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Early Millet Use and Its Environmental Impact Factors in Northern Shaanxi, Northwest China

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Abstract: Northern Shaanxi is important in understanding the ancient use and northward spread of foxtail millet (*Setaria italica*) and broomcorn millet (*Panicum miliaceum*). Nonetheless, due to the lack of millet remains, AMS radiocarbon data, and environmental background, the emergence, crop structure, and environmental factors of millet use in northern Shaanxi remain ambiguous. To address this knowledge gap, a systematic survey was conducted along the Beiluo River. Forty-two relic units at 19 Neolithic sites were selected for analysis through phytolith, AMS radiocarbon dating, and spatio-temporal approaches. Phytolith and AMS radiocarbon dating analyses traced the utilization of millets in the Beiluo River to 6280 cal. BP. In addition, broomcorn millet was more prevalent than foxtail millet during the Neolithic period, although the prevalence of the latter increased during the late Longshan period. Spatio-temporal analysis demonstrated that millets initially appeared in the Beiluo River during the Yangshao period, gradually moving away during the Longshan period, which was probably first related to the nearest rivers and then the spread of cattle and sheep. However, the millet cultivation altitude remained at 1400 m throughout the Yangshao and Longshan periods. Collectively, these findings provide evidence for the use and northward spread of millets in northwest China.

Keywords: northern Shaanxi; Neolithic period; millet farming; crop structure; environmental factors; phytolith analysis

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1. Introduction

As a turning point in the development of human society, the emergence of agriculture in a region brings change to the economic structure, social ideology, and organization of the region, in addition to accelerating cultural exchange and integration and setting a solid economic foundation for the further formation and development of civilization [1–5]. Historically, millet formed the core crop in Northern China; therefore, the study of its origin, spread, domestication, and the different developmental processes of foxtail millet (*Setaria italica*) and broomcorn millet (*Panicum miliaceum*) is of great significance to understanding the formation and development of Chinese civilization [6–9].

Recently, with the establishment, improvement, and application of identification standards for carbonized millet seeds, starch grains, and phytoliths [10–12], our ability to trace the origin and spread of millet use and delimit the history of millet use in China has increased significantly (Figure 1). AMS radiocarbon data from carbonized foxtail and broomcorn millets, or cotemporaneous carbonized annual plants, show that the utilization of millets in China dates back to the Shizitan site [7] in Shanxi Province and the Nanzhuangtou site [8] in Hebei Province. Direct evidence of carbonized millet seeds was first found at

the Donghulin site (10,500–9500 cal. BP) in Beijing, North China [13]. Between 8500 and 7000 cal. BP, millet continues to increase significantly. These finds are concentrated in the middle and lower reaches of the Yellow River, West Liaohe River, Haidai, and Weihe River areas [6,10,14–20]. The crop structure appears to have been dominated by broomcorn millet, with foxtail millet being of secondary importance. From 7000 to 4000 cal. BP, the number of archaeological sites found to contain traces of millet increased over a wider geographical area [21–25]. This includes areas to the south and southeast [26–32], northeast [14,15,20,33], and northwest [34–37] of the original region in which such crops were found in earlier periods. To the north, millet spread into the northern Shaanxi region at about 5500 cal. BP [38], including the modern-day city districts of Yan'an and Yulin, both of which are located within the farming-pastoral zone. This means that northern Shaanxi is a key area for understanding the northward propagation of millet [39].

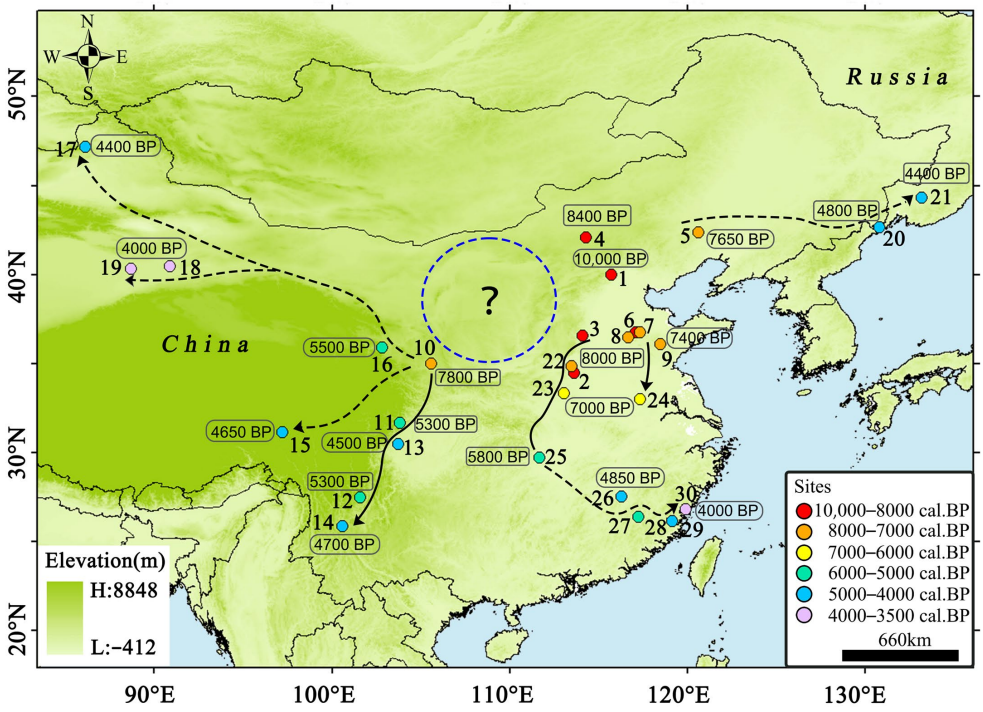


Figure 1. Archaeological sites where archaeobotanical research with millet was executed and the main areas for the spread of millet in China. The dashed arrows indicate the possible routes; the solid arrows indicate the relatively certain routes.

The distribution of early Neolithic sites with millet remains: 1. Donghulin (10,192–9766 cal. BP [13]); **the middle reaches the region of the Yellow River**; 2. Peiligang (8500–7000 cal. BP [18]); 3. Cishan (10,300–7500 cal. BP [6]); **the West Liaohe River area**: 4. Yumin (8400–7600 cal. BP [20]); 5. Xinglonggou location 1 (7650 cal. BP [14]); **the Haidai area**: 6. Zhangmatun (9025–8410 cal. BP [18]); 7. Xihe (8100–7300 cal. BP [40]); 8. Yuezhuang (7796–7666 cal. BP [16]); 9. Bianbiandong (7400–6900 cal. BP [9]); **the Weihe River area**: 10. Dadiwan (7800–7350 cal. BP [10]).

The main spread routes of millet in China. (1) Southwest [25,26,41]: From 6000 to 4000 cal. BP years ago, the millet farming in Gansu-Qinghai regions continued to develop and expand southward, then affected the northwest of the Sichuan basin [21], further moved southward to the Sichuan basin and Hengduan mountain region [23,26], Yun-gui plateau area [24], and southern Tibetan plateau [25]. **Representative sites**, 11. Yingpanshan (5300–4600 cal. BP [21]); 12. Guijiabao (5300–4883 cal. BP [26]); 13. Baodun (4500–3700 cal. BP [42]); 14. Baiyangcun (4726–4522 cal. BP [41]); 15. Karuo (4650–4250 cal. BP [43]). **(2) Northwest** [44,45]: At about 5000 cal. BP, millet farming in Gansu-Qinghai regions expanded westward to the western Hexi Corridor and then went westward to

the Xinjiang region [35–37]. **Representative sites**, 16. Hulijia (5583–5316 cal. BP [34]); 17. Tongtiandong (4410–4225 cal. BP [37]); 18. Gumugou (3835–3692 cal. BP [36]); 19. Xiaohe graveyard (3515–3377 cal. BP [35]). **(3) Northeast** [33]: The millet probably spread from the West Liaohe region to the Far East of Russia. **Representative sites**, 20. Gvozdevo 4 (4821–4529 cal. BP [33]); 21. Rettikhovka-Geologicheskaya (4406–4014 cal. BP [33]). **(4) South and Southeast** [22,27,28,31]: The early spread of millets began in the Peiligang culture area in Henan province and the Beixin culture area in Shandong province and then spread to the Dazhangzhuang site in the Nanyang basin of Henan province [22], the Chengtoushan site in Hunan province, and the Shuangdun site in Anhui province [27]. It probably went through Jiangxi province and continued to spread to the southeast coast and south China, including Nanshan, Tanshishan, Baitoushan, and Huangguansha sites [29–32]. **Representative sites**: 22. Zhuzhai (8010–7678 cal. BP [19]); 23. Dazhangzhuang (6901–6442 cal. BP [22]); 24. Shuangdun (7300–6800 cal. BP [27]); 25. Chengtoushan (5800 cal. BP [46]); 26. Guodishan (4849–4414 cal. BP [28]); 27. Nanshan (5000 cal. BP [47]); 28. Tanshishan (4725–4351 cal. BP [31]); 29. Baitoushan (4762–4691 cal. BP [30]); 30. Huangguashan (3976–3840 cal. BP [48]).

At present, flotation remains the main method through which to study Neolithic millet use in northern Shaanxi. This study examines data collected from thirteen sites, including Shimao [49,50], Zhaimaoliang [51], Muzhuzhuliang [52], Shengedaliang [52], Wangyangpan [53], Yangjiesha, Dagujie, Dayangwa, Miaoliang, Yuangeda, Huoshiliang, Jiadamao [54], and Panshang [38]. Of the thirteen sites, twelve are located in Yulin City in northern Shaanxi, while one is located in Yan'an City in northern Shaanxi. In terms of age, foxtail and broomcorn millets appeared in northern Shaanxi during the late Yangshao period. However, direct AMS radiocarbon dating from the carbonized millet still lacks. As for the crop structure, broomcorn millet was the main crop, and foxtail millet was the auxiliary from early Yangshao culture to early Longshan culture. The percentage of foxtail millet and broomcorn millet is debatable during the late Longshan culture; that is, foxtail millet was dominant in terms of unearthed probability and percentage content, whereas broomcorn millet was dominant from the viewpoint of 1000-grain volume. Regarding the reason for the change in crop structure, scholars have speculated that it was closely related to environmental changes [55]. Since the northern Shaanxi region is located in the farming-pastoral zone, it is especially vulnerable to environmental changes. In summary, the study of millet remains in northern Shaanxi provides important clues for understanding millet use during the Neolithic period. However, the lack of AMS radiocarbon dating, numbers, and environmental background materials in millet limits our understanding of the emergence, crop structure, and environmental factors that led to millet use in northern Shaanxi.

Systematic regional archaeological surveys can provide direct evidence of regional plant use and can be used to comprehensively evaluate crop species and diachronic change characteristics in a certain archaeological cultural region [56,57]. Since the upper reaches of the Beiluo River and Yan'an City in northern Shaanxi represent a significant lacuna in our understanding of the northward spread of millet during this period, they were selected for our present survey. During the course of the survey, neolithic relics and cultural sediments were collected. Then the cultural sediments were analyzed by flotation and phytolith. The carbonized millet remains recovered from the flotation were sent to test the date by AMS radiocarbon dating to determine the occurrence time, and the phytoliths recovered from the phytolith analysis were used to estimate millet's diachronic changes in northern Shaanxi. Finally, ArcGIS spatial analysis was employed to process the spatial features of millet in northern Shaanxi and enhance our understanding of subsistence strategies and social development processes in the agro-pastoral belt of northern China.

2. Materials and Methods

2.1. Research Area

Northern Shaanxi, which is located between the Eurasian Steppe and Central Plains cultural zones, consists of the modern city districts of Yan'an and Yulin Cities in Shaanxi

Province. This region is an agro-pastoral area. Over 5500 Neolithic sites have been discovered in northern Shaanxi since the 1950s [58]. Two ultra-large prehistoric sites in northern China, Lushanmao (4350–4100 cal. BP [59]) and Shimao (4200–3800 cal. BP [60]) were identified. Thus, the northern Shaanxi area is important for research on Chinese civilization. The prehistoric archaeological cultures in northern Shaanxi, including the Yangshao and Longshan cultures, are generally divided into five phases: the early Yangshao culture (approximately 7000–6000 cal. BP), the middle Yangshao culture (approximately 6000–5500 cal. BP), the late Yangshao culture (approximately 5500–5000 cal. BP), the early Longshan culture (approximately 5000–4500 cal. BP), and the late Longshan culture (approximately 4500–4000 cal. BP) [61–63]. There are few sites attributed to the early Yangshao culture, so there is limited information on crop use during this period. In contrast, several sites attributed to the Middle and Late Yangshao cultures have been fully or partially excavated. It is during the middle and late Yangshao cultures that evidence for social stratification started to appear in the archaeological record. This coincides with millet agriculture becoming the mainstay of the economy. In the Longshan cultural period, there is further evidence for differentiated social stratification, while urban settlements start to appear in the archaeological record. In addition to millets, soybeans (*Glycine max*) and a small amount of rice (*Oryza sativa*) have also been identified in the bioarchaeological record during the Longshan cultural period, indicating an increase in the complexity of agriculture in the region [64]. These rich and diverse crops laid a solid foundation for the rise and development of ultra-large settlements, such as the Lushanmao and Shimao sites, during the Longshan cultural period [64].

Currently, Yan'an City in northern Shaanxi is the most scarce area for archaeobotanical research in northern Shaanxi. Based on the third national cultural relic census data of northern Shaanxi and the working foundations of the Yan'an Institute of Cultural Relics, the upper reaches of the Beiluo River, the largest river in Yan'an city, were selected as the investigating area. The Beiluo River, also known as the Luohe River, is the second branch of the Yellow River and the primary branch of the Weihe River. The Beiluo River, the largest river in Yan'an City, runs through 19 counties/cities in Shaanxi and Gansu Provinces, northwest China. The upper reaches of the Beiluo River (107°32′40″ E–108°32′45″ E, 36°44′53″ N–37°19′28″ N) belong to mid-temperate sub-humid semi-arid zones with typical temperate continental monsoon climate characteristics. It is cold and dry in the winter, and strong winds and drought are common in the spring. The mean temperature and precipitation in January and July are −7.2 °C, 2.7 mm, and 21.9 °C, 92 mm, respectively (available online: https://data.cma.cn/; accessed on 18 January 2023). Alternating floods and droughts occur in the summer since the loess plateau leads to fast run-off and limited retention within the soil. The autumn is cool and wet [65]. With an average elevation of 1500 m, the upper reaches of the Beiluo River have landforms of ravines, ridges, and knolls and are located in the center of the Loess Plateau hilly and gully region [66]. In modern times, most of the land on the slopes has been plowed and converted into farmland. Modern crops are ripened once a year, including maize (*Zea mays*), potato (*Solanum tuberosum*), soybean, foxtail millet, broomcorn millet, common wheat (*Triticum aestivum*), and rice.

2.2. Research Materials

Working in collaboration with the Yan'an Institute of Cultural Relics, a field survey of over 130 Neolithic sites in the upper reaches of the Beiluo River was undertaken. Of these 19 sites, 19 were selected as research targets based on the exposure conditions of the relics (Figure 2). All 19 of these sites are in close proximity to the Beiluo River, within the landform of the Loess Plateau. The cultures from these 19 sites included those from Yangshao and Longshan, which were divided into five types: early Yangshao, middle Yangshao, late Yangshao, early Longshan, and late Longshan. During the field survey, most relics at the 19 sites were exposed to the Loess Fault and buried 10–220 cm below the fault surface. Based on the number of visible relics and whether they could be excavated, one to six study samples were collected from each site. We collected samples from 42 relic units

from 25 cultural stages across 19 sites. Of the 42 phytolith samples collected, 38 were ash pit samples, two pottery kiln samples, one house site sample, and one stove sample (Table 1).

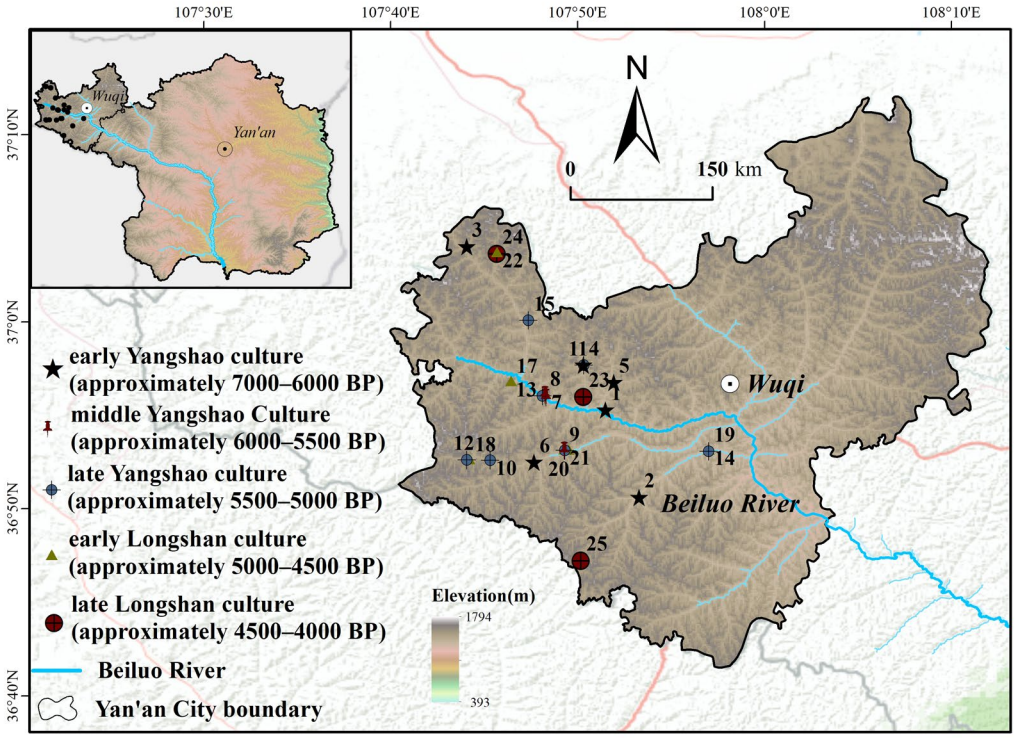


Figure 2. The distribution of 25 cultural stages of the 19 sites in the upper reaches of the Beiluo River in Yan'an City, northern Shaanxi.

Table 1. The number of samples collected from different cultural stages of the sites in the upper reaches of the Beiluo River in Yan'an City, northern Shaanxi.

Cultural Stages	Early Yangshao	Middle Yangshao	Late Yangshao	Early Longshan	Late Longshan	Total
Number of sites	6	3	8	6	3	19
Number and unit of relics from different sites	9, (Baitun H1, H3; Shuifantai F1; Panfenzui H1, H2; Majian H1, H4; Zhangcheng H1; Yaoqiao Miaozui H1	3, (Sigou Yapantai H1; Zhangwanzi H3; Huaqu H1)	17, (LiguaiGou H1, H2; Majian H2; Tashanlaing Z1, H1, H2 ① and ②; Zhang Wanzi H1 ①–④, H2; Fengzimao Y1; Pipa H2; Huaqu H2, Y1; HuangdimaoH1)	7, (Huangdimao H1, H2; Yuanshan H1, H2; Fengzimao H1; Miaogou H1; Huaqu H4; Yingpanliang H2)	6, (Shuwa H1, H2, H3; Yingpanliang H1; Xiayuanmao H1 and H2)	42
Number of phytolith samples	9	3	17	7	6	42

Early Yangshao cultural sites: 1. Baitun; 2. Shuifantai; 3. Panfenzui; 4. Majian; 5. Zhangcheng; 6. Yaoqiao Miaozui. **Middle Yangshao cultural sites**: 7. Sigou Yapantai; 8. Zhangwanzi; 9. Huaqu. **Late Yangshao cultural sites**: 10. Li Guaigou; 11. Majian; 12. Tashanliang; 13. Zhangwanzi; 14. Fengzimao; 15. Pipa; 16. Huaqu. **Early Longshan cultural sites**: 17. Huangdimao; 18. Yuanshan; 19. Fengzimao; 20. Miaogou; 21. Huaqu; 22. Yingpanliang. **Late Longshan cultural sites**: 23. Shuwa; 24. Yingpanliang; 25. Xiayuanmao.

Archaeological relic dating and AMS radiocarbon dating were used together in our study. The relics for dating included pottery chips unearthed from 19 sites and samples for AMS radiocarbon dating collected from 10 sites. To improve dating accuracy, annual

carbonized foxtail or broomcorn millet seeds were used for AMS radiocarbon dating. Field sample collection followed three principles: First, samples should be collected from various cultures and landforms at these sites. Second, the sampling units for the relics and the cultural attributes of the stratum should be clear. Third, the sampling stratum had clear boundaries with no evidence of disturbance [67].

2.3. Research Methods

2.3.1. Phytolith Analysis

Phytolith extraction, identification, and analysis were performed at the Environmental Archaeology Laboratory of Northwest University, employing the experimental system established by Wang and Lu [68]. The collected sediment samples from the cultural layers were weighed (5 g each), a total of 30% H_2O_2 was added to remove organic matter, and the samples were then washed with water bath heating and ultrapure water. Stone pine spore tablets (10,315 ± 846 grains/pc) were also added and used for quantity statistics. Next, 10% HCl was added to remove calcium impurities and washed to a neutral pH. $(NaPO3)_6$ was added to disperse the clay impurities. Then, a heavy liquid of 2.35 g/cm^3 $ZnBr_2$ was added, and the supernatant containing the phytolith granules was decanted into a fresh tube, centrifuged, washed twice with ultrapure water, and washed once with anhydrous ethanol to obtain a phytolith residue. Phytolith slides were prepared by mounting the recovered residue in a neutral resin and fixing it with a cover glass. The prepared phytolith slides were then placed on a flat surface, dried, observed, identified, counted, and photographed using a Leica DM 750 microscope at 400× magnification. To ensure data accuracy, no less than 500 phytoliths were observed per sample. The identification and classification of phytoliths was mainly conducted by referring to the accumulated modern phytolith database of the laboratory and pictures published in similar studies [11,69,70].

2.3.2. Dating Methods

Archaeo-cultural and AMS radiocarbon dating methods were used to date the samples. During the field survey, we initially determined the archaeological age of the pottery samples collected from the ash pit and cultural layer sediments. We then sent 12 samples of carbonized foxtail or broomcorn millet seeds to Beta Lab, USA, for AMS radiocarbon dating. The date measured was calibrated using OxCal 4.4 (https://c14.arch.ox.ac.uk/oxcal/OxCal.html; accessed on 18 January 2023) and the IntCal 20 curve [71]. 1–sigma error was applied. The confidence intervals were 1σ (68.3%) and 2σ (95.4%).

2.3.3. Environmental Factors Analysis

Spatial distribution characteristics: The spatial aggregation characteristics of millet remaining in the upper reaches of the Beiluo River were obtained by analyzing geographic location data using Inverse Distance Weight (IDW). The concrete steps are as follows: (1) according to the AMS radiocarbon dating results of millet remains in the study area, the weight coefficient of the neighborhood cell increases as the age increases and decreases as the age decreases; (2) the distance between known and unknown points is processed by smoothing to assign values to unknown points and obtain the temporal change characteristics of the millet remains.

Surface and Hydrology Analysis: To determine the geographic characteristics of millets in the upper reaches of the Beiluo River in northern Shaanxi, buffer analysis in ArcGIS was used to process the landscape features based on the elevation of millet remains. We also calculated the distances between the millet remains and the nearest river. Considering the low probability of diversion of the middle and upper reaches of the ancient Yellow River during this period [72,73], we used the Euclidean distance from the sites to present-day rivers. DEM data with a resolution of 90 m, a 1:250,000 scale China River classification dataset, and a 1:100,000 scale China Lake dataset extracted from the mirror site conducted and published by the Computer Network Information Center, Chinese Academy of Science (http://www.gscloud.cn; accessed on 18 January 2023) were used for analysis in this study.

The longitudes and latitudes of the archaeological sites were based on coordinates obtained during field surveys.the The principle was as follows: assuming that the coordinates of the archaeological site are (x_1,y_1), the coordinates of the nearest river are (x_2, y_2), and the shortest distance between the two is $\rho = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$.

3. Results

3.1. Chronostratigraphic Framework

The AMS radiocarbon dating results of the 12 samples taken from ten sites in the upper reaches of the Beiluo River in Yan'an City in northern Shaanxi are shown in Table 2. The dates ranged from 6283–3831 cal. BP. After considering the unearthed pottery types associated with the samples, it can be concluded that 42 units of samples from 19 sites trace back to the Neolithic period, while the cultures can be divided into five stages: early Yangshao culture, middle Yangshao culture, late Yangshao culture, early Longshan culture, and late Longshan culture (Tables 1 and 2).

Table 2. AMS dating radiocarbon results of carbonized millet seeds in the upper reaches of the Beiluo River in Yan'an city, northern Shaanxi.

Lab Code	Context No	Dated Material	Uncalibrated ^{14}C Date (BP)	Calibrated Date (cal. BP)	
				1σ (68.2%)	2σ (95.4%)
BA604998	Shuifantai F1	Broomcorn millet	5380 ± 30 BP	6275 (30.8%) 6236 6215 (24.1%) 6182 6141 (13.3%) 6120	6283 (66.0%) 6173 6149 (17.2%) 6113 6077 (2.9%) 6060 6049 (9.4%) 6009
BA605000	Panfenzui H2	Broomcorn millet	5030 ± 30 BP	5891 (46.5%) 5815 5760 (21.8%) 5722	5898 (87.9%) 5707 5694 (7.6%) 5661
BA604999	Majian H1	Foxtail millet	4920 ± 30 BP	5658 (68.3%) 5595	5718 (95.4%) 5591
BA605001	Huaqu H1	Foxtail millet	4470 ± 30 BP	5278 (45.9%) 5169 5134 (11.9%) 5103 5067 (9.3%) 5041 4997 (1.2%) 4993	5289 (50.7%) 5155 5148 (35.5%) 5025 5014 (9.2%) 4975
BA583981	Liguaigou H2	Broomcorn millet	4520 ± 30 BP	5302 (14.3%) 5271 5185 (28.4%) 5126 5109 (25.6%) 5055	5309 (31.3%) 5212 5196 (64.1%) 5050
BA605002	Tashanliang H2: ①	Foxtail millet	4430 ± 30 BP	5295 (2.6%) 5248 5233 (2.6%) 5223 5216 (8.9%) 5191 5052 (50.2%) 4960 4926 (2.2%) 4917 4895 (1.8%) 4887	5227 (23.6%) 5176 5133 (4.3%) 5104 5061 (67.5%) 4873
BA605004	Huangdimao H1	Foxtail millet	4360 ± 30 BP	4960 (30.0%) 4925 4918 (18.6%) 4893 4888 (19.7%) 4865	5034 (6.1%) 5008 4979 (89.3%) 4852
BA605003	Huaqu H2	Foxtail millet	4320 ± 30 BP	4957 (16.2%) 4935 4880 (52.1%) 4842	4962 (95.4%) 4838
BA609018	Xiayuanmao H1	Foxtail millet	3710 ± 30 BP	4140 (5.3%) 4131 4091 (17.7%) 4064 4048 (45.3%) 3986	4150 (94.2%) 3974 3941 (1.2%) 3933
BA605006	Shuwa H1	Foxtail millet	3700 ± 30 BP	4087 (18.8%) 4061 4051 (49.5%) 3985	4148 (9.6%) 4115 4099 (82.4%) 3968 3945 (3.4%) 3929
BA605005	Yingpanliang H1	Foxtail millet	3640 ± 30 BP	4061 (4.6%) 4052 3985 (63.7%) 3899	4084 (18.0%) 4031 4008 (76.2%) 3870 3861 (1.3%) 3849
BA609019	Xiayuanmao H2	Foxtail millet	3600 ± 30 BP	3967 (15.4%) 3946 3928 (46.9%) 3869 3860 (6.0%) 3850	4060 (0.7%) 4052 3985 (94.8%) 3831

3.2. Results of Phytolith Analysis

Of the 42 phytolith samples collected from 19 sites, 24,823 phytolith grains and 24 phytolith types were identified. Two types of crop phytoliths were identified: interdigitating of η-type phytoliths from the husks of broomcorn millet (Figure 3c,d) and interdigitating of Ω-type phytoliths from the husks of foxtail millet (Figure 3a,b). Other phytolith types were identified as Rondel (Figure 3h), Crenate (Figure 3i), and elongate dendritic (Figure 3g) in the subfamily Pooideae; Bilobate (Figure 3o), Polylobate (Figure 3p), and Cross (Figure 3q) types in the subfamily Panicoideae; Bulliform Flabellate (Figure 3l) and Long Saddle (Figure 3k) types in the subfamily Bambusoideae; Short Saddle (Figure 3j) type in the Eragrostidoideae; and Reed Bulliform (Figure 3m) type in the Arundinoideae. In addition, there are polyhedral types (Figure 3v,w) and "Y" shapes (Figure 3x) from woody plants, as well as the acute bulbosus (Figure 3r), elongate entire (Figure 3s), elongate dentate (Figure 3t), fan (Figure 3n), tracheary (Figure 3y), and silicified stomata (Figure 3z) in plants, and a few ferns (Figure 3aa), diatoms (Figure 3ab,ac), and sponge spicules (Figure 3ad) were also found.

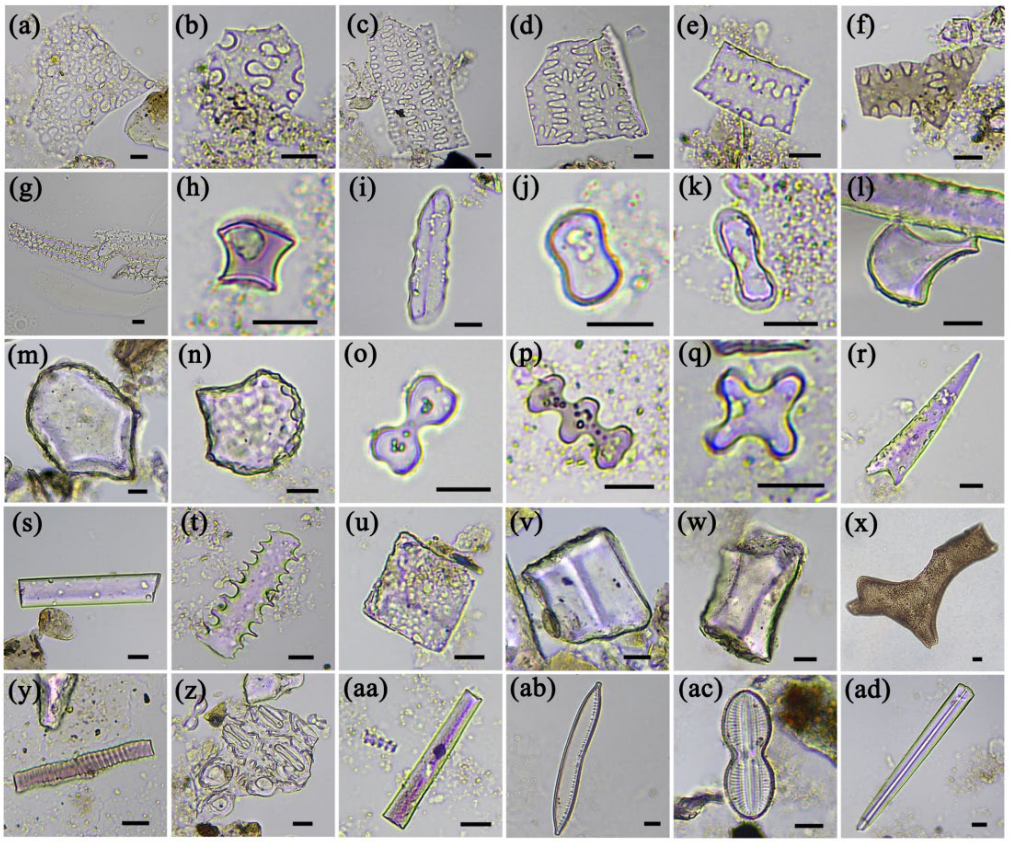


Figure 3. Phytolith types identified from Neolithic sites in the upper reaches of the Beiluo River in Yan'an city, northern Shaanxi. (**a**,**b**) Interdigitating Ω-type; (**c**,**d**) Interdigitating η-type; (**e**,**f**) Interdigitating; (**g**) Elongate Dendritic; (**h**) Rondel; (**i**) Crenate; (**j**) Short Saddle; (**k**) Long Saddle; (**l**) Bulliform Flabellate; (**m**) Reed Bulliform; (**n**) Fan; (**o**) Bilobate; (**p**) Polylobate; (**q**) Cross; (**r**) Acute Bulbosus; (**s**) Elongate Entire; (**t**) Elongate Dentate; (**u**) Blocky; (**v**–**x**) woody plants: (**v**,**w**) Polyhedral; (**x**) "Y" shape; (**y**) Tracheary; (**z**) Silicified Stomata; (**aa**) Ferns; (**ab**,**ac**) Diatom; (**ad**) Sponge Spicules (scale bar: 10 μm).

The combination of phytolith types at different cultural stages of the Neolithic sites in the upper reaches of the Beiluo River was similar; however, the percentages and occurrence probabilities of phytoliths varied (Table 3 and Figure 4). During the Yangshao culture period, the crops found in 29 relic units in the upper reaches of the Beiluo River were foxtail and broomcorn millet. To clarify the overall crop structure during the Yangshao culture

period, we analyzed the crop phytoliths separately and calculated the relative percentages and occurrence probabilities of each crop (Table 3). These results suggest that both the ratio of broomcorn millet in the overall crop structure and its occurrence probability were higher than those of foxtail millet during the Yangshao culture period. During the Longshan culture period, the crops collected from the sites were still foxtail and broomcorn millet; broomcorn millet still occupied a higher ratio in the overall crop structure and had a higher occurrence probability than foxtail millet. However, the proportion of foxtail millet increased from 0.02% during the early Longshan cultural period to 0.46% during the late Longshan cultural period.

Table 3. Phytolith concentration, types, and percentages in all cultural stages in the upper reaches of the Beiluo River in Yan'an city, northern Shaanxi.

Cultural Stages	Early Yangshao	Middle Yangshao	Late Yangshao	Early Longshan	Late Longshan
Average concentration of phytoliths (million grains/g)	2.48	2.59	2.10	0.67	2.58
Phytolith types (species) identified	22	18	24	23	23
Total number of phytoliths	5353	1742	10,055	4383	3290
Total number of identifiable phytoliths	5157	1638	9550	4173	3157
Types of crops identified	Foxtail millet & broomcorn millet	broomcorn millet	Foxtail millet & broomcorn millet	Foxtail millet & broomcorn millet	Foxtail millet & broomcorn millet
Percentage of Foxtail millet	0.13%	0%	0.10%	0.02%	0.46%
Percentage of broomcorn millet	1.01%	0.46%	0.64%	0.34%	2.40%
Occurrence probability of Foxtail millet	66.67%	0%	41.18%	12.50%	50%
Occurrence probability of broomcorn millet	66.67%	66.67%	76.47%	37.50%	83.33%

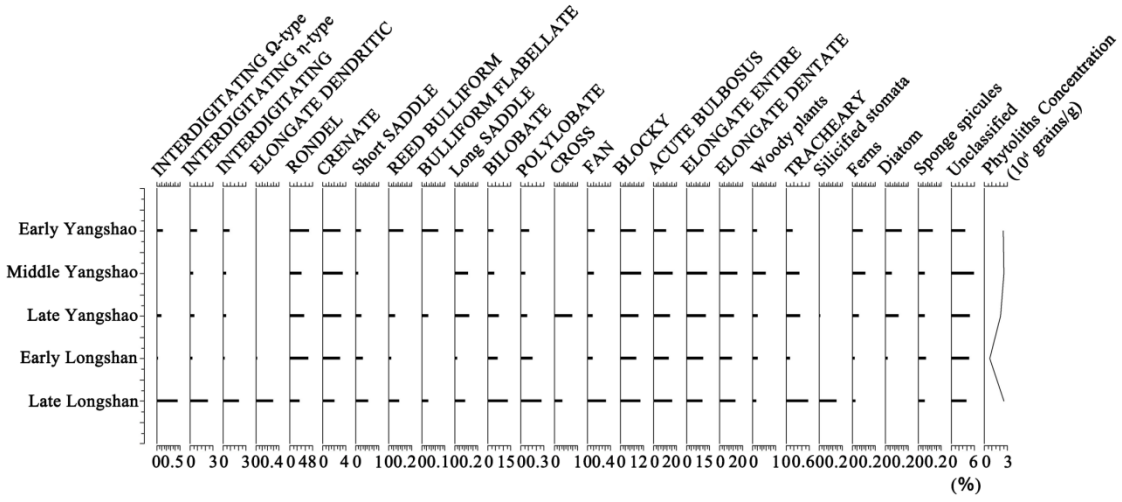


Figure 4. Changes in percentages of phytolith types identified in various cultural stages of the Neolithic age in the upper reaches of the Beiluo River in Yan'an city, northern Shaanxi.

Among the other phytolith types, the Rondel phytoliths had the highest percentage (above 20%) at all cultural stages of the Neolithic sites (Figure 4).

3.3. Geographical Characteristics

3.3.1. Spatial Distribution

According to the kernel density analysis (Figure 5), in the upper reaches of the Beiluo River, millet agriculture exhibits a trend of diffusion from the valley zones of the Beiluo River and its tributaries towards the surrounding regions. The agricultural activities of foxtail and broomcorn millets in the vicinity of the Beiluo River and its tributaries have a longer history than those situated farther away. Based on chronological records, around 6283 cal. BP, foxtail, and broomcorn millets were found simultaneously at the Shuifantai site, a tributary of the Beiluo River. Over time, the remains of the foxtail and broomcorn millets gradually spread to the surrounding areas. By the late Longshan culture, approximately 4000 cal. BP, the areas where foxtail and broomcorn millet existed had gradually expanded to the Xiayuanmao and Yingpanliang sites in the southwest, located in the northernmost part of Wuqi County, Yan'an City.

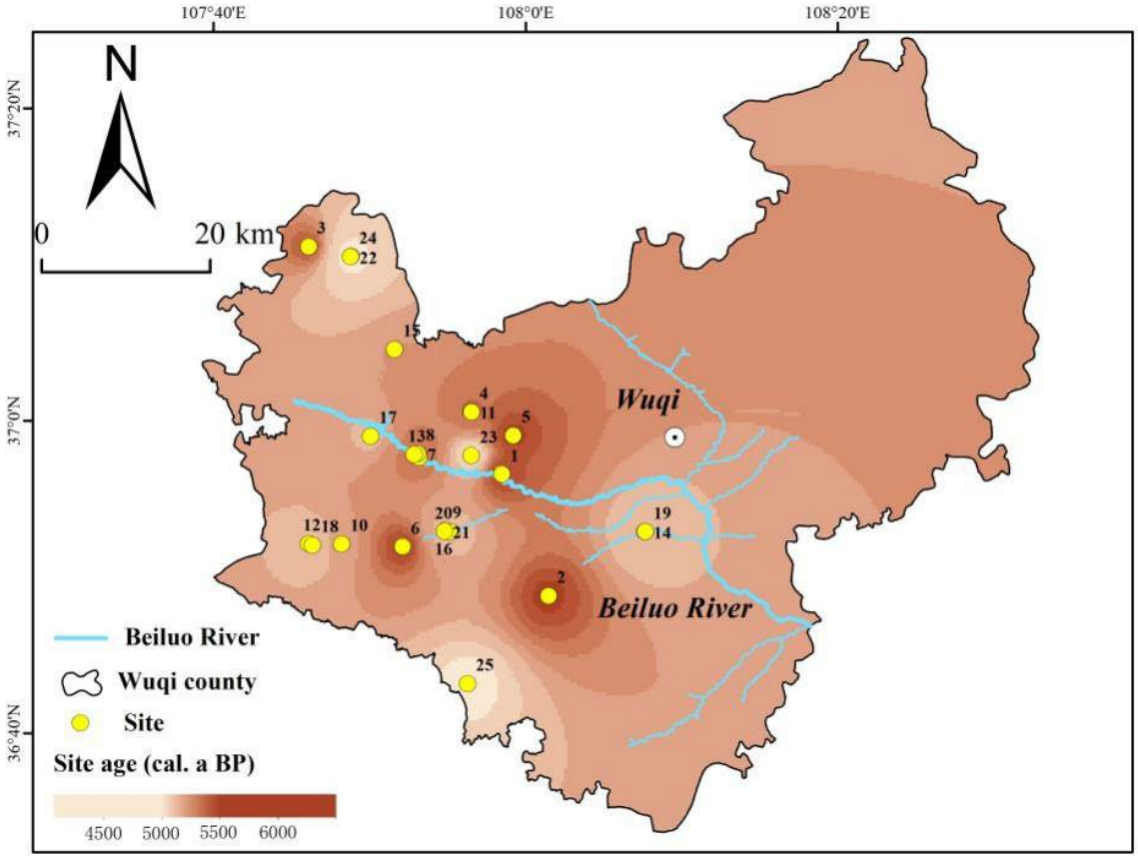


Figure 5. Temporal interpolation results of sites with millet remains in the upper reaches of the Beiluo River in Yan'an city, northern Shaanxi.

3.3.2. Surface and Hydrology Characteristics

As shown in Figure 6a, we extracted the elevation of each site using the latitude and longitude of the sites in ArcGIS. Among the 25 cultural stages with millet remains, the highest elevation was 1628 m from the Xiayuanmao site of the late Longshan culture, and the lowest elevation was 1319 m from the Fengzimao site of the late Yangshao culture. During the Yangshao culture period, the average altitude of millet remains was 1428.3 m, while during the Longshan culture period, the average altitude of millet remains increased to 1451.0 m.

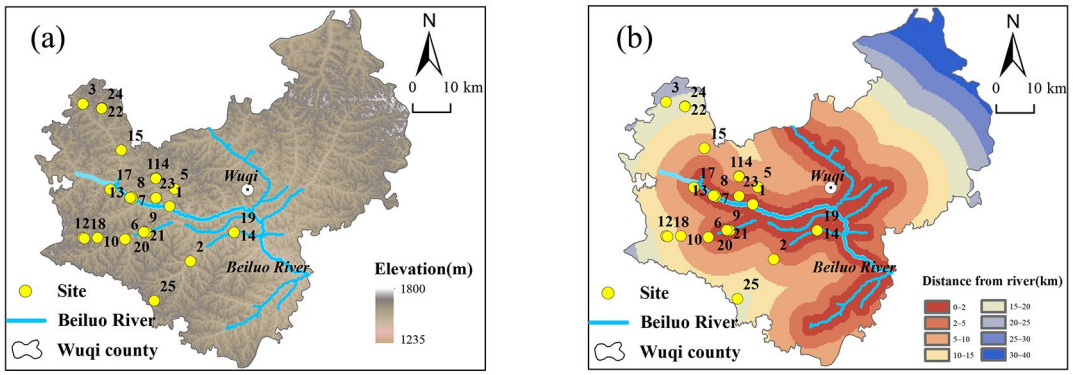


Figure 6. (**a**) Elevation and (**b**) distance from the nearest river of sites with millet remains in the upper reaches of the Beiluo River in Yan'an city, northern Shaanxi.

The Euclidean distance analysis in ArcGIS was used to analyze the correlation between the sites with millet remains in the upper reaches of the Beiluo River and the locations of the nearest rivers. As shown in Figure 6b, most sites from the Yangshao cultural period were scattered along the course of the rivers in a linear or forked pattern and near the Beiluo River or its tributaries. However, sites from the Longshan cultural period gradually moved away from the river. Most archaeological sites (64.0%) were within a 7-km radius of the nearest river (Table 4). The number of sites decreased steadily with increasing distance from the nearest river, and only one site (4.0%) was located >20 km from the nearest river. The average distance between sites with millet remains from the Yangshao cultural period and the nearest river was 6.564 km, whereas that for the Longshan cultural period was 9.788 km, indicating a difference of approximately 3.2 km.

Table 4. Distance from river for sites with millet remains in the upper reaches of the Beiluo River.

Distance (km)	Site Number	Proportion (%)
0–1	4	24.0
1–3	2	36.0
3–5	3	12.0
5–10	6	32.0
10–15	4	24.0
15–20	7	12.0
>20	2	4.0

4. Discussion

4.1. Changes in the Use of Millet in the Upper Reaches of the Beiluo River over Time

From the AMS radiocarbon dating results of carbonized foxtail and broomcorn millets, the ages of the eight sites were consistent with the archaeological chronology based on pottery typology; only the ages of the Panfenzui and Majian sites were 102 and 289 years younger than the archaeo-cultural chronology, respectively. Meanwhile, the results of the archaeological chronology show that the age of the archaeological stages of different cultures in northern Shaanxi is 200–300 years behind the corresponding stages in the Guanzhong, Central Plains, and Haidai areas [74]. Therefore, the remains taken from the upper reaches of the Beiluo River in northern Shaanxi can be used to discuss the use of millet in this region.

The Yangshao cultural period has previously been highlighted as a critical stage in the transition from millet farming. During this period, the crop structure in which broomcorn millet was the most significant crop changed to foxtail millet with absolute dominance, and broomcorn millet was in an auxiliary position in most parts of northern China [9]. In this study, the results of phytolith analysis showed that foxtail and broomcorn millets were recovered from 29 relic units in the upper reaches of the Beiluo River in northern

Shaanxi (Table 3); however, the contribution of broomcorn millet was higher than that of foxtail millet during the Yangshao culture period. Considering the relative percentage and occurrence probability of millet phytoliths, broomcorn millet had a larger proportion of crop structure in the upper reaches of the Beiluo River, probably indicating that humans consumed more broomcorn millet than foxtail millet. The results of our phytolith analysis based on plant micro-remains align with the plant macro–remains of the Yangjiesha [54], Wangyangpan [53], and Panshang sites [38], where broomcorn millet was also the principal crop with foxtail millet only forming a minor component during the Yangshao culture period. This is in direct contrast to the Guanzhong Plain in central China and the Haidai areas of eastern coastal China, where the ratio of foxtail millet to broomcorn millet was significantly higher. The reason why the ratio of broomcorn millet was higher than that of foxtail millet in Northern Shaanxi during the Yangshao culture period is probably due to the harsh weather conditions in the farming-pastoral transitional zone. The annual average temperature and precipitation in Northern Shaanxi are about 8~9 °C and 300~450 mm, respectively, while the former is about 9~15 °C and 500~700 mm [75]. Broomcorn millet is better adapted to harsh environments.

During the Longshan culture period, foxtail and broomcorn millets were recovered from 13 relic units in the upper reaches of the Beiluo River in northern Shaanxi. From the perspective of the relative percentage and occurrence probability of phytoliths, broomcorn millet still formed a larger proportion of the crop structure in the upper reaches of the Beiluo River (Table 3). However, the proportion of foxtail millet increased greatly from 0.02% to 0.46% from the early Longshan culture period to the late Longshan culture period (Table 3). Our phytolith analysis results were the same as the macro-remain results of the Jingyaogelian, Miaopan, Shangyangwa, Wacita, Houyangwa, Dayangwa, Miaoliang, Yuangeda, and Huoshiliang sites [54], but contrary to the macro-remain results of the Zhailiangmao [51], Muzhuzhuliang [52], and Shimao sites [49]. The reasons for the inconsistency with the Zhailiangmao, Muzhuzhuliang, and Shimao sites are likely related to the different relative proportion measurement methods of millet remains and/or the different properties of the Shimao site. More basic work is needed to further improve the criteria for distinguishing the contributions of foxtail and broomcorn millets. In addition, wheat crops, sheep, and cattle, which were first domesticated in Western Asia, spread through the Hexi corridor and northern grasslands into northwestern China between 4500 and 4000 cal. BP during the Longshan culture period [45,76,77]. Scholars have previously indicated that Northern Shaanxi was an important route for wheat propagation [78]. However, phytolith evidence indicates that millet crops were still dominant in northern Shaanxi during the Longshan culture period, which is consistent with the results of the Zhaishanmao, Muzhuzhuliang, Shenqigeliang, and Wangyangpan sites in Yulin City, northern Shaanxi. Therefore, our results, along with the flotation results for plant macro-remains, do not support northern Shaanxi as the route through which Triticeae crops entered Central China. This is further demonstrated by the results of carbon and hydrogen isotopes from human bones at the Shenqigeda site in northern Shaanxi, which indicated that the ancient humans at that site mainly consumed C4 millet plants and rarely consumed C3 Triticeae crops [79].

In addition to foxtail and broomcorn millet, herb plants from Pooideae, Panicoideae, Bambusoideae, Eragrostoideae, Reed (*Phragmites australis)*, woody plants from broad-leaved trees, and pteridophytes were also found at 19 Neolithic sites in northern Shaanxi. Plants from Pooideae had the highest total phytolith contents of 35.76% and 42.57% in the Yangshao and Longshan cultures, respectively. The appearance of phytoliths from these plants indicates that gathering and/or collecting surrounding plant resources remains an important supplementary resource for the occupants of northern Shaanxi. New species such as sheep and cattle also appear in high proportions in many Longshan sites in the upper reaches of the Beiluo River in Yan'an city, northern Shaanxi [80]. Since plants from Pooideae are most commonly used as forage to feed animals, this marked increase in Pooideae during the Longshan culture period strongly indicates an increase in the husbandry of ruminants. Some scholars believe that the high proportion of legume plants produced by flotation

was also related to feeding animals during the Longshan culture period because of the important position of animals in forage feed [64].

In summary, the results of phytolith analysis indicate that millet use started in the early Yangshao culture period in the upper reaches of the Beiluo River in Yan'an city, northern Shaanxi. Foxtail and broomcorn millet appeared at approximately 6280 cal. BP at the Shuifantai site, which is the earliest evidence of millet use in northern Shaanxi. In addition, the contribution of broomcorn millet was higher than that of foxtail millet from the early Yangshao to the early Longshan culture periods. During the late Longshan cultural period, the contribution of foxtail millet increased.

4.2. Environmental Factors of Millet Use in the Upper Reaches of the Beiluo River

Northern Shaanxi is located in a farming-pastoral zone, and its agricultural system is relatively fragile and susceptible to climate change. Climate change affects the development of human civilization by impacting regional livelihood patterns [81,82]. Scholars unanimously believe that one of the important reasons for the changes in the structure of millet crops from the Yangshao to the Longshan cultures in the northern Shaanxi area is environmental change [55]. Unfortunately, there is a lack of research on the environmental factors that influence the agricultural patterns of millet in northern Shaanxi. Therefore, in this study, we utilized interpolation and distance analyses in ArcGIS to explore the environmental factors related to changes in millet in the upper reaches of the Beiluo River in northern Shaanxi.

According to the age interpolation results of the 25 cultural stages with millet from the upper reaches of the Beiluo River (Figure 5), millet first appeared at the Shuifantai site, located on a tributary of the Beiluo River. The subsequent spread of foxtail and broomcorn millet in the upper reaches of the Beiluo River differed both temporally and spatially, gradually expanding from the river and its tributaries to surrounding areas. However, from the early Yangshao culture to the late Longshan culture, the Beiluo River and its tributaries remained a region of millet agriculture and played an important role in the spread of foxtail and broomcorn millet.

For every 100-m increase in elevation, the temperature decreases by 0.6 °C [83]. The elevation of the sites affects the temperature, which influences the suitability of crops. Statistical analysis revealed that 96% of the millet remains in the upper reaches of the Beiluo River were located at an elevation of between 1300–1600 m, and the average elevation difference between the sites of the Yangshao and Longshan cultures was approximately 20 m. Therefore, the influence of temperature caused by altitude on the distribution of millet remaining in the upper reaches of the Beiluo River was limited. To explore the influence of hydrological factors on the distribution of millet remains, we used the frequency distribution method to analyze all the data on millet remains, elevation, and distance from the river based on statistical analysis. The results are shown in Figure 7. Figure 7a shows that there is a significant normal distribution relationship between millet remains and elevation. Millet remains are mainly distributed in the area between 1300 m and 1600 m, with the number of sites decreasing gradually with increasing altitude. In other words, the sites of the Yangshao and Longshan cultures were concentrated in the middle- and low-altitude areas rather than randomly distributed in various regions, reflecting that the settlements of ancient people in the upper reaches of the Beiluo River during the Neolithic period were concentrated in the middle- and low-altitude areas. Figure 7b shows that there was no significant normal distribution between the millet remains and distance from the river, and the majority of sites were within seven kilometers of the river. On the one hand, this phenomenon may be related to the ancient people's need for water. On the other hand, during the Longshan culture period, with the advent of "food globalization", livestock such as cattle and sheep from the Western continent began to be integrated into the dry farming economic system in the northern Shaanxi area of China [80,84], and the grazing of cattle and sheep may require more extensive space. Therefore, water sources

or methods of raising livestock may have led to millet remaining farther away from the Beiluo River and its tributaries during the Longshan culture period.

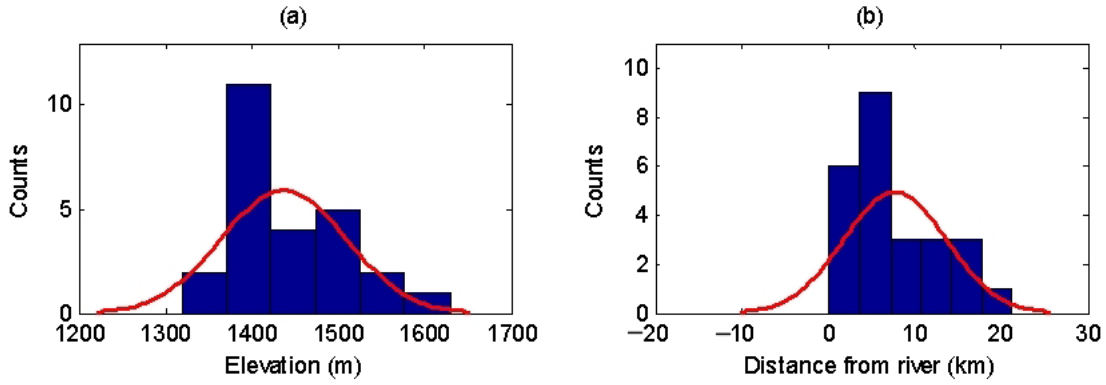


Figure 7. The normal distribution fitted plot for the relationship between the sites with millet remains in the upper reaches of the Beiluo River and (**a**) the elevation, and (**b**) the distance from the nearest river.

Throughout the agricultural development process of the Neolithic period in the upper reaches of the Beiluo River, the overall proportion of millet farming showed an upward trend during the Yangshao culture period. However, during the early Longshan culture, there was a decline in millet farming, which returned to a high level during the late Longshan culture (Table 3). Approximately 5000 cal. BP, the temperature and precipitation in the northern Shaanxi area decreased significantly. Compared with the peak stage of the Holocene Megathermal in China (6000 cal. BP), the annual precipitation decreased by 60 mm and the temperature decreased by about 1 °C [85]. This can partially explain the decline in agriculture from the late Yangshao culture to the early Longshan culture. However, around 4000 cal. BP, against the background of a trend towards dryness, coldness, and desertification [86], the number of archaeological sites in the northern Shaanxi area increased significantly. The second national cultural relic census in China showed that the number of archaeological sites from the Longshan cultural period in the Wuqi region, located in the upper reaches of the Beiluo River, increased by 78.57% compared to the Yangshao cultural period, while the overall number of sites in the northern Shaanxi area increased by 130% [87]. The phytolith analysis results of this study show that the proportion of millet farming during the Longshan culture in the northern Shaanxi area gradually increased. At the same time, the appearance of large settlements, such as the Lushanmao and Shimao sites in the late Longshan culture, further promoted social development [59,60]. This indicates that climate change is not a dominant factor affecting the development of millet farming in northern Shaanxi.

In conclusion, regarding the environmental factors affecting foxtail and broomcorn millets in the upper reaches of the Beiluo River in northern Shaanxi, the impact of the temperature difference caused by altitude was moderate, but the river had a significant impact on the distribution of millets. Moreover, with the inclusion of livestock, such as cattle and sheep, in the livelihood system, archaeological sites during the Longshan culture period gradually moved away from the Beiluo River and its tributaries.

5. Conclusions

Our analysis of phytoliths, together with AMS radiocarbon data and ArcGIS spatial data of 42 relic units from 5 different periods at 19 sites, sheds new light on the primary development of early millet uses during the Neolithic period in the upper reaches of the Beiluo River in northern Shaanxi. The results showed foxtail and broomcorn millet were present at 6200 cal. BP at the Shuifantai site, which is the earliest evidence of millet in northern Shaanxi. A detailed comparison of crop patterns at the 19 sites revealed that the contribution of broomcorn millet was higher than that of foxtail millet from the

early Yangshao to the early Longshan culture periods. In the late Longshan culture, the contribution of foxtail millet increased, leading to a cold and dry climate in this region. However, the crop structure in the upper reaches of the Beiluo River in northern Shaanxi was probably affected by the distance to the nearest river because most sites were mainly concentrated along the Beiluo River and its tributaries. However, with the arrival of cattle and sheep during the Longshan culture period, humans in the upper reaches of the Beiluo River were 1.33 km away from the nearest rivers, which promoted improvement in the utilization of Poaceae grasses.

The analysis of phytoliths, together with the AMS radiocarbon date, revealed the crop structure and diachronic characteristics of millet use in the upper reaches of the Beiluo River in Yan'an city, northern Shaanxi. ArcGIS analysis enhanced our understanding of the environmental background of why the millet congregated near the river during the early and middle Neolithic periods and far away from the river during the late Neolithic period. This study deepens the understanding of millet use in northern Shaanxi during the Neolithic period and is significant for analyzing the influence of environmental factors using ArcGIS technology.

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