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Wood from the 4th – 7th century CE in Kuča Caves in Xinjiang, China: Past vegetation and preliminary wood utilization

Fan Yang [a], Lihui Miao [b], Ji Wang [b], Xin Yan [a], Anaerguli aobulikasimu [b], Yin Jia [c,*]

[a] National Centre for Archaeology, Beijing 100020, China
[b] Xinjiang Kizil Grottoes Research Institute, Baicheng 842300, China
[c] Confucius Museum, Qufu 273100,China

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ABSTRACT

Taitai'er Grottoes and Mazabha Grottoes are integral components of the Kuča Caves , and the date of the caves were from the 3th to 9th century CE. To investigate how monks utilized wood during this period and to analyze the climate and vegetation characteristics of that era, we conducted a systematic identification of 58 wood samples found in fireplaces, wooden architectural components, and woodware within the two caves using dendrological identification methods. Five species of wood were identified: *Populus* sp. (poplar) , *Salix* sp. (willow) , *Hippophae* sp. (sea-buckthorn) ,*Morus* sp. (mulberry) , and *Elaeagnus* sp.(elaeagnus).

Based on the archaeological context of these samples, it is inferred that *Populus* sp. and *Salix* sp. species were more extensively utilized. These woods may have served as fuel, for constructing dwellings, and making for crafting daily utensils, which was because of their wood properties. Archaeological investigations further reveal that both caves were situated near rivers,which were favorable conditions for the growth for *Populus* sp. and *Salix* sp.. It could be inferred that these wood in the caves were collected by monks locally. Although the number of wood samples discovered is relatively limited, by integrating existing climatic research findings and historical literature records about this area, we deduce that the climate during this period fluctuated between cold and warm phases, while the vegetation surrounding the sites predominantly consisted of *Populus* sp., *Salix* sp. and some shrubs.

1. 1.Introduction

Wood plays a vital role in human life with its extensive range of applications. It serves not only as a source for heating and lighting but also as a material for crafting a variety of products, including tools, weapons, ornaments, furniture, and even housing. Furthermore, the multifunctional uses of wood date back to the Paleolithic Era and continue to be integral to various domains of production and daily life in contemporary society(Aranguren et al., 2018; Picornell-Gelabert et al., 2017). And the wood remains discovered in archaeological sites serve as crucial materials for analyzing how ancient humans utilized wood, investigating the interrelationship between ancient peoples and natural vegetation, understanding regional woody plant species, and reconstructing the ancient environmental climate(The Institute of Archaeology Class, 2012). When examining the utilization of woody plants by ancient peoples, it is crucial to integrate the discussion with the archaeological context of the wood samples unearthed. Additionally, as a vital component of the ecological environment, woody plants also provide insights into the climatic and environmental conditions, as well as vegetation compositions. Xinjiang region, serving as a pivotal junction between East Asia and West Asia, has historically been a climate-sensitive area. Although numerous studies have explored the climate and environment of this region, relatively a few have addressed these issues from an archaeological perspective.

Kuča Caves, the significant archaeological complex with regional economic prosperity and cultural richness as a product of the Silk Road's influence(Han and Zhu, 1990), there were lot of research about it. And it has primarily concentrated on the periodization and dating of the caves, based on their architectural style and mural composition(Liao, 2006), the display of the Buddha's life story in one cave(Yan, 2017) or the specialized Buddha images in others(Huo, 2012) and so on. However there is a notable gap in research concerning the environmental context, vegetation, and wood usage during the caves' formation and use. Taitai'er Grottoes and Mazabha Grottoes were the important components of

* Corresponding author.
E-mail addresses: yangfan33@mail.sdu.edu.cn (F. Yang), 791660132@qq.com (L. Miao), 951089531@qq.com (Y. Jia).

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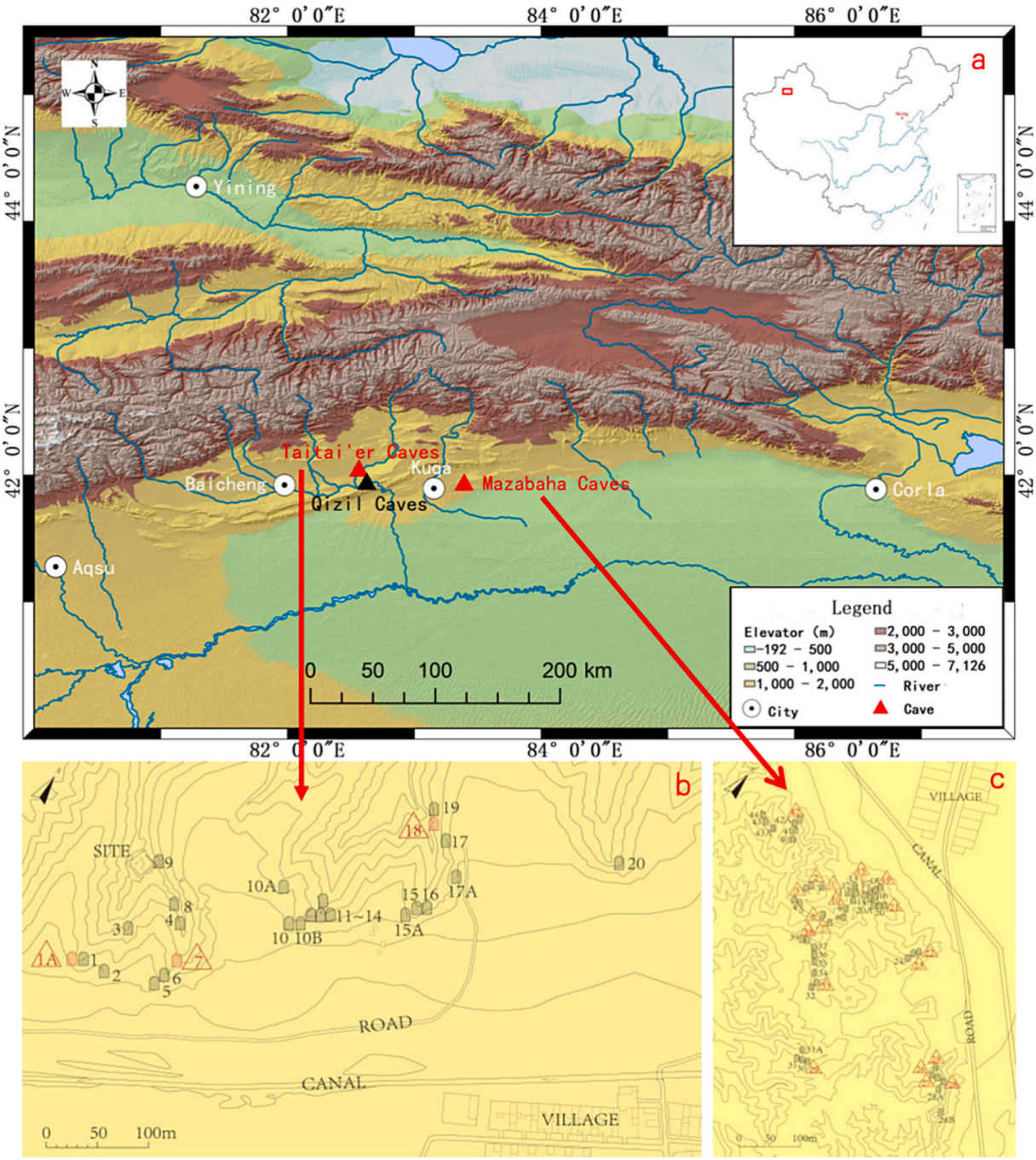

Fig. 1. a. Geographical location map and main grottoes distribution map of Kuča area; b. Diagram of the plan distribution of the Taitai'er Grottoes; c. Diagram of the plan distribution of the Mazabaha Grottoes.

the Kuča Caves, therefore during the excavation process, we consciously collected samples of charcoal and wood products, aiming to explore the utilization of woody plants by ancestors at that time in combination with the background of the archaeological context, and further discuss the vegetation combination and climatic environment at that time.

2. Site background

In 2022, the Xinjiang Qizil Caves Research Institute (formerly known as Xinjiang Kuča Caves Research Institute) collaborated with the reinforcement and maintenance projects of the Taitai'er and Mazabaha Grottoes, to conduct cleaning work in the caves and discovered some new caves, as well as several important cultural relics, which have corrected and supplemented previous interpretations of the Kuča Caves (Miao, 2023). During these excavations, targeted wood samples were collected, including wooden structural elements, charcoal from wall fireplaces, and wooden tools, with the goal of understanding the Kuča peoples' wood utilization practices and to gain insights into the vegetation and environment of that era.

2.1. Taitai'er Grottoes

Taitai'er Grottoes (41°52′25.7″ ~ 41°53′14.9″ N, 082°26′22.4″ ~ 082°27′27.1″ E) are located approximately six kilometers northeast of Qizil Town, about sixty kilometers east of Baicheng County, and roughly twelve kilometers north of the Qizil Caves. They are nestled at an

Fig. 2. Samples from Mazabaha Grottoes: a. wooden structural element in K3 between the gateway and doorframe; b. a long wood strip in the corridor of K42; c. a wooden structural element and long wood strip in the main room of K21; d. a plinth in the atria of K6-K7.

altitude ranging from 1240 to 1270 m above sea level (masl hereafter). Baicheng County is encircled by mountains, creating a long and skinny valley that decreases in elevation from the northwest to the southeast. The terrain is diverse; the Tianshan Mountains form the northern area, while the Queletag Mountains forms the south. The climate is characterized as a temperate continental arid climate, with cold winters and hot summers. The average temperature is 7.6 °C, the frost-free period lasts 133 to 163 days, the average annual sunshine is 2789.7 h, and the average annual precipitation is 171.13 mm. The predominant vegetation in the Baicheng Basin consists mainly of shrubs and herbaceous plants, with wheat, corn, and cotton as the primary crops.

The Taitai'er Grottoes (Fig. 1b) extend roughly 400 m east to west and 160 m north to south. There are a total of 25 caves mainly spread across both the eastern and western hillocks, and the cave types only include central pillar caves and monastery caves. Based on the murals discovered, the form of the caves, the findings and the pictures in the caves, and according to the Carbon-14 dating results, the Taitai'er Grottoes can be divided into two periods. The first period caves were dating from the 5th century CE to 6th century CE; the second period was from the 7th century CE to the 9th century CE. During the first period, there was only one niche in the wall of the main room in the caves, however in the second period, most became two or more. Besides, in the second period, the left and right corridors both emerged the niches in the wall.

Wood samples were collected from caves numbered 1A, K7, and K18. 1A is belonging to the first phase, K7 and K18 are both classified as belonging to the second phase of the Taitai'er Grottoes. And the samples we discussed in this artical were both fond the caves dating from 5th century CE to 7th century CE in Taitai'er Grottoes.

2.2. Mazabaha Grottoes

Mazabaha Grottoes (41°46′44.3″ N ~ 41°46′55.4″N and 83°12′11.7″E ~ 083°12′30″ E), are located on the Gobi Slope at 1080—-1090 masl, approximately 500 m southwest of Mazabaha Village, 30 km northeast of Kuqa City, and about 7 km to the south of the Simsim Caves. Kuqa City is nestled at the southern foot of the central Tianshan Mountains and the northern edge of the Tarim Basin. The climate is characterized by abundant heat, dry conditions, scarce precipitation, hot summers, and dry, cold winters with significant annual and daily temperature variations. This region falls within the warm temperate continental arid climate category. The annual average temperature is 10.7 °C, with an average annual precipitation of 73.3 mm and a sunshine duration of 2915.9 h. On the hillsides ranging from 1600 to 2000 masl, one can find aspen, bitter poplar, and alpine poplar, among other trees. Various shrubs thrive on the hillsides and along the banks of rivers and valleys in the foothills. The dominant shrubs include *Sabina vulgaris*, rose, and honeysuckle. The primary agricultural crops in the region are wheat, corn, and cotton.

The Mazabaha Grottoes complex contains 50 previously identified grottoes, with some severe collapsed caves(Fig. 1c) , and only about 40 grottoes that can be identified by their shape. The types of grottoes include central pillar caves, square caves, monks caves, and meditation caves. There are only a few caves with murals at Mazabaha Grottoes, and the main surviving murals are found in caves 1, 8, 24, 25, 29, and 41. The murals depict a variety of subjects, including stories from the Buddha's life, celestial scenes, depictions of deities and donors, landscape paintings arranged in lozenge patterns, animals, and decorative motifs. Based on the characteristics of the grottoes form and composition, mural themes and styles, and the Carbon-14 dating results, the caves were built from the 2th century CE and abandoned after the Uyghur ruled the Kuča(Xinjiang Uygur Autonomous Region Bureau of Cultural Relics, 2015).

3. Materials and methods

The analyzed samples are primarily divided into three categories: wood crafted into utensils, such as combs and bowls; wooden structural elements within the caves, including columns and thresholds, which served as building materials for the construction of the caves; and charcoal remnants from the fireplaces, which were used by the monks. Regarding the charcoal samples found in the fireplace, we first sieve it

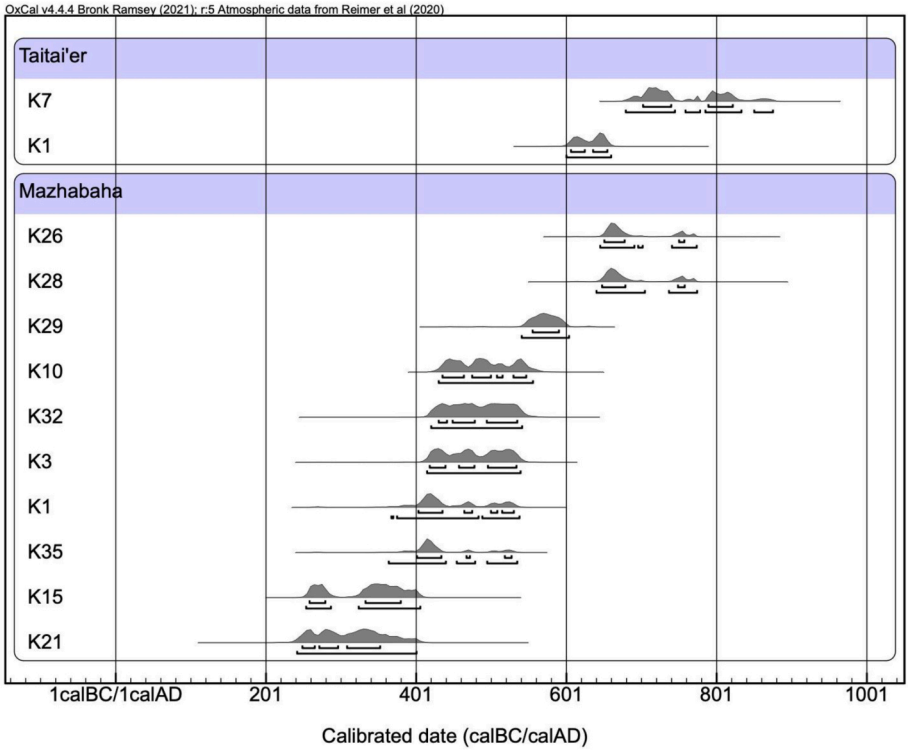

Fig. 3. AMS radiocarbon dates from Taitai'er and Mazhabaha Grottoes, using OxCal v4.4.4 and IntCal20 calibration curve.

using a 4 mm-diameter mesh to separate particles, and selected larger than 4 mm for identified and we quantified the samples as a complete and independent sample was counted as one sample. For the wood crafted and wooden structural elements samples discovered, we also took a complete piece of wood as a sample for identification and analysis. Among the 25 samples collected from the Taitai'er 3 different caves, 6 are building components found within the caves, 1 is an unidentified fragment of a wooden utensils, and 18 are pieces of charcoal which were collected from the bottom of Cave K7. In Mazabaha Grottoes (Fig. 2), 47 samples were gathered. Among these, 43 samples were taken from wooden structural elements in 21 different caves, encompassing columns, crossbeams, and arches. Additionally, 3 samples are unidentified fragments of wooden items, the above 50 samples were well preserved and uncarbonized. 1 sample was charcoal fragments retrieved from a fireplace inside Cave K15. The samples from near the fireplace conservation as charcoal , wood crafted and wooden structural conservation as wood.

Because of the wood excavated in the grottoes is in a poor state of preservation, and the method of slicing wood through a freezer and then identifying couldn't obtain complete and observable wood sample slices direct. We charred the uncarbonized wood samples in a muffle furnace with NOBODY model number NBD-M1200-20TI, at 300℃ for 2 h. Subsequently, we cut the carbonized charcoal sample into three surfaces for taxa identification: the transverse section, tangential section, and radial section. We used a Nikon Ci-L metallographic microscope with a reflecting light source, bright field, and with the 10 times eyepiece and objective magnification ranging from 5 to 100 times to examine the charcoal samples. Identifications and the description of wood characteristics were made with the softwood and hardwood identification codes and texts of IAWA and "China Woodography" (Cheng et al., 1992a) also be referenced in this article. Each sample was then attached to an aluminum sample table, gold-plated, and photographed under a Phenom XL scanning electron microscope.

In addition, in order to accurate the period of the grottoes, we selected some wood samples and sent them to the Carbon-14 dating laboratory at Peking University for accelerator mass spectrometry (AMS) carbon-14 testing.

4. Results

4.1. Dating results

The dating results indicate that the wood from the Taitai'er Grottoes in this study falls within the period CE 600–700. The Mazabaha Grottoes date to CE 400–700 Therefore, the samples discussed in this article are mainly from the 4th century to 7th century CE(Fig. 3).

4.2. Wood identification results

4.2.1. Taitai'er Grottoes

The samples from the Taitai'er Grottoes, although limited in number, offer valuable insights. Of the 18 charcoal samples retrieved from K7, most were identified as belonging to the *Hippophae* sp. (sea-buckthorn). We identified two samples as *Populus* sp. (poplar) and four as broad-leaved trees. Two samples could not be assigned to a specific taxa due to their poor preservation conditions. Of the 7 wood structural elements samples collected, we identified *Populus* sp. (poplar) , *Morus* sp. (mulberry) , and *Salix* sp. (willow) , and two *Elaeagnus* sp. (elaeagnus) (Fig. 4; Table 1). Overall, the species of wood found in the Taitai'er Grottoes are mainly Elaeagnaceae and Salicaceae. It is important to note that *Populus* sp. and *Salix* sp. belong to the same family of woody plants, and many of their distinguishing characteristics are highly similar. The primary criterion for differentiating between the two is the presence of upright cells in the radial section of the wood. Samples with a predominance of upright cells in the radial section are classified as *Salix* sp.

4.2.2. Mazabaha Grottoes

Comparatively, we analyzed 40 samples from the Mazabaha 19 Caves and found very limited taxa present: *Populus* sp. (poplar) and *Salix* sp. (willow) (Fig. 4; Table 2). Due to poor preservation conditions, we could identified three samples as broad-leaved trees and three as unknown.

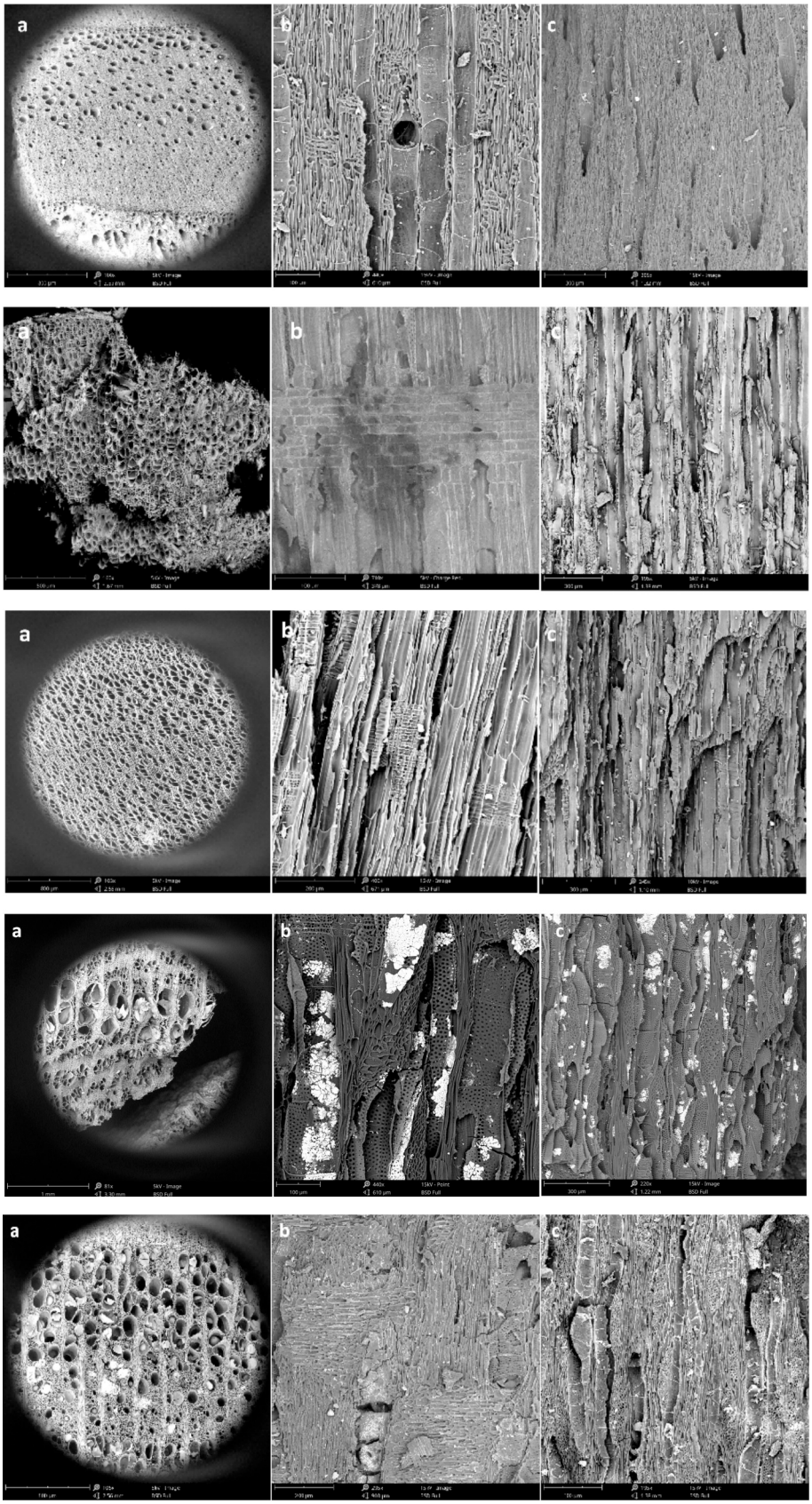

Fig. 4. SEM images showing the structure of the identified wood from top to bottom: *Hippophae* sp., *Salix* sp., *Populus* sp., *Morus* sp., and *Elaeagnus* sp. (a) transverse section (b) radial section(c) tangential section.

Table 1
Taitai'er Grottoes wood identified results.

Relic unit	Sample Position	Broad-leaved tree	*Salix*sp.	*Populus* sp.	*Morus* sp.	*Elaeagnus* sp.	*Hippophae* sp.	Unidentified
wooden utensils and building components (Uncarbonized)								
K1	Inner Column	1						
	Jamb		1					
	Anteroom Column	1						
	Inner Column					1		
K7	Woodware			1				
	Jamb of main door				1			
K18	Woodware					1		
Charcoal nearby fireplaces (Carbonized)								
K7	Charcoal bottom of the cave	4		2			10	2
Totel		6	1	3	1	2	10	2

Table 2
Mazabaha Grottoes wood identification results.

Relic unit	Sample Position	*Populus* sp.	*Salix* sp.	Broad-leaved tree	unidentified
wooden utensils and building components (Uncarbonized)					
K1	Beam of main door		1		
K2	Grotto window		1		
	Corbelling				1
	Corbelling		1		
	Grotto window		1		
K2-K3antechamber	Wooden structure of gateway	1			
K3	Wooden structure of gateway	1			
	Wooden structure		1		
	Pin chips				1
K6	Wooden structure of gateway	1			
	Doorframe of the main room		1		
	Column of main door		1		
	Beam of main door		1		
	Beam of main door		1		
	Anteroom Column		1		
K6-K7antechamber	Anteroom wooden structure	1			
	Anteroom plinths	1			
*K*10	Woodware	1			
K19	Corridor stringer	1			
	Corridor wooden structure	1			
	Corridor wooden structure	1			
K21	Wooden structure	1			
	Wooden structure of the main room	1			
	wooden structure of window				
	Anteroom wooden structure		1		
		1			
K22	Wooden structure		1		
	Stringer of window		1		
K23	Beam of main door	1			
K25	Corridor wooden structure	1			
K26	Wooden structure of gateway	1			
	Anteroom beam		1		
	Woodware		1		
K27	Wooden structure of gateway			1	
K28	Wooden structure of window		1		
	Wooden structure of gateway	1			
	Corridor wooden structure		1		
K29	woodcarving		1		
	Anteroom beam		1		
	Wooden structure of gateway		1		
	Anteroom beam		1		
K33	Corridor wooden structure	1			
K37	Wooden structure			1	
	Wooden structure of gateway			1	
K38	Wooden structure				1
K42	Corridor wooden structure	1			
	Corridor wooden structure		1		
K45	wooden structure		1		
	Column of grotto		1		
	wooden structure		1		
	Wooden structure of gateway	1			
	Corridor wooden structure	1			
Charcoal (Carbonized)					
K15	Fireplace charcoal	1			
Totel		21	26	3	3

5. Discussion

5.1. Wood utilization

5.1.1. Fuel

The remains of charcoal collected in the fireplaces of the Mazabaha Grottoes K15 and Taitai'er Grottoes K7 were predominantly from *Populus* sp., *Salix* sp. and *Hippophae* sp. The charcoal found at the bottom of K7 in the Taitai'er Grottoes was spread evenly in the cave, leading the excavator to interpret the charcoal might be from a collapsed building or wood intentionally burned to make the ground of the cave flat and dampproof. A greater number of eating utensils have been unearthed in caves K15 and K7, leading to the hypothesis that these caves may have served as the living quarters for monks during that era. The charcoal discovered in the fireplaces is likely the residue from daily activities, such as burning wood for warmth and cooking food. So considering the archaeological contexts of these charcoal found, we could infer these wood were used as fuel. And it should be inferred that there were only 18 pieces charcoal found in the two caves to make us need more evidence to demonstrate it.

These two caves were spread the hillocks the transportation cost for the monks to collect large-volume timber as fuel was relatively high. In addition, the scarcity of vegetation in Xinjiang further limited monks to choice fuel. Moreover due to small area of the caves the monks lived, choosing small timber as fuel was more convenient and feasible. And the samples are relatively small in diameter and some still had bark attached, according the research ofThéry-Parisot et al. (2016) that the diameter of charcoal were extremely correlated with the wood diameters, and twigs and branches were the preferred firewood(Martín, 2011). So we thought the wood found in these caves when burnt were in small diameter. It meant the monks may have collected small branches of *Populus* sp. and *Salix* sp. nearby to use as firewood, and just like Abric Romaní site(Ethel et al., 2017), the wood was collected from nearby sources and probably selected from among the available twigs.

And there are the literature and the archaeological sites founds both some evidences to prove that the ancients used *Populus* sp. and *Salix* sp. as fuel. Historical literature in the 4th century BCE records, such as the phrase "spring fire with *Ulmus* sp.(elm) and *Salix* sp., summer fire with *Ziziphus* sp.(jujube) and *Prunus* sp.(apricot), and the last month of summer fire with *Morus* sp. and *Cudrania* sp.(cudrania)(Shi, 2010)," indicated that the use of *Salix* sp. as fuel has a long-standing historical tradition in China. These types of wood have a long history as common fuel sources were found in many archaeological sites in northern China, such as at the Bronze Age site of Adunjoru in the western Tianshan region in Xinjiang, where the first inhabitants selected *Populus* sp., *Salix* sp., and grass around the site for fuel(Wang and Cong, 2022). There were also many *Populus* sp. and *Salix* sp. charcoal recovered from a pit at the Erdaojingzi site in Inner Mongolia, which may have been used as fuel by the inhabitants(Wang, 2022). At the JinchanKou site during the Qijia culture period in Gansu province, the ash pits and fireplaces of houses and cave-dwelling hearths had a higher percentage of *Salix* sp. and *Pinus* sp.(pine) species, which may have been used by the early inhabitants of the region as their main fuel sources(Wang et al., 2016).

5.1.2. Building material

The analysis of wood structural elements from two caves reveals that *Populus* sp. and *Salix* sp. might were the primary building materials. The *Populus* sp. and *Salix* sp. were also found in some archaeology sites in Xinjiang, it might be a tradition to use them for building. This preference for local wood species resonates with archaeological evidence from the Bronze Age Adunqiaolu site in the western Tianshan Mountains of Xinjiang, where *Populus* sp. and *Salix* sp. charcoal remains were identified in the houses(Wang and Cong, 2022). Additionally, in the ancient city of Loulan, located in the Lop Nur region of Xinjiang, *Populus euphrus* (Populus diversifolia), was one of the most extensively used wood materials for construction. This indicates that ancient people at the time favored the use of local vegetation over materials from more distant mountainous regions (Li et al., 2019). Such as the Loulan ancients, the monks selected *Populus* sp. and *Salix* sp. might consider that like *Populus* sp. with hard wood were suitable as building materials to support the caves.

Table 3
Some research and recording about the wood objects in Xinjiang area.

sites	wood	wood objects	date	reference
Aisikexiaernan cemetery	the local *Populus* euphrus,	wooden shovels, plates, and harps, as well as agricultural tools and musical instruments	2700—2499 BP	Jiang et al., 2016
Gilzankal cemetery	*Populus* sp.	wooden plate, hand drill, woodware and shoo koonghou	2500 yr BP	Shen et al., 2015
	Salix sp.	wooden plate, hand drill, wooden stick, woodware and crutch		
Yanghai eemetery	*Populus* sp.	barrel, plate,	13th century BCE–2th century CE	Jiang, 2022
	Salix sp.	arrow		
The Subexi culture sites	*Salix* sp.	arrow shaft and self-bow	13th century BCE-2th century CE	Nong et al., 2023

The choice of *Populus* sp. and *Salix* sp. might have been based on Buddhist doctrines. Since the 4th century CE, Buddhism has been prevalent in Xinjiang, the Buddhist precepts and strict rules have imposed requirements on the clothing, food, transportation and so many details of monks. Moreover, there seems to be greater emphasis on the craftsmanship of Buddha statues and murals in the caves which may have led to a reduced focus on the selection of building materials. The preference for wood that was more readily available could have influenced the choice of materials.

Besides according to the "most labor-saving principle" model which meant that the selection of resources is influenced by the effort required to obtain them(Miller, 1985; Shackleton et al., 1992). This indicates that ancient populations select resource depended on their aim and the wood property. And such as the same caves site in Türkiye(Barbaros and Hamza, 2023), the buliding material were more diversiform, *Quercus* L. (maple) was the most genus and the timber found in the caves were obtained from nearby local resources. In Xinjiang, however, the ancestors had to contend with an arid climate and sparse vegetation, leading to a more limited selection of building materials. *Populus* sp. and *Salix* sp.trees, such as the *Populus euphrus*, which thrives up to an elevation of 1800 masl on the southern slopes, and the blue willow, which can be found at 1900 masl in the Tianshan Mountains are more prevalent in lower-elevation valleys. Picea sp.(spruce), meanwhile, is distributed in the higher-elevation valleys and moist areas on the southern slopes between 2200 and 3500 masl. Given these conditions, it is likely that the ancestors favored the more accessible *Populus* sp. and *Salix* sp. wood from lower altitudes.

5.1.3. Wooden objects

In the Taitai'er Grottoes, only two types of woodware samples were discovered and were identified as *Populus* sp. and *Elaeagnus* sp. Similarly, in the Mazabaha Grottoes, three wood products were unearthed, two identified as *Populus* sp. and one *Salix* sp. It was a pity that due to the poor preservation condition of the samples when they were discovered in the two caves, the types of the wooden artifacts were difficult to be identified. However we could find some evidence from other sites in Xinjiang to infer the uses of the wood we found.

According to the others research (Table 3), we could suppose that

Table 4
Some research and recording about the climate from the 4th to 7th century CE.

Period	Area	Climatic indicator	Climate Characters	Manifestation	reference
CE400-700	Longgan Lake area in Anhui in the mid-east of China	diatom and pollen	changable	the temperature and the precipitation was fluctuation change,the changes in temperature was alternate	Tong et al.,1997
CE324	Hexi region in the northwest of China	historical documents	cold	not suitable for the growth of *Styphnolobium* L. (locust tree) and *Catalpa* L. (catalpa)	Fang, 1974
about CE 328——376	Gansu in the northwest of China	historical documents	cold	it was thawing in May and latter about 10 days than today the temperature was relatively colder than today	Yuan
CE 383	Hexi region in the northwest of China	historical documents	warm	*Morus* sp. was growing very well	Fang, 1974
CE 348–413	the central and eastern of the Tibetan Plateau in the northeast of China	tree-rings	fluctuated greatly	the temperature of CE 348——366 is the coldest apex of 2485a in the past, while the temperature of CE 401——413 exceeds today	Liu et al., 2009
CE 600–720	mid-east area in China	historical documents	warmer than today	the periods of warmer above 0.5 °C in winter than 1961–2000 were CE 601-620、CE 641-660、CE 702–720	Ge et al., 2010a
CE 500——720	the Tibetan Plateau in the northeast of China	the ice core of temperature and the accumulation of precipitation ice	from warm to wet	the warm period was CE 500——600, and the wet period was CE 561——720	Yao et al.,1996
CE 250–640	Urumqi River in Xinjiang in the northwest of China	pollen,Magnetic susceptibility, loss on ignition and particle size analysis	cold	High-precision analysis of the sedimentary profile indicates that between CE 250 and 640, the dominant vegetation around the lake was desert grassland, which is indicative of a cold climate period	Yan et al., 2004
CE100-500	the Niya section of southern Xinjiang in the northwest of China	the frequency rate susceptibility, carbon isotope of carbonates, geochemical elements and pollen	warm	the ratios of certain elements and the variations in $\delta^{13}C$ and XIf content, all point towards significant warmth and aridity during this period	Zhong et al., 2001
CE100-500	Niya profile and the Tarim Basin n in the northwest of China	pollen and geological record	warm and dry	By examining multiple environmental proxy indicators warm and dry	Shu et al., 2003

ancient communities selected *Populus* sp. and *Salix* sp. for their wood objects were traditional. *Populus* sp. and *Salix* sp. were not only made as weapon such as arrow shaft and self-bow, but also as daily tools such as plate, hand drill, wooden stick and so on. Besides, in the cave site in Türkiye(Gülden et al., 2025), the basketmaking were made by *Taxus baccata* L. (European yew) and *Acer campestre* L.(field maple). The relatively widespread practice of crafting daily tools from wood in handicraft workshops reflects how humans utilize natural resources to create functional objects, as well as the interplay between the environment and technology.

Populus sp. trees, known for their height and rapid growth, produce straight-grained, uniformly structured wood that is lightweight. They exhibit moderate dry shrinkage and possess low to medium strength and impact toughness, making them suitable for residential construction, general furniture, and everyday appliances in China(Cheng et al., 1992b). *Salix* sp., with its straight grain and fine, uniform structure, is lightweight, soft, yet strong and possesses notable toughness and elasticity. It also has good dry shrinkage and impact toughness, qualities that render it ideal for furniture, agricultural tools, construction, and daily necessities(Cheng et al., 1992c). Thus, the presence of Salicaceae wood products in both grottoes represents a deliberate selection, informed by the local vegetation and the intrinsic properties of the wood material.

5.2. Environment and vegetation

The wood samples discovered in Taitai 'er Grottoes and the Mazabha Grottoes were relatively few, and the identification results show that the species and categories of the samples were also relatively single, which were not conducive to our full discussion of the environment and vegetation combination of this area. However, the discovery of wood samples within the sites can also reflect the climatic environment and vegetation. Meanwhile, Xinjiang is a climate-sensitive area with many related studies. Combined with historical documents about plants and climate, we can still have some discussions on the environment and vegetation conditions at that time.

Studies have shown that from the 4th to 7th century CE, the climate was colder than now, but there was also a relatively short warmer period, although because of the monsoon, the eastern and central regions with the western regions in China were not completely synchronized, the whole area in China are not completely synchronized, they all experienced fluctuations in climate(Zhu, 1972; Zhang et al., 1994; Ge et al., 2010b). Besides the climate in the 3rd and 5th to 6th century CE were significantly cold, while the climate in the 4th century CE was relatively warmer in the western China(Ge et al., 2010; Yan et al., 2003; Xiang, 2023).

Such as the Table 4 shows, there were also some changes in climate from the 4th to 7th century CE, the overall climate trend was a process of change from cold to hot and then back to cold, but some small geographical units also had fluctuating changes of alternating cold and hot. This is due to the influence of geographical location and monsoons, and the climate change in the western and eastern regions of China is not synchronous.

A piece of *Morus* sp. charcoal was found in K7 in Taitai'er Grottoes, dated to CE 548 – 652. And because the natural distribution of the *Morus* sp. in China's Xinjiang region is limited today, given that *Morus* sp. trees require warm temperatures and adequate humidity for growth, the discovery of *Morus* sp. remains in Xinjiang could serve as an indicator of relatively warmer climatic conditions. And according to the related studies, the average annual temperature in northwest China was 0.7–0.9 °C higher and wetter than the present roughly between CE 630–640(Ge et al., 2010). So the *Morus* sp. was an important indicator feature of the climate fluctuation changes between the early and late periods of the Taitai 'er Grottoes.

The local vegetation composition and dominant species were significantly influenced by the climate. Identification of the samples found in the Taitai'er Grottoes and Mazabaha Grottoes suggest that *Populus* sp. and *Salix* sp. trees might be occupied a certain position of the vegetation composition in Kuča area. *Populus* sp. and *Salix* sp. trees mostly grow in river valleys, and according to field archaeological investigations, the Taitai 'er Grottoes are not far from the river valley. Moreover, *Populus* sp. and *Salix* sp. trees have good wood properties and were one of the main choices for wood utilization by ancestors. Besides there were some *Hippophae* sp., *Morus* sp., and *Elaeagnus* sp. with some shrubs and herbs vegetation.

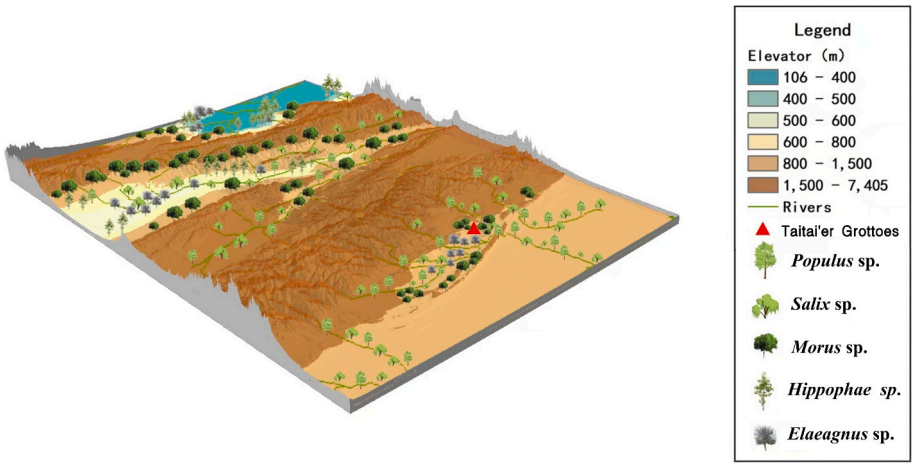

Fig. 5. Restoration of vegetation distribution around Taitai'er Grottoes.

Populus sp. are deciduous trees or small trees with approximately 62 species in China. They are considered a riparian tree species and can also be found in mountainous and hilly regions alongside the birch genus. Xinjiang is known for its extensive habitat and rich variety of poplar species resources. Based on external morphological characteristics, the poplar genus can be categorized into several groups, including the *Populus nigra* (black poplar) , *Populus lasiocarpa* (Large-leaf poplar) and *Populus euphratica*. *Salix* sp., part of the willow family, are predominantly shrubs with a few tree species, totaling about 520 species globally, mainly in the northern hemisphere's temperate zone. China is home to 257 species of *Salix* sp., found across all provinces and regions, with a notable presence in Xinjiang.

Populus sp. and *Salix* sp. are typically found in river valleys, while *Elaeagnus* sp. trees are adapted to Gobi beaches or dune lowlands at 400——660 masl, often near wet areas, fields, and roadsides. *Hippophae* sp. trees grow in river lowlands and open deciduous forests around 500 masl, and *Morus* sp. trees are found at higher elevations of 800–1500 masl in mountainous or forested regions. Based on the distribution environment of these trees, we can infer that the vegetation distribution at the time in the Taitai'er Grottoes,which was as depicted in Fig. 5.

However, it should be acknowledged that while *Picea* sp. have been found in some archaeological sites, such as the Adunqiaolu site(Wang and Cong, 2022), Yanghai cemetery(Jiang, 2022), Yuergou site(Jiang et al., 2013), and Gilzankele cemetery(Shen et al., 2015), we did not identify any *Picea* sp. in this study. We suspect this might be caused by two potential factors. On the one hand, Xinjiang, the largest province in China, is divided by mountain systems and basins surrounded by high mountains, forming a unique geomorphic feature of "three mountains and two basins". The climate system is complex and the natural environment is strongly unstable and transitional. The complex and diverse terrain leads to ecological niches with distinct vegetation. On the other hand, due to the special nature of the caves in this study, the sample size is small, which reduces the possibility of the presence of *Picea* sp. in the samples. Further work on vegetation reconstruction both at these cave sites and other sites in the region are needed to fully understand the wood resource use and paleoclimate in the 4^{th}- 7^{th} centuries CE.

6. Conclusion

Based on the analysis of wood charcoal from fireplaces, wooden structural elements, and wooden products from the Taitai'er and Mazabaha Grottoes, we argue that the monastic communities selectively used small branches of *Populus* sp. *Salix* sp., and *Hippophae* sp. for fuel. *Populus* sp. and *Salix* sp. wood were selected for building in the inside of caves and making domestic wooden products. From comparative paleoclimate data and historical documents, we infer the climate of the Kuča region from 4^{th} to 7^{th} centuries CE was changable from cold to warm and to cold, during 7^{th} centuries CE it was warmer than today. The *Populus* sp. and *Salix* sp were the important part of the vegetation alongside with *Hippophae* sp.*Morus* sp., and *Elaeagnus* sp.

CRediT authorship contribution statement

Fan Yang: Writing – original draft, Software, Formal analysis, Data curation. **Lihui Miao:** Writing – original draft. **Ji Wang:** Writing – original draft. **Xin Yan:** Data curation. **Anaerguli aobulikasimu:** Writing – original draft. **Yin Jia:** Visualization, Resources, Methodology.

Data availability

The data that has been used is confidential.

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