers roughly 2700–2000 BP. At Wupaer, we collected wood charcoal samples from two sections, S1 and S3, and the date of the S3 section is about 2900–2800 BP. The S1 section shows two different time spans of occupation, specifically ca. 3400–3300 and 2500–2300 BP.

3.2 Wood charcoal assemblages

The identification of wood charcoal was accomplished via scanning electron microscopy, with 2960 fragments of charcoal analyzed and reported here (Appendix A). Three of the sites are located in oases, and wood charcoal assemblages show clear similarities, with a dominance of *Tamarix* wood (Fig. 3). In sediments from Xintala, we identified 878 wood charcoal fragments, with *Tamarix* accounting for 74 %–95 %. *Elaeagnus* increased across the chronology and reached its highest level (13 %) in the latest layer. There were limited occurrences of *Populus*, *Salix*, and a species that was assumed to be *Nitraria*. The wood charcoal from Wupaer also shows an abundance of *Tamarix* (ca. 80 %), followed by fragments of *Populus*, *Salix*, and Chenopodioideae. Fruit tree remains

Table 1. Dates for the seven archeological sites in this study.

Site	Latitude	Longitude	Culture	Lab no.	Material	Date (BP)	Calibrated date (2δ, BP)	References
Xintala	42.22	86.39	Xintala type	OZM448	Charcoal	3395 ± 30	3815–3561	Zhao et al. (2013)
				OZM449	Charcoal	3515 ± 30	3877–3696	
				OZM450	Charcoal	3335 ± 30	3680–3469	
				OZM451	Wheat	3460 ± 35	3835–3593	
				OZL437	Wheat	3515 ± 50	3960–3642	
Qiongkeke	43.83	82.75	Andronovo	Beta-642945	Charcoal	3220 ± 30	3482–3375	This study
				Beta-642946	Charcoal	3320 ± 30	3591–3458	
Xiakalangguer	46.74	83.03	Andronovo	Beta-642943	Charcoal	3140 ± 30	3447–3327	
				Beta-642944	Charcoal	3070 ± 30	3365–3209	
Sidaogou	43.79	90.19	Nanwan type	OZK664	Wheat	3030 ± 50	3362–3075	Dodson et al. (2013)
				OZK665	Wheat	3080 ± 60	3445–3080	
Xicaozi	44.00	89.68	Unknown	OZM674	Wheat	2975 ± 45	3331–2997	
Wupaer	39.28	75.52	Wupaer	Beta-642939	Charcoal	3160 ± 30	3451–3339	This study
				Beta-642940	Charcoal	2450 ± 30	2544–2361	
				Beta-642941	Charcoal	2420 ± 30	2515–2351	
				Beta-642942	Charcoal	2800 ± 30	2967–2844	
Shirenzigou	42.56	94.09	Shirenzigou type	Beta-642947	Charcoal	2350 ± 30	2466–2329	
				Beta-642948	Charcoal	2180 ± 30	2313–2099	
				Beta-642949	Charcoal	2150 ± 30	2178–2041	
				Beta-642950	Charcoal	2470 ± 30	2715–2414	

include *Prunus*, usually less than 3 % in abundance. At the Xiakalangguer site, *Salix* and *Tamarix* account for 44 and 28 % of the assemblage, respectively, followed by Chenopodiaceae (17 %). A small number of *Betula* and *Prunus* fragments were also identified.

In the eastern Tianshan, wood charcoal from three sites revealed an abundance of coniferous wood fragments. At Shirenzigou, wood charcoal fragments from cultural strata included *Picea*, *Juniperus*, *Tamarix*, *Populus*, *Salix*, and *Rhamnus*, with conifers accounting for over 90 % of the fragments. However, 14 wood samples taken from coffins suggest that they are all made from coniferous woods, including *Picea* (11) and *Juniperus* (3). At Sidaogou, wood charcoal from five samples was dominated by *Picea* and *Populus*, followed by *Salix* and *Tamarix*. Progressively, over time, *Picea* fragments decreased from 52 % to less than 20 %, while *Populus* increased quickly from 37 % to over 70 %. Similarly, *Picea* and *Populus* also constituted a dominant percentage of the Xicaozi assemblage, whereas the other taxa only covered a small percentage, represented by *Prunus*, *Juniperus*, *Salix*, and *Betula*. The Qiongkeke site is located in the Ili Valley, with five taxa identified among 229 wood charcoal fragments. *Prunus* and *Rhamnus* account for 30 % each. The proportion of *Picea* is around 20 %, followed by *Tamarix* and Maloideae.

In addition, we compiled wood charcoal data from published studies. In the Altai Mountains, wood charcoal from Tongtian Cave indicates that people widely collected *Larix*, *Picea*, *Betula*, *Populus*, *Salix*, Maloideae, and *Prunus* (Zhou et al., 2020). On the Pamir Plateau, the data that we have assembled from the Jirzankal Cemetery show that *Populus* was used for making fire tools, *Betula* for wooden plates, *Salix* for wooden sticks, *Juniperus* for fire altars, and *Lonicera* for arrow shafts (Shen et al., 2015). Similarly, in the Turpan Basin, *Populus* was also selected for making fire tools at the Yanghai Cemetery, and there was selective use of a variety of other woods, including *Picea*, *Spiraea*, *Tamarix*, *Betula*, *Morus*, *Salix*, *Clematis,* and *Vitis vinifera* (Jiang, 2022). *Lonicera* was also used for arrow shafts and composite bows at the Jiayi and Shengjindian cemeteries (Nong et al., 2023). *Picea* was widely used at Yuergou for coffin manufacture and firewood (Jiang et al., 2013). Meanwhile, in the Tarim and Hami basins, *Populus* and *Tamarix* were largely used for coffins and wooden utensils, as revealed by studies at the Xiaohe, Gumugou, South Aisikexiaer, and Wupu cemeteries (Institute of Cultural Relics and Archaeology of Xinjiang, 2007; Zhang et al., 2017, 2019; Wang et al., 2021).

In the Hexi Corridor, *Picea* and/or *Juniperus* constituted the dominant portion of wood charcoal fragments at sites located near the Qilian Mountains, such as Xihetan and Zhaojiashuimo (Shen et al., 2018). Meanwhile, wood charcoal samples from oasis sites, like Huoshaogou, Huoshiliang, and Ganggangwa, also record the abundance of *Tamarix*, and woody Polygonaceae and *Salix* disappear from later phases of Huoshiliang, presumably due to over harvesting for fuel (Shen et al., 2018; Li et al., 2011). The other sites in this area are characterized by abundant broadleaved taxa, with a small percentage of coniferous wood fragments, such as at the Li-

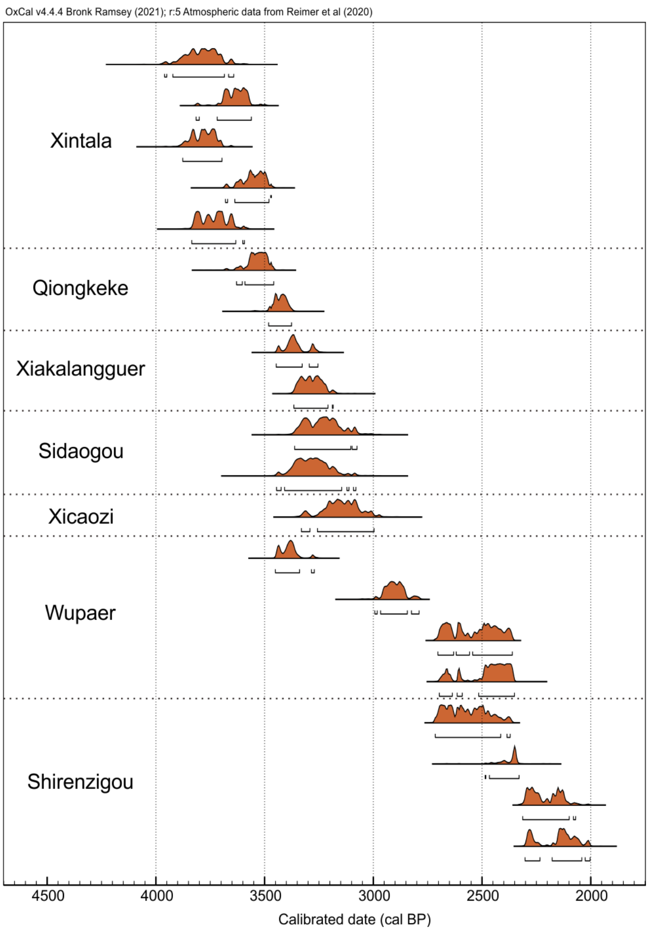

Figure 2. The chronology of the seven archeological sites in this study.

fuzhai, Xichengyi, and Sanjiao sites (Wang et al., 2014; Shen et al., 2018; Liu et al., 2019). Meanwhile, wood charcoal assemblages from the Mozuizi and Donghuishan sites suggest a rapid decline of local wood sources, including those of *Picea*, Maloideae, and *Betula* (Shen et al., 2018). Additionally, an abundance of *Prunus* wood fragments was found in these two sites, and people might have transported *Picea* wood over long distances to burn at Donghuishan (Shen et al., 2018). The long-distance transport of *Picea* and *Pinus* was also recognized in the assemblage from the Jingbaoer jade mine (Liu et al., 2021). At the Yingwoshu and Sanjiaocheng sites, abundant *Morus* wood fragments were identified, possibly indicating the early cultivation of mulberry (Shen et al., 2018).

As with the Hexi Corridor, wood taxa recovered from the western Loess Plateau also suggest a quick decline in the abundance of *Picea*, notably from 37 % to less than 4 % at Majiayao (Shen et al., 2021). In the assemblage from Xishanping, *Picea*, *Betula*, *Acer*, and *Quercus* decreased markedly after 4600 BP, and *Picea* declined from a peak value of 28 % to less than 5 %, while Bambusoideae increased sharply (Li et al., 2012). The sudden spike on abundance of bamboo is thought to be due to rapid successional colonization after significant deforestation or clearing of woody competitive species. Meanwhile, fruit trees, including *Castanea*, *Prunus* (what the wood specialists in this study called *Cerasus* and *Padus*), and *Diospyros* expressed a considerable increase in abundance (Li et al., 2012). The use of fruit tree wood was also recognized at the Dadiwan, Shannashuzha, Daping, and Gaozhuang sites, with an abundance of *Prunus* (these researchers subdivided this group into *Prunus* and *Padus*, which we have clumped together in this study for consistency, as that is the wide conception of *Prunus*: *Prunus* sensu stricto includes *Prunus*, whereas it sensu lato includes *Amygdalus*, *Cerasus*, *Padus*, and *Armeniaca*), Maloideae, and *Ziziphus* (Sun et al., 2013; An et al., 2014; Li et al., 2017).

4 Discussions and conclusion

4.1 Wood collection strategies and the transport of conifers

As the result of wood fuel use, wood charcoal provides insights into the decision-making process regarding collection strategies. In this study, we found that wood charcoal assemblages from all oasis sites were dominated by *Tamarix*. Most species from the *Tamarix* genus are deciduous shrubs, generally 2–5 m high, with slender and soft branches (Yang and Gaskin, 2007). The twigs are often browsed by sheep, camels, and donkeys, and the branches can serve as a rapidly regenerating fuel (Editorial Board of Flora of China, CAS, 1990). Therefore, this widely distributed, arid-tolerant, and rapid-growing shrubby *Tamarix* would have constituted the best fuel for ancient oases groups. For the archeological sites located in mountainous areas, wood fragments from coniferous trees are more prevalent. For example, abundant *Picea* and *Juniperus* wood fragments were found at Shirenzigou in the eastern Tianshan. Similarly, *Picea* and *Juniperus* constitute the dominant portion of the fragments from sites near the Qilian Mountains (Shen et al., 2018). All of the assemblages show that people were largely opportunistic in their choices and that the availability of wood sources played a key role in the wood collection strategies.

Additionally, as wood resources in arid northwestern China are relatively limited, coping with localized wood shortages would have been an issue that people inevitably dealt with. Among these wood charcoal assemblages, we found that there are some fragments of coniferous wood that likely represent people traveling over long distances on collection trips. The earliest known evidence might come from Donghuishan (3700–3400 BP), in which *Picea* charcoal experienced a sharp decrease and then suddenly increased to its highest level (Shen et al., 2018). Given that spruce forests are very slow to regenerate, the sudden increase in spruce fragments was likely the result of long-distance collection from the Qilian Mountains (Shen et al., 2018). Generally, spruce

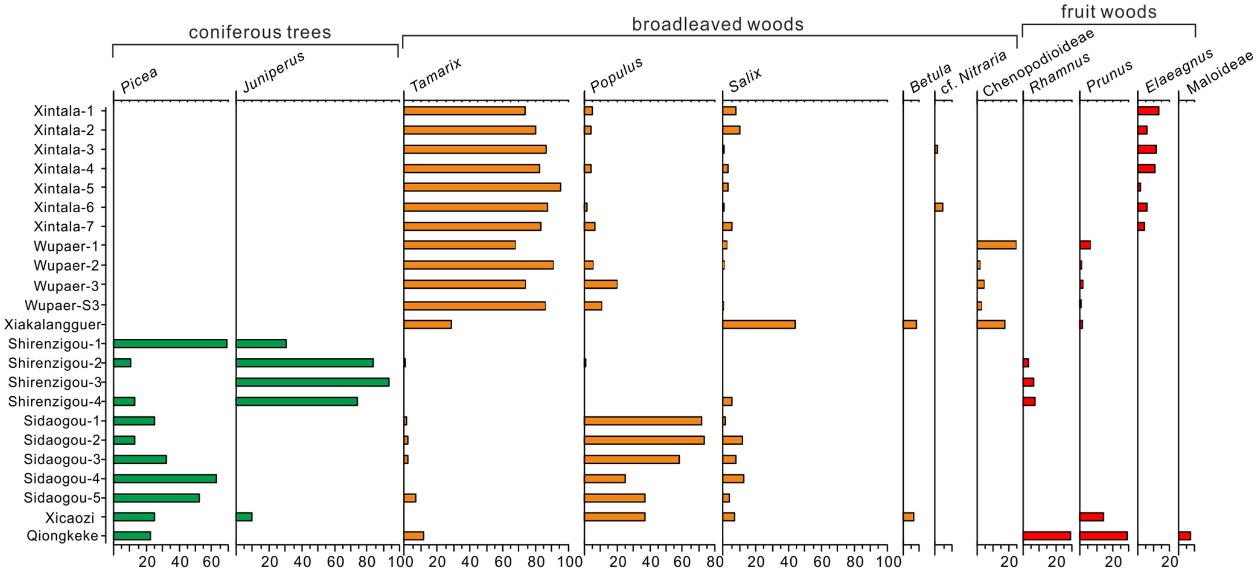

Figure 3. Wood charcoal assemblages from seven archeological sites in northwestern China.

wood has preferential properties, as its timber is straight, tall, and easily worked, presumably contributing to the selection and transportation of this specific species. Since 2500 BP, the long-distance collection of coniferous woods seems to have been a more regular activity, as evidenced at the Jingbaoer jade mine, where *Picea* and *Pinus* wood fragments are recovered well outside their natural ecological distribution (Liu et al., 2021). In the Turpan Basin, *Picea* wood fragments were found in sediments from a series of Subeixi sites, which may have been collected from the Tianshan Mountains (Jiang et al., 2013; Jiang, 2022).

In addition to noting the likely long-distance collection of coniferous woods, the abundance of conifers at most of our study sites hints at the likelihood that people might also have a preference for this specific wood type. At Sidaogou, spruce wood fragments comprise more than 60 % of the total fragment assemblage. Similarly, charcoal from Majiayao recorded spruce fragments as the most used taxon right from the onset of when people settled at the location (Shen et al., 2021). Meanwhile, the exclusive use of coniferous wood for coffin construction is also recognizable in this study. At Shirenzigou, the analysis of 14 wooden coffins show that they were all made of coniferous woods. However, in sediments from the site, we found a variety of carbonized wood types, such as *Tamarix*, *Populus*, *Rhamnus*, and *Salix*. Historically, a preference towards coniferous woods is widely noted in ancient China (Ding, 2022), and archeological wood studies in Central Asia have also noted similar patterns (Spengler and Willcox, 2013). Many ethnographic and historical references to ritual juniper twig burning as incense are noted from across Central Asia. The fact that the wooden coffins at Shirenzigou are all constructed from conifers suggests that the ritual significance of the resinous trees may stretch much further back in time. An awareness of the properties and special meaning of these woods probably plays a key role in their wide use.

4.2 Collection and cultivation of fruit trees

In addition to the prehistoric expansion of agricultural systems, the significant numbers of fruit wood fragments in our study may imply that anthropogenic processes were increasing the density of fruit trees near human settlements. Presently, scholars continue to grapple with the question of what evidence is necessary to differentiate between wild foraging, conservation of economically significant trees, and low-investment cultivation of wild populations (Dal Martello et al., 2023). In our study, fruit wood fragments before 4600 BP were usually found in low percentages, indicating the limited collection of seasonally available wild fruits (Sun et al., 2013; Li et al., 2017; Shen et al., 2021). Roughly between 4600 and 4300 BP, *Castanea*, *Prunus*, and *Diospyros* charcoal shows a rapid increase in abundance at Xishanping on the western Loess Plateau (Li et al., 2012). Pollen data at this time also demonstrate that *Castanea* became the dominant broadleaved taxon, which is quite different from the reconstructed natural vegetation, likely indicating the management of wild chestnut forests, or at least that humans were choosing not to cut these trees down, thereby increasing their populations (Li et al., 2007). Moreover, archeobotanical records at this site illustrate that a complex agricultural system based on a variety of crops, including millets (*Setaria italica* and *Panicum miliaceum*), rice (*Oryza sativa*), oat (*Avena* sp.), soybean (*Glycine soja*), and buckwheat (*Fagopyrum* sp.), appeared synchronously with the management of chestnut. This co-occurrence probably suggests that the exploitation of secondary crops was closely related to and underpinned by the well-organized agricultural system.

During the period from 4300 to 3500 BP, an increase in the abundance of fruit wood remains is observed in Xinjiang and the Hexi Corridor. For example, *Elaeagnus* charcoal was found throughout the whole section and shows a gradually increasing trend at Xintala. In the Hexi Corridor, *Prunus* wood fragments were discovered in great abundance at Mozuizi and Donghuishan, far higher than its percentage is believed to have been in the natural vegetation, possibly showing an intensive collection of *Prunus* (Shen et al., 2019). However, there is no clear sign of fruit management during this period, given that a wide range of wild fruit types, such as *Nitraria* and *Cotoneaster*, were also widely exploited (Zhou et al., 2016; Shen et al., 2019). Meanwhile, previous studies have shown that, although a mixed agricultural system consisting of both millets, wheat, and barley existed in Xinjiang and the Hexi Corridor after 4000 BP, people still relied heavily on animal herding and/or feeding (Dong et al., 2020b; Li, 2021).

From 3500 to 2500 BP, the cultivation or maintenance of *Prunus* and *Morus* trees was probably adopted into the agricultural system. In Wupaer, located in the Kashgar Oasis, *Prunus* charcoal remains were recovered beyond the natural distribution of the tree and outside of climatic conditions suitable for *Prunus* growth, which likely resulted from anthropogenic planting. On the other hand, considering that the distribution of wild *Prunus* trees had largely shrunk or even disappeared, presumably due to long-term human activity, we should still be cautious about this conclusion. Almost simultaneously, people in the Hexi Corridor probably also started engaging in horticultural practices, supported by the discovery of abundant *Morus* charcoal (Shen et al., 2019). Synchronously, a high-yield wheat and barley farming system was developed in the Hexi Corridor (Zhou et al., 2012), and a more intensified agricultural system developed in Xinjiang (Li, 2021), likely providing a fundamental basis for the exploration of delayed-return perennial crops.

After 2500 BP, the cultivation of fruit trees was probably widely practiced in northwestern China. For instance, evidence from the Turpan Basin shows the presence of *Morus* woods and *Vitis vinifera* stems at the Yanghai Cemetery (Jiang, 2022; Jiang et al., 2009), *Vitis vinifera* seeds in the Shengjindian Cemetery (Jiang et al., 2015), and *Ziziphus jujuba* stones at the Yuergou site (Jiang et al., 2013). At the Sampula Cemetery, fruit, nut, and seed types were more abundant, including *Prunus persica*, *P. armeniaca*, *Juglans regia*, and *Coix lacryma-jobi* (Jiang et al., 2008). The appearance of such a rich and diverse array of fruit crops indicates that people in northwestern China had developed complex indigenous knowledge for survival in this hyper-arid environment and conducted more frequent exchange across the Eurasian continent.

4.3 Indigenous knowledge of plant resources

Due to the extreme arid climate, wooden objects found in our study area are usually well preserved, and the data suggest that people might have also captured the knowledge of deliberately selecting certain types of woods when making various utensils. For example, within the Subeixi groups in the Turpan Basin, *Lonicera* was harvested from wild stands to make arrow shafts at Jiayi and Shengjingdian (Nong et al., 2023). At the Yanghai Cemetery, *Betula* was selected to make dippers or ladles, due to its rigidity, and flammable *Populus* and *Picea* were used for fire tool manufacture (Jiang et al., 2018, 2021). People at this time also used *Lithospermum officinale* seeds for decoration (Jiang et al., 2007a), *Nitraria tangutorum* to make necklaces (Jiang, 2022), and *Cannabis* for ritualized consumption and/or medical purposes, as revealed in both the Turpan Basin (Jiang et al., 2006, 2007b, 2016) and on the Pamir Plateau (Ren et al., 2019).

Similarly, on the Pamir Plateau, *Betula*, which has high rigidity and density as well as a homogeneous texture, was selected for making wooden plates (Shen et al., 2015). Additionally, the study of other wooden objects suggests that people specifically chose flammable *Populus* wood to make fire tools; *Salix*, with long and straight branches, was used for fashioning wooden sticks; resinous-scented *Juniperus* was the preferred choice for making fire altars; and *Lonicera* was selected for arrow shaft manufacture (Shen et al., 2015). Such conscious utilization of different wood properties illustrates the ingenuity of these ancient people. Although the current archeobotanical data related to wooden utensils are still limited, studies from the Turpan Basin and the Pamir Plateau clearly suggest that the conscious selection of wood types for their specific properties was a particularly pronounced practice after 2500 BP, especially among cultural contexts of a well-established agriculture based on millets, wheat, and barley. Meanwhile, the appearance of horticulture based on a variety of secondary crops at the time indicated a more settled lifestyle, which might have provide opportunities for prehistoric people to fully explore and make the best use of the indigenous plant resources.

4.4 Anthropogenic deforestation

Largely due to slash-and-burn agriculture, people have largely altered terrestrial ecosystems across the globe (Zong et al., 2007; Schlütz et al., 2009; Li et al., 2009; Neumann et al., 2012; Innes et al., 2013; Ma et al., 2020; Zheng et al., 2021). For northwestern China, wood charcoal data in this study show that, apart from diversified cultural adaptions, human-induced landscape alteration also occurred widely, not only throughout the whole history of agricultural activity but also across different vegetation contexts. Along the Tianshan Mountains, pollen records from the Bosten and Balikun lakes suggest a relatively stable climate during 3900–3500 BP as well as a long-term increase in humidity after

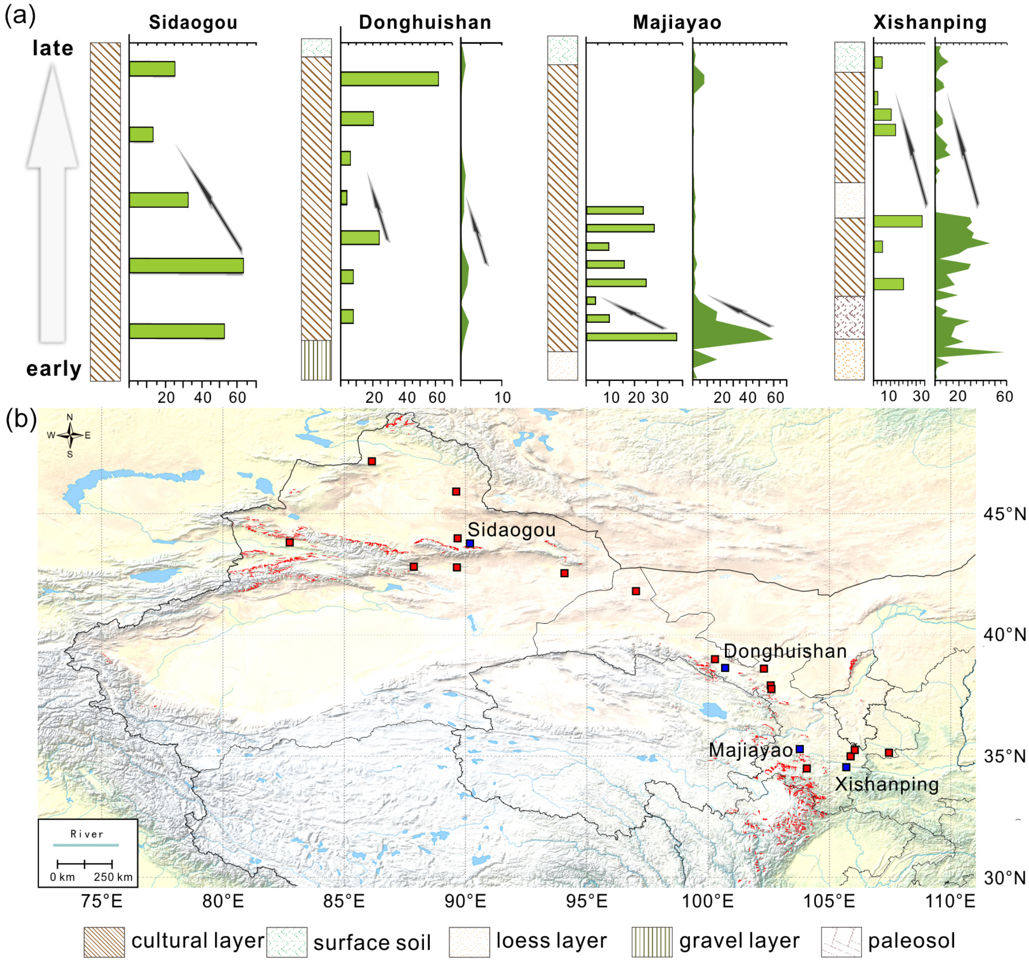

Figure 4. The wood charcoal and pollen records show synchronous deforestation of spruce forests across all of northwestern China. **(a)** The change in *Picea* wood charcoal (bar graph) and pollen (curve graph) from archeological sites, including Sidaogou, Donghuishan (Zhou et al., 2012; Shen et al., 2018), Majiayao (Zhou, 2009; Shen et al., 2021), and Xishanping (Li et al., 2007, 2012). The column charts on the left of the panels show the stratum layer. **(b)** The comparison of spruce forests between prehistoric times and now: the squares represent archeological sites with *Picea* charcoal remains; the red areas show the current distribution of spruce forests in northwestern China (after Hou, 2019).

3800 BP (Chen et al., 2006; Huang et al., 2009; An et al., 2012). However, wood charcoal data from Sidaogou (3400–3000 BP) recorded a significant decrease in the abundance of spruce wood fragments (Fig. 4). Meanwhile, *Tamarix* and *Salix* nearly disappeared in the later stage, showing that the sharp attenuation of spruce forests and broadleaved woodlands was caused by intensive woodcutting rather than climate change. Similarly, *Tamarix* charcoal from Xintala (3900–3500 BP) in the Yanqi Oasis firstly increased and then decreased to its lowest level in the upper layer. At the same time, *Populus* and *Salix* charcoal disappeared in the middle layer, implying that local riparian woodlands were largely deforested.

The Neolithic deforestation and reduction in range of spruce forests have also been widely recognized across the western Loess Plateau and the Hexi Corridor. On the western Loess Plateau, high-resolution (ca. 5-year increments) stalagmite $\delta^{18}O$ data recorded no abrupt climate changes at around 5300–5100 and 4600 BP (Tan et al., 2020). Meanwhile, the wood charcoal record from the Majiayao site showed a rapid decline in *Picea* ,from its highest level of nearly 40 % to its lowest level of less than 4 %, during the early stages of the site's occupation at ca. 5300–5100 BP, implying that anthropogenic exploration exerted a significant impact on local spruce forests (Fig. 4a; Shen et al., 2021). Not far from Majiayao, wood charcoal from the Xishanping section revealed a similar pattern, with *Picea*, *Betula*, *Acer*, *Ulmus*, and *Quercus* illustrating a marked decrease after 4600 BP, while Bambusoideae quickly colonized after the clearing of the original forest (Li et al., 2012). In the Hexi Corridor, studies of wood charcoal fragments from the Mozuizi and Donghuishan sites also show a quick de-

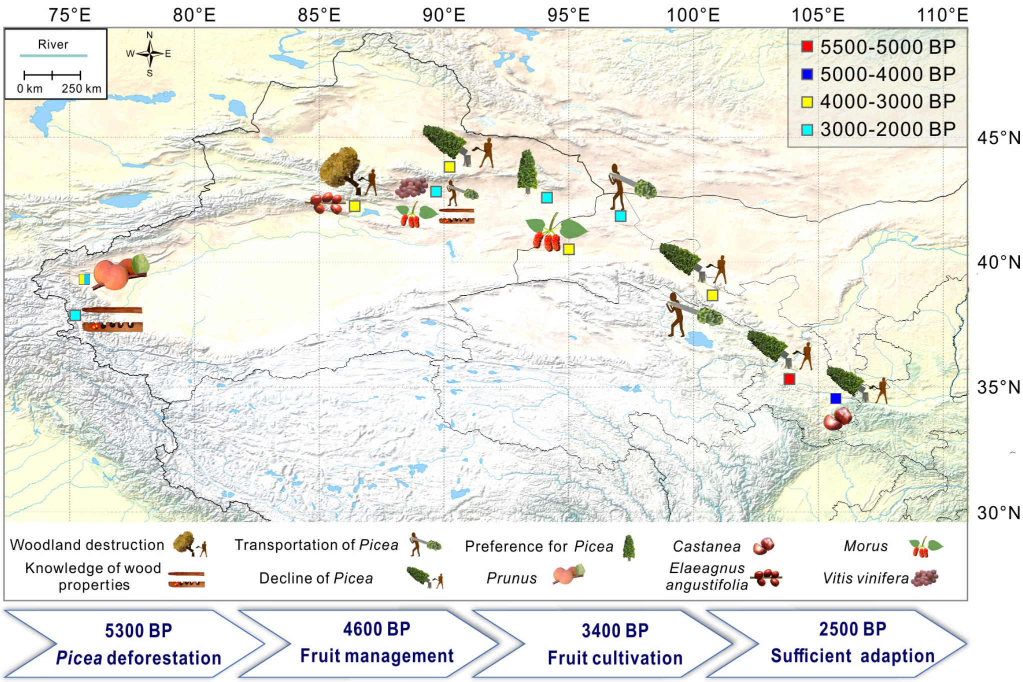

Figure 5. A summary of prehistorical human–environmental interactions in northwestern China.

cline in plant diversity concurrent with human settlement, and the percentage of *Picea* from Donghuishan experienced a sharp decrease (Fig. 4; Shen et al., 2018). Similarly, wood charcoal fragments from Huoshiliang show that *Salix* and Polygonaceae almost disappear, likely due to the large demand for fuel used in bronze-smelting activities (Li et al., 2011). Collectively, we interpret the broader trend throughout all of these wood charcoal assemblages as revealing a rather rapid process of deforestation across northwestern China, especially shown in the large-scale reduction in spruce forests. Our results are also supported by evidence from pollen records, especially *Picea* pollen from Majiayao (Zhou, 2009), Xishanping (Li et al., 2007), Donghuishan (Zhou et al., 2012), and other sections from the Loess Plateau (Zhou and Li, 2011). All of these records document a considerable reduction in spruce forests (Fig. 4a). Today, the distribution of spruce forests has shrunk down to a few constrained small forest patches (Fig. 4b).

5 Data availability

The datasets of archeobotanical wood charcoal records in northwestern China, including taxa types, absolute counts of wood charcoal fragments, and the locations and AMS ^{14}C dates of each archeological site, are available from the open-access Zenodo repository (https://doi.org/10.5281/zenodo.8158277, Shen et al., 2023).

6 Summary

The synthesis of wood charcoal data from nearly 40 archeological sites shows that prehistoric human–environmental interactions in northwestern China were closely related to the development of agriculture and considerably more complicated than previously thought (Fig. 5). Although anthropogenic deforestation occurred throughout the whole period, most evidently relating to the decline in spruce forests, people also actively applied a range of adaptive strategies to survive in this harsh environment. As early as 4600 BP, people on the western Loess Plateau might have started managing or at least conserving chestnut trees, likely underpinned by the development of a complex agricultural system. Since ca. 3500 BP, with the appearance of high-yielding agriculture based on wheat and barley in Xinjiang and the Hexi Corridor, people appear to have been planting perennial tree crops, such as *Prunus* and *Morus*. Additionally, they likely engaged in long-distance transportation of preferred woods, specifically coniferous trees. After 2500 BP, people successfully mastered a wide range of adaption strategies along the ancient Silk Road, as they began manufacturing wooden utensils with conscious selection of wood properties. Moreover, the consumption of a further diversity of fruit types, including grapes, signalled more intensive horticultural practices and complex social structure.

Appendix A

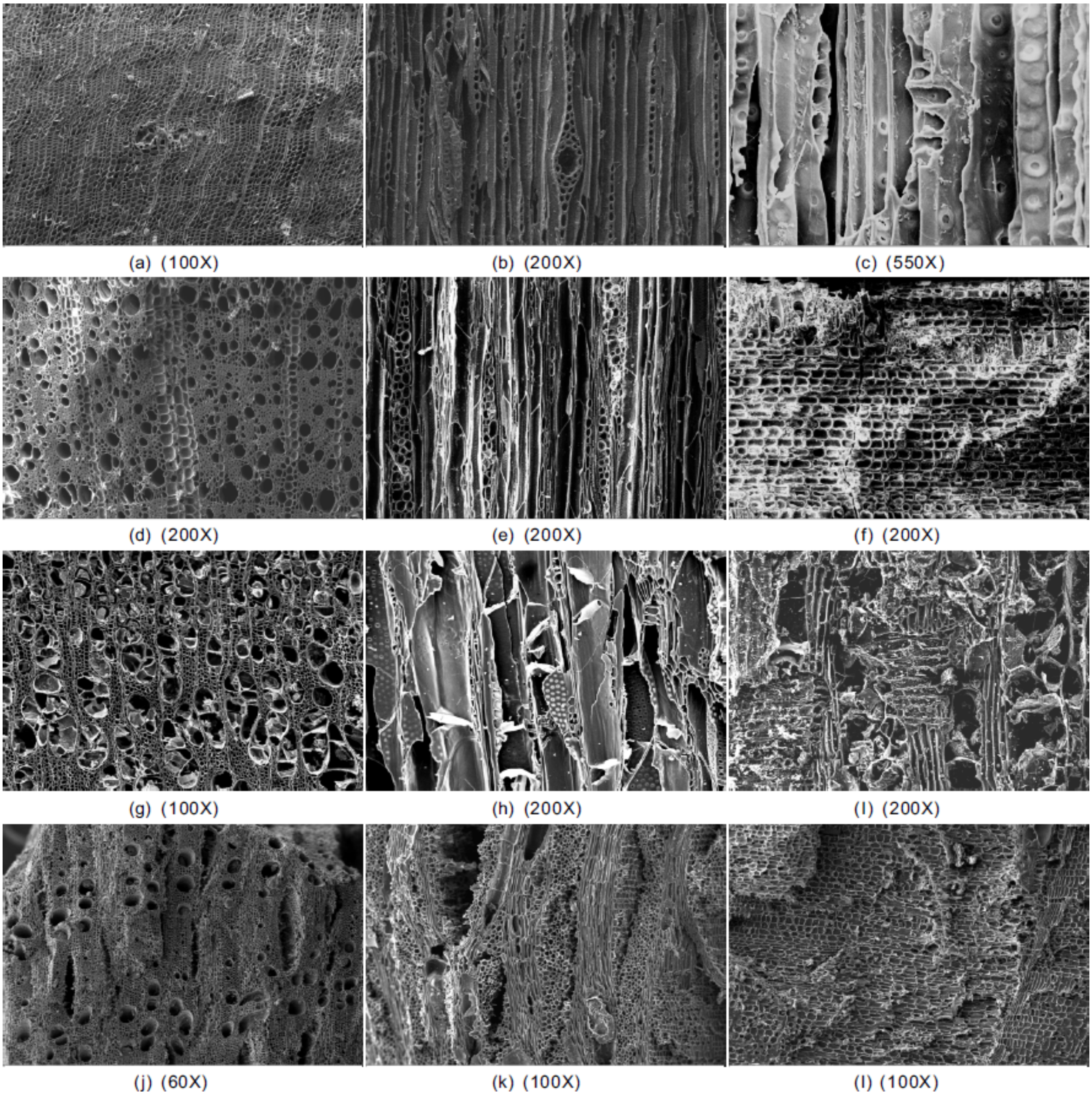

Figure A1. Selected scanning electron microscopic images of wood charcoal in Xinjiang: **(a–c)** *Picea*, **(d–f)** *Prunus*, **(g–i)** *Populus*, and **(j–l)** *Tamarix*.

Author contributions. HS and XL designed the archeobotanical dataset; HS was responsible for the construction of the database; HS performed the numerical analyses and organized the manuscript; and XZ, RS, PJ, and AB revised the draft of the paper. All authors discussed the results and contributed to the final paper.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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