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Multicropping Pattern Reveals Human Adaptation at the Wanbei Site (ca. 5.7–4.4 ka cal. BP) in the Middle and Lower Huai River Valley, China

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Abstract: The middle and lower Huai River Valley, located between the Yangtze and Yellow Rivers, was a key transitional zone for the northward spread of rice and southward migration of millet agriculture in central-eastern China during the Holocene. Knowing when millets spread here, how they were combined with rice in mixed farming, the reasons for their spread, and the temporal variation of cropping patterns is of crucial significance to the development of our understanding of ancient adaptation strategies adopted by human societies in response to climatic and cultural changes. Focusing on crops, phytolith analyses of the soil samples, in tandem with radiocarbon dating from the Wanbei site, reveal evidence of a multicropping pattern of combining rice (*Oryza sative*), broomcorn millet (*Panicum miliaceum*), and foxtail millet (*Setaria italica*) during the Dawenkou culture period between 5720 and 4426 cal. BP in the middle and lower Huai River Valley, China. The data show that rice was always the principal crop of the pattern, and that domesticated rice was developed during the early and middle Dawenkou culture periods. However, its domestication rate became lower during the late Dawenkou culture period. Broomcorn millet and foxtail millet with domesticated traits appeared only in lower proportions of the total produced throughout the period. The proportions of rice and foxtail millet increased slightly, while the proportions of broomcorn millet decreased over time. Finally, the formation of the multicropping pattern at Wanbei may have been primarily influenced by both the warm and wet climatic environment and the cultural exchange and communication between the Haidai region and the middle and lower Huai River Valley during the Dawenkou culture period. The findings in this paper may not only contribute to mapping the spatiotemporal route for the northward expansion of rice agriculture and southward spread of millet agriculture, but also assist in understanding the human adaptation strategies employed in eastern China during the Holocene.

Keywords: phytolith; multicropping pattern; middle and lower Huai River Valley; Wanbei site; Dawenkou culture period; human adaptation

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1. Introduction

Cereal crops are the solid material basis required for the origin and subsequent evolution of civilizations, a fact that was most notable in ancient society [1,2]. It is generally believed that climatic change and cultural exchange were the driving forces behind the development and dispersal of prehistoric agriculture [3–5]. Hence, studies into the choice of cropping pattern and related behaviors in prehistory are of crucial significance to our understanding of the ancient adaptation strategies adopted by human societies in response to climatic and cultural changes.

China is an essential origin center of agriculture in the world, with at least two distinct agricultural systems [6–10]. With the Holocene climatic variations [11,12] and human population shifts and admixture during the Neolithic age [13], continued expansions of and interactions between Neolithic cultures brought spatial and temporal variation in cropping patterns in Neolithic China [14]. The middle and lower Huai River Valley, located in central-eastern China between the Yangtze and Yellow Rivers, was not only a transitional zone for climate and agriculture. Indeed, it also constituted an interaction area of many Neolithic archaeological cultures during the Holocene [15,16]. The region, which is sensitive to climate change and easily influenced by cultural exchange, is therefore supposed to be an ideal area for analysis in order to understand ancient human adaptation strategies.

With the progress made in paleoethnobotanical investigations, the middle and lower Huai River Valley is believed to be a key transit zone of the possible route for the northward spread of rice and the southward advance of millet agriculture in central-eastern China [14,17]. To date, the earliest published evidence of rice (*Oryza sative*) in the middle and lower Huai River Valley is from the Shunshanji, Hanjing, and Xuenan sites in north Jiangsu Province, and traces back to ca. 8500 cal. BP [18–23]. Since then, rice has been intermittently cultivated as an important food resource [16,24–35]. The first evidence of millets is from scattered Shuangdun cultural sites (ca. 7300–6800 BP). Several phytoliths, starch granules of millets, and miliacin from one human coprolite have been recovered from the Shuangdun, Houjiazhai, and Yuhuicun sites in Anhui province, respectively [27,28,36]. Millet evidence is basically absent after the Shuangdun cultural period, although a few millet starch granules were found from phase II of the Houjiazhai site (6200–5600 BP) [26]. However, millet cultivation appears again in the late Dawenkou cultural sites (ca. 5000 BP) [31–33,37] and occupies a different position with rice, indicating the emergence of mixed farming here [16].This gap in evidence of millets in the middle and lower Huai River Valley between 5600 and 5000 BP makes it difficult to understand when millets spread here again, how exactly they were combined with rice in mixed farming, the reasons for their spread, and the temporal variation in cropping pattern. Recently, a previous analysis of charred plant remains from the Wanbei site demonstrated that mixed farming of rice and millets occurred during the Dawenkou culture period, in which rice outnumbered other crops [38]. However, data are relatively scarce. It is essential that further studies be conducted of the exact ages of crops, the formation and evolution process of the cropping pattern over time, and its driving mechanism.

Phytoliths, which are inorganic siliceous inclusions of plant cells, are very durable compared to many other plant remains. They are well preserved in various environments; however, they have also found an immense role in the species-specific identification of plants, especially for various cereal crops and their wild ancestors worldwide [39–42]. Double-peaked glume cell phytoliths and bulliform cell phytoliths, unique to the genus *Oryza*, can distinguish domesticated rice from wild rice and provide the identification of rice varieties based on morphological and morphometrical analyses [43–46]. The Ω-type and η-type undulation are typical phytolith morphotypes from foxtail millet (*Setaria italica*) and broomcorn millet (*Panicum miliaceum*), respectively. Moreover, the percentage of ηIII patterns and the size of ΩIII type phytoliths are relatively reliable tools for distinguishing domesticated broomcorn millet from its weed/feral type (*Pannicum ruderale*) and foxtail millet from green foxtail (*Setaria viridis*), respectively [40,47]. In addition, descriptive statistics based on the relative inflorescence proportions of the phytoliths extracted from rice, foxtail millet, and broomcorn millet seeds can be utilized to better reflect the true weights or yields of some crop seeds at archaeological sites [48] (Figure 1). Phytolith analyses, therefore, can complement and strengthen interpretations drawn on the basis of other botanical remains within an archaeological record [42].

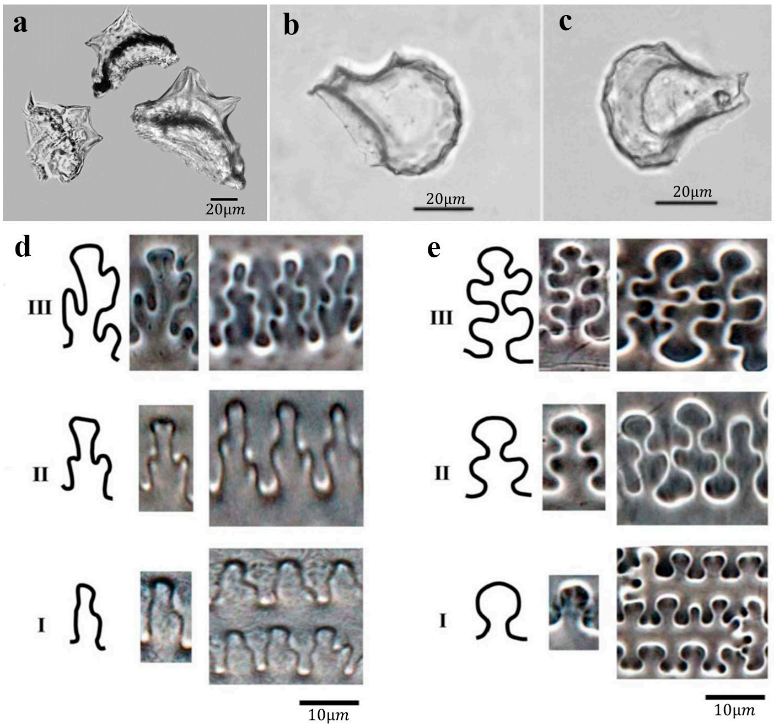

Figure 1. Species-specific cereal crop phytoliths: (**a**) double-peaked glume cells from rice chaff, after [46]; (**b**,**c**) rice cuneiform bulliform cells, after [27]; (**d**) the η-undulated type ending structures of epidermal long cell from boomcorn millet, after [49]; (**e**) the Ω- undulated type ending structures of epidermal long cell from foxtail millet, after [49].

In this study, systematic phytolith analyses were performed on sediment samples taken from the Wanbei site during the middle Holocene in the middle and lower Huai River Valley. The new results, in tandem with radiocarbon dating, the interpretation of charred seeds [38], and the utilization of cultural models reveal the cropping pattern and its temporal variation of the site between 5720 cal. BP and 4426 cal. BP, as well as their response to changes in the climatic environment and cultural exchange. The findings will assist in understanding the spatiotemporal route for the northward expansion of rice agriculture and southward spread of millet agriculture, not to mention the human adaptation strategies in this climatic, cultural, and agricultural transitional zone of eastern China during the Holocene.

2. Materials and Methods

The Wanbei site (34°15′22.3″ N, 118°49′57.6″ E) (Figure 2), located at Wanbei Village in Shuyang County of Jiangsu Province, lies at the intersection of Yi River and Shu River, two tributaries of Huai River. The region is characterized by a warm temperate humid monsoon climate and warm temperate deciduous broadleaved forest vegetation. The average annual precipitation and temperature are about 937.5 mm and 13.8 °C, respectively [50]. Today, the cultivated crops here comprise wheat (*Triticum aestivum*), rice, maize (*Zea mays*), and other cereals.

Discovered in 1987, the archaeological site of Wanbei has been excavated a total of four times, in the years 1987, 1988, and 2015. The cultural deposits include the Qingliangang culture (ca. 7300–6400 BP)/Beixin culture (ca. 7000–6000 BP), Dawenkou culture (ca. 5800–4600 BP), Yueshi culture (ca. 3900–3500 BP), Shang Dynasty (ca. 1600–1046 BC), Western Zhou Dynasty (1046–771 BC), Han Dynasty (202 BC–220 AD), Tang Dynasty (618–907 AD), and Song Dynasty (960–1127 AD) [51–53]. Some ash pits, tombs, and a large quantity of pottery, stone, and bone artifacts, as well as animal bones, freshwater shells, and charred plant remains, were recovered. This variety in artifacts can provide reliable materials for studying the regional cultural development and human adaptation [38,51,53–55].

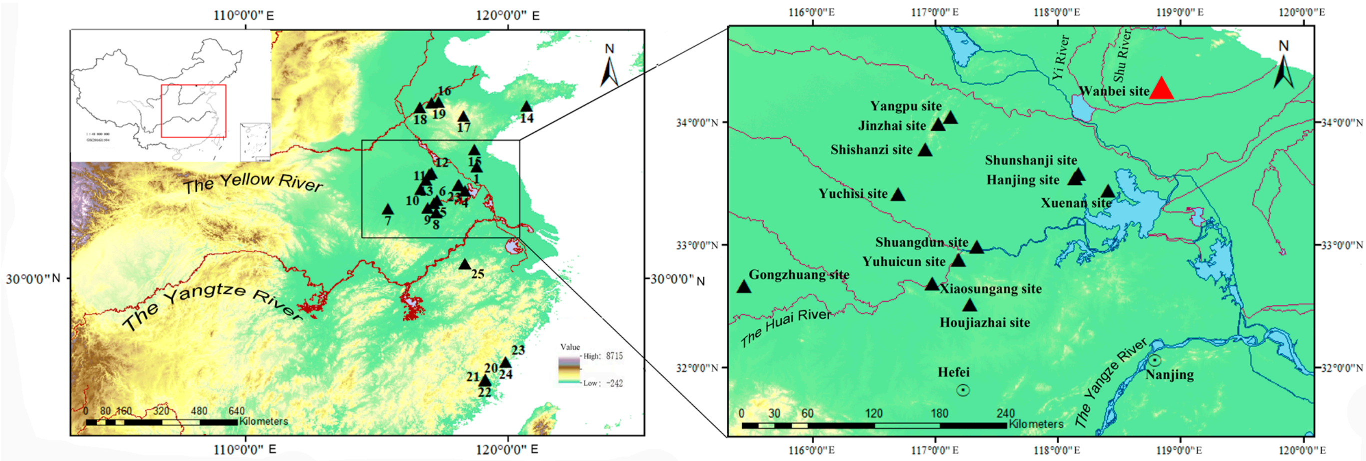

Figure 2. Graphic maps showing the locations of Wanbei site and other related sites in the article. 1. Wanbei site; 2. Shunshanji site; 3. Hanjing site; 4. Xuenan site; 5. Shuangdun site; 6. Yuhuicun site; 7. Gongzhuang site; 8. Houjiazhai site; 9. Xiaosungang site; 10. Yuchisi site; 11. Yangpu site; 12. Jinzhai site; 13. Shishanzi site; 14. Beiqian site; 15. Dongpan site; 16. Zhangmatun site; 17. Bianbiandong site; 18. Yuezhuang site; 19. Xihe site; 20. Baitoushan site; 21. Tanshishan site; 22. Zhuangbianshan site; 23. Huangguashan site; 24. Pingfengshan site; 25. Jingshuidun site.

In this study, a total of 77 samples, drawn from the profile of an archaeological layer from the southern wall of Excavation Unit 1, as well as deposits from ash pits at Excavation Unit 1, were collected and subjected to phytolith analysis. The deposits from the profile (215 cm in thickness) can be divided into nine layers, ranging from layer 10 to layer 18 from top to bottom, according to the structure of the stratigraphy, soil color, and the archaeological remains (Figure 3). A total of 30 and 47 soil samples were successively obtained at ca. 5 cm intervals from this profile and the deposits of ash pits, respectively. In addition, a total of seven samples of charred plant seeds or charcoals from layers 5, 8, 10, 11, 14, 15, and 18 were successively collected and sent to the Center for Applied Isotope Studies, University of Georgia for AMS ^{14}C dating.

Phytolith extraction was conducted from soil samples on the basis of the procedure outlined by Piperno [56] and Luo et al. [27]. Firstly, each soil sample (ca. 5 g) was placed in a 500 mL beaker, and 500 mL 5% SHMP (sodium hexametaphosphate) solution was added and stirred for deflocculation. Secondly, the samples were treated with 30% hydrogen peroxide (H_2O_2) and cold 10% hydrochloric acid (HCl) to remove organic matter and carbonates, and then a *lycopodium* spore tablet (10,315 grains/tablet) was added to each sample to detect the densities of phytoliths. Thirdly, the phytoliths were separated using zinc bromide ($ZnBr_2$, density 2.35 g/cm^3) heavy liquid and then rinsed with 95% ethanol until the supernatants were clear. Nearly 500 phytoliths were counted to draw the percentage diagram, and 200 fields of vision were randomly scanned in order to determine the primary phytolith morphotypes of the cereal crops in each sample under a Leica DM4500P optical microscope. The identification and classification of phytoliths were aided by the published references and criteria [40,41,44,49,57] and their designations were issued in accordance with the International Code for Phytolith Nomenclature 1.0 (ICPN 1.0) [58]. The concentration of phytoliths was calculated according to the formula $Cp = L_N \times L_S/(n \times G)$, where Cp represents the concentration of phytoliths, L_N represents the number of phytoliths we counted, L_S represents the number of *lycopodium* spores added, n is the number of stained *lycopodium* spores encountered, and G is the weight of each sample, respectively.

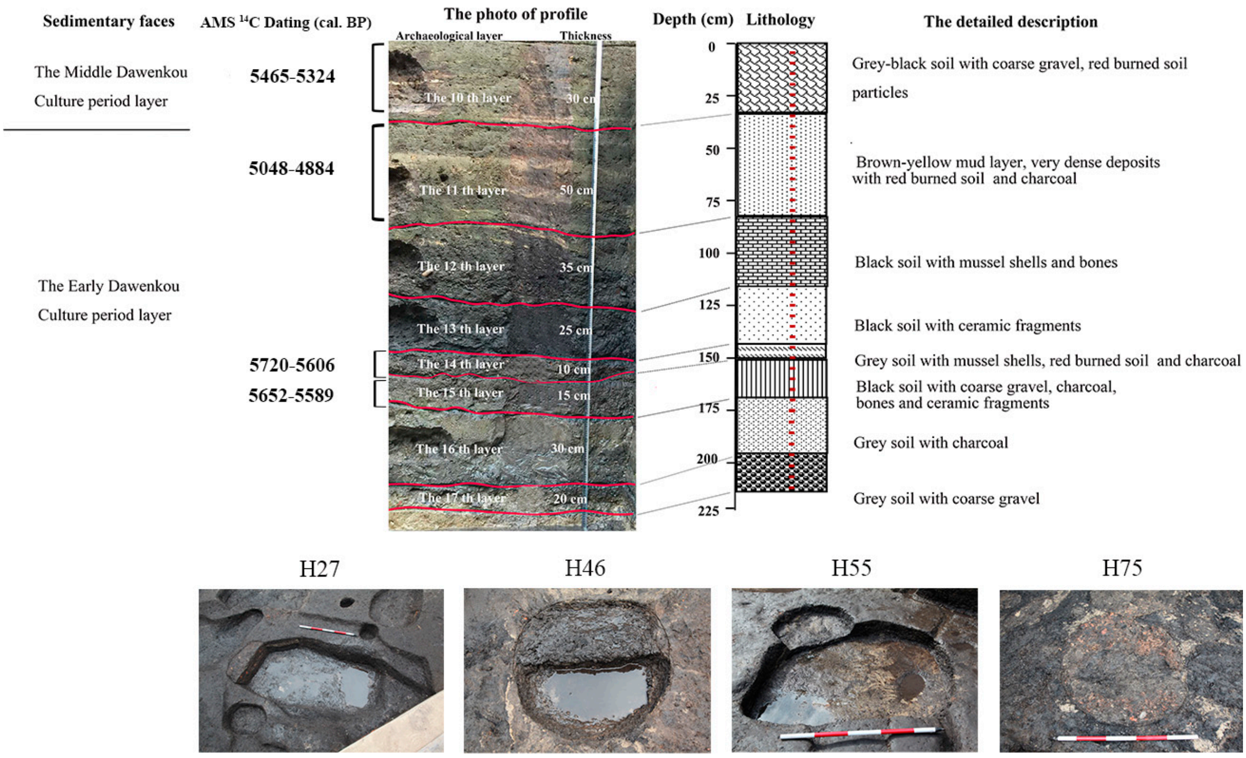

Figure 3. Stratigraphic characteristics of the profile and some ash pits sampled at the Wanbei site. (The red points on the profile represent the sampling locations).

3. Results

3.1. Chronology

Seven samples successfully yielded AMS radiocarbon dates. All AMS ^{14}C dates fell within the range between 5720 and 4426 cal. BP (68.3%). These results were calibrated via OxCal 4.4 using the IntCal 20 Northern Hemisphere radiocarbon age calibration curve [59], although the two dates from layer 11 and layer 14 were slightly inconsistent with an age–depth model (Figure 4). Combined with these radiocarbon dates, and the stratigraphy of the Wanbei site, cultural layers 18–11 and 14 ash pits selected in this study correspond to the early Dawenkou culture period (6100–5400 BP); cultural layers 10–8 and 21 ash pits correspond to the middle Dawenkou culture period (5400–4700 BP); and cultural layers 7–5 and 12 ash pits correspond to the late Dawenkou culture period (4700–4400 BP) [60,61].

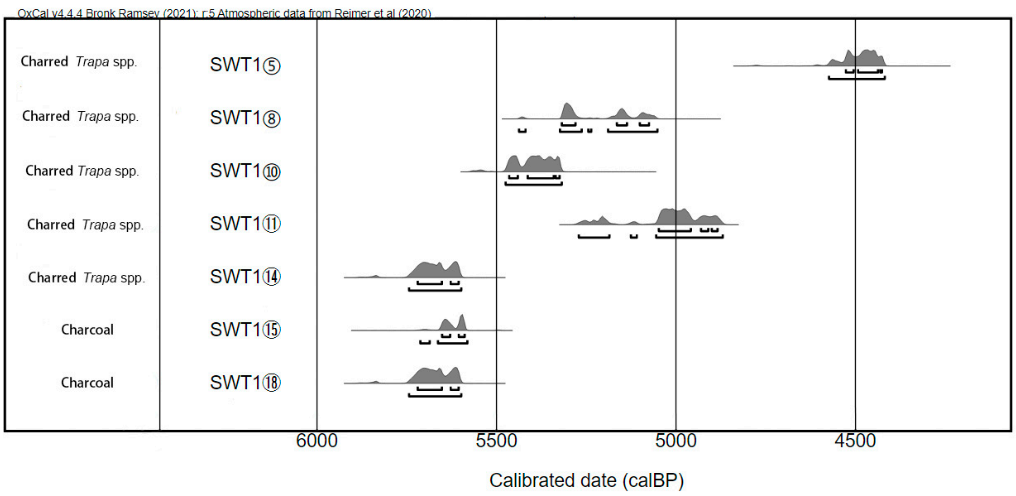

Figure 4. Calibrated1σ probability distribution of radiocarbon dating of Wanbei Site profile [59].

3.2. Phytolith Results

Phytoliths were well preserved in every sample analyzed. The identified crop phytoliths consisted of rice cuneiform bulliform cells, a paralleled arrangement for bilobate short cells from the leaves of rice and double-peaked glume cells from rice chaff, an η-shaped undulating pattern from the inflorescence bracts of broomcorn millet, and an Ω-shaped undulating pattern from the inflorescence bracts of foxtail millet. We discovered common bulliform cells, scutiform bulliform cells from reeds, square bulliform cells, rectangular bulliform cells, bilobate short cells, saddle short cells, rondel short cells, wavy trapezoid short cells, smooth elongate long cells, β-undulated-type ending structures of epidermal long cells from barnyard millet (*Echinochloa* spp.) elongate echinate long cells, acicular hair cells, vascular tissues, polyhedrons with conical projection, silicified stomata, and other varieties of tissue (Figure 5).

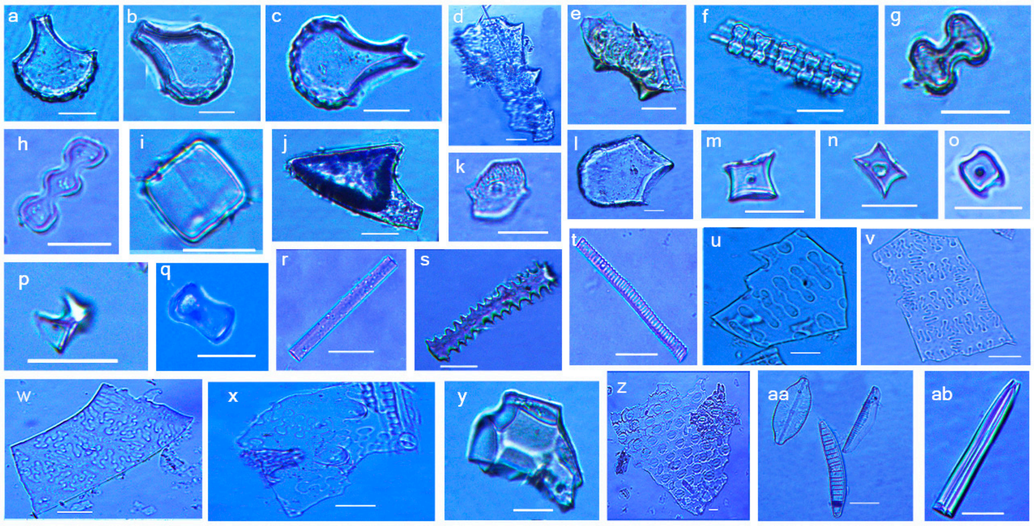

Figure 5. Main phytoliths extracted from the Wanbei site: (**a**–**c**) rice cuneiform bulliform; (**d**,**e**) double-peaked glume cells; (**f**) bilobate short cells with scooped-end paralleled arrangements; (**g**) bilobate short cell; (**h**) polylobate short cell; (**i**) square bulliform cell; (**j**) acicular hair cell; (**k**) polyhedrons with conical projection; (**l**) scutiform bulliform cell from reed; (**m**,**n**) rondel short cell; (**o**,**p**) short saddle short cell; (**q**) long saddle short cell; (**r**) smooth elongate long cell; (**s**) elongate echinate long cell; (**t**) vascular tissues; (**u**) β-undulated-type ending structures of epidermal long cell from barnyard millet; (**v**,**w**) η-undulated-type ending structures of epidermal long cell from broomcorn millet; (**x**) Ω-pattern undulated-type ending structures of epidermal long cell from foxtail millet; (**y**) multifaceted blocky; (**z**) silicified stomata; (**aa**) diatom; (**ab**) sponge spicule (scale bar: 20 μm).

3.2.1. Phytoliths from Ash Pits

A total of 6909 phytoliths were counted from 14 samples corresponding to the early Dawenkou culture period. The phytolith assemblages were characterized by a high proportion of smooth elongate long cells (33.86%), followed by silicified stomata (10.32%), cuneiform bulliform cells (6.18%), elongate echinate long cells (5.37%), bilobate short cells (5.11%), double-peaked glume cells (4.82%), rectangular (4.88%), square (4.29%), and other cell varieties (Figure 6). In phytolith assemblages, in total, 88 rice bulliform phytoliths (for a ubiquity of 92.86%), 332 double-peaked glume cells (for a ubiquity of 100%), 3 bilobate short cells with scooped-end paralleled arrangements (for a ubiquity of 21.43%), 4 Ω-type undulations (for a ubiquity of 21.43%), and 18 η-type undulations (for a ubiquity of 71.43%) were found. The estimated average concentration of these phytoliths was 1490.56 grains/g, 8022.65 grains/g, 80.70 grains/g, 79.34 grains/g, and 355.79 grains/g, respectively (Figure 6) (Table S1). Statistics obtained for these crop seed phytoliths show that rice, foxtail millet, and broomcorn millet comprised 93.79%, 1.13%, and 5.08% of the total crops, respectively (Figure 7) (Table S3). In addition, fast scanning was used to focus on seven samples of these products with relatively greater numbers of crop phytoliths in order to encounter sufficient crop phytoliths for morphometric analysis to be viable. The proportion of 392 rice bulliform phytoliths encountered with ≥9 fish-scale decorations was 66.43 ± 9.36% (Figure 8) (Table S5).

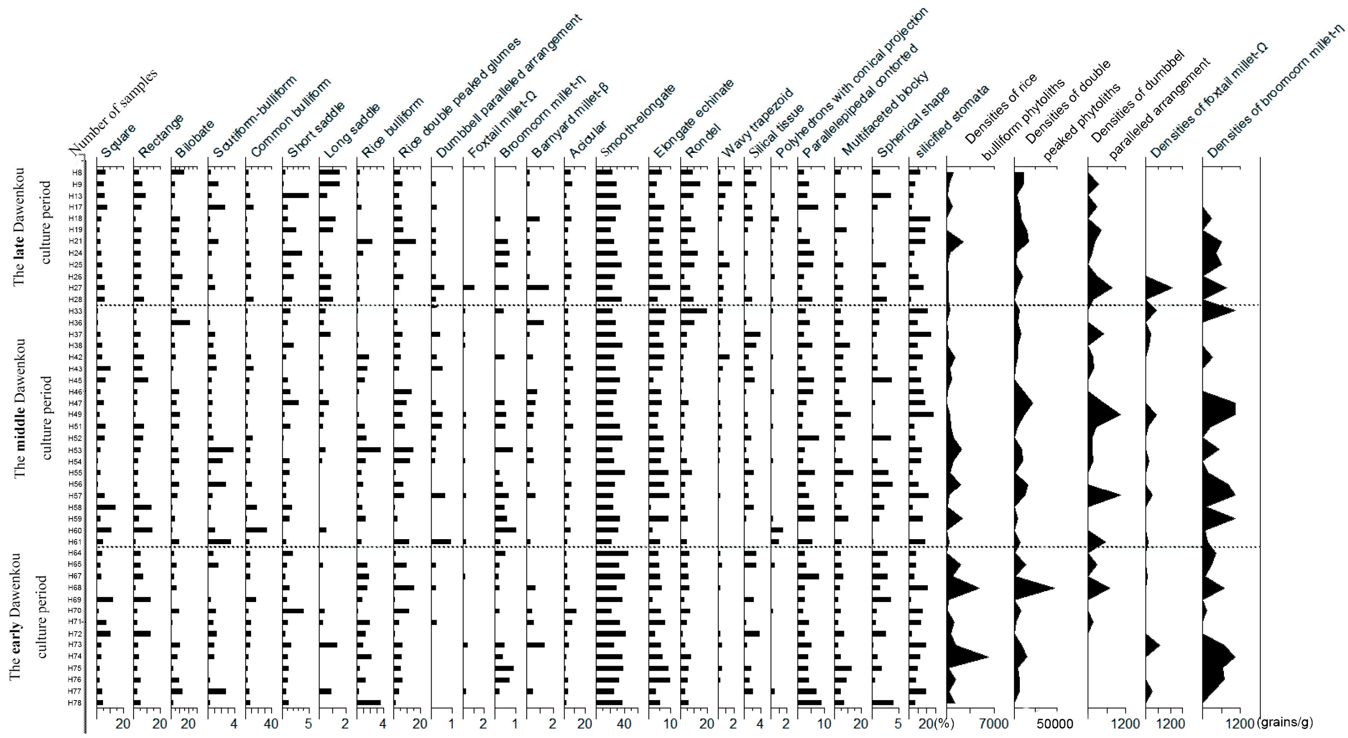

Figure 6. Percentage diagram of main phytoliths found from the ash pits of the Wanbei site.

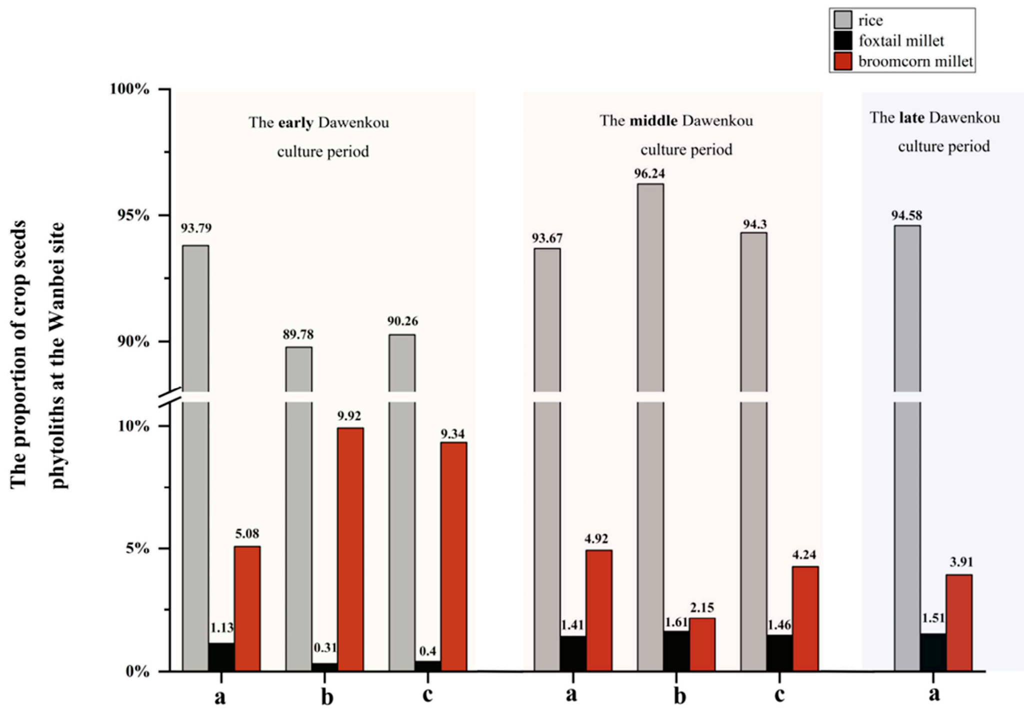

Figure 7. The proportion of crop seed phytoliths at the Wanbei site. a represents the proportion of crops from the ash pits, b represents the proportion of crop from the profile, and c represents the average value of a and b.

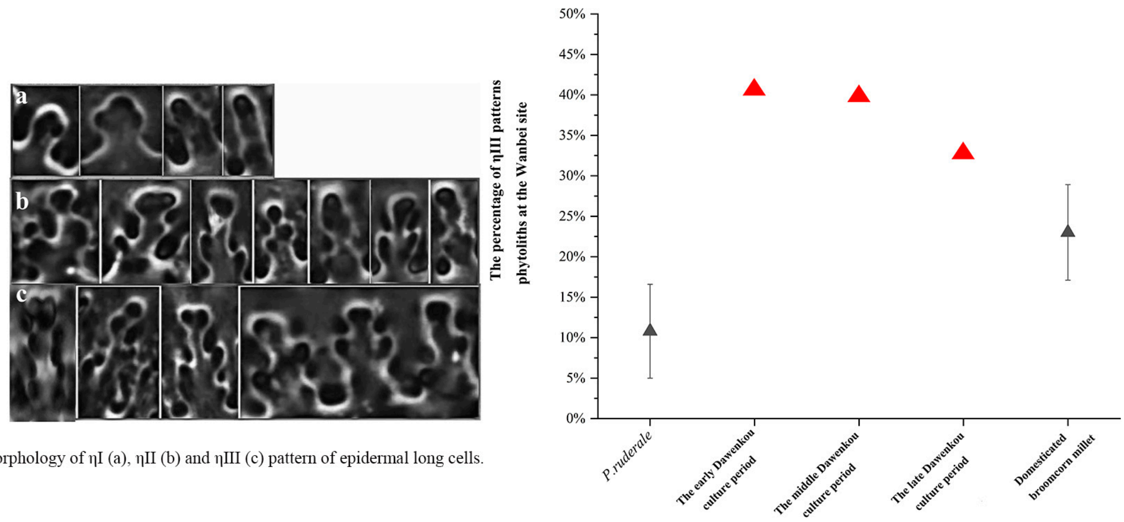

Figure 8. The left picture is morphology of ηI (**a**), ηII (**b**), and ηIII (**c**) pattern of epidermal long cells, after [40] The right picture is the proportion of ηIII patterns phytoliths at the Wanbei site.

The results of analyses performed on 21 sediment samples dated to the middle Dawenkou culture period revealed a total of 9673 phytoliths. The phytolith assemblages were dominated by smooth elongate long cells (28.45%) and silicified stomata (12.72%), followed by cuneiform bulliform cells (6.82%), bilobate short cells (6.22%), elongate echinate long cells (5.79%), double-peaked glume cells (5.36%), and others (Figure 6) (Table S1). A total of 533 double-peaked glume cells (for a ubiquity of 85.71%), 83 rice bulliform phytoliths (for a ubiquity of 85.71%), 20 bilobate short cells with scooped-end paralleled arrangements (for a ubiquity of 52.38%), 8 Ω-type undulations (for a ubiquity of 38.1%), and 28 η-type undulations (for a ubiquity of 61.9%) were recovered. The estimated average concentrations of these phytoliths were 6347.68 grains/g, 715.63 grains/g, 222.03 grains/g, 105.66 grains/g, and 359.93 grains/g, respectively (Figure 6) (Table S3). Statistics for these crop seed phytoliths show that rice, foxtail millet, and broomcorn millet comprised 93.67%, 1.41%, and 4.92% of the total crops, respectively (Figure 7). A total of 861 rice bulliform phytoliths with clear fish-scale decorations were encountered via the application of fast scanning to multiple slides, as were 80 η-type undulations. The results show that the proportion of rice bulliform phytoliths with ≥9 fish-scale decorations and ηIII-type undulation was 57.12 ± 11.07% and 40% (Figures 9 and 10) (Tables S5 and S7).

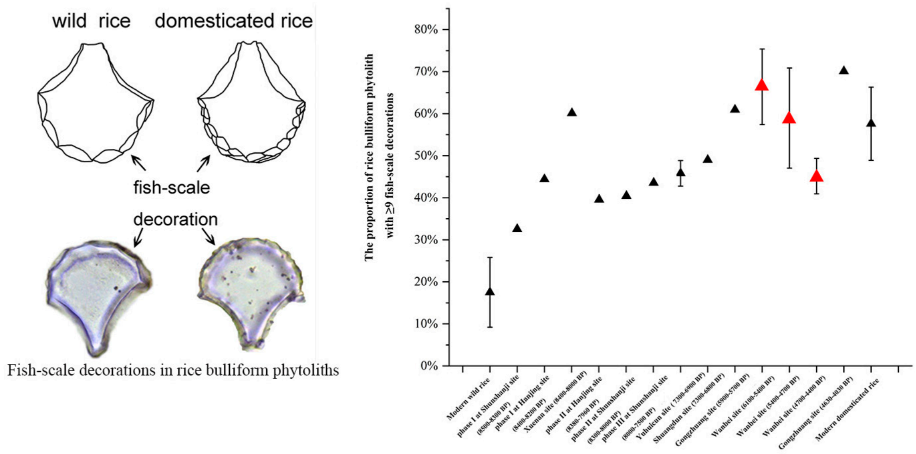

Figure 9. The left picture is the fish-scale decorations in rice bulliform phytoliths after [43]. The right picture is the proportion of rice bulliform phytoliths with ≥9 fish-scale decorations at the Wanbei site and other related sites in this article.

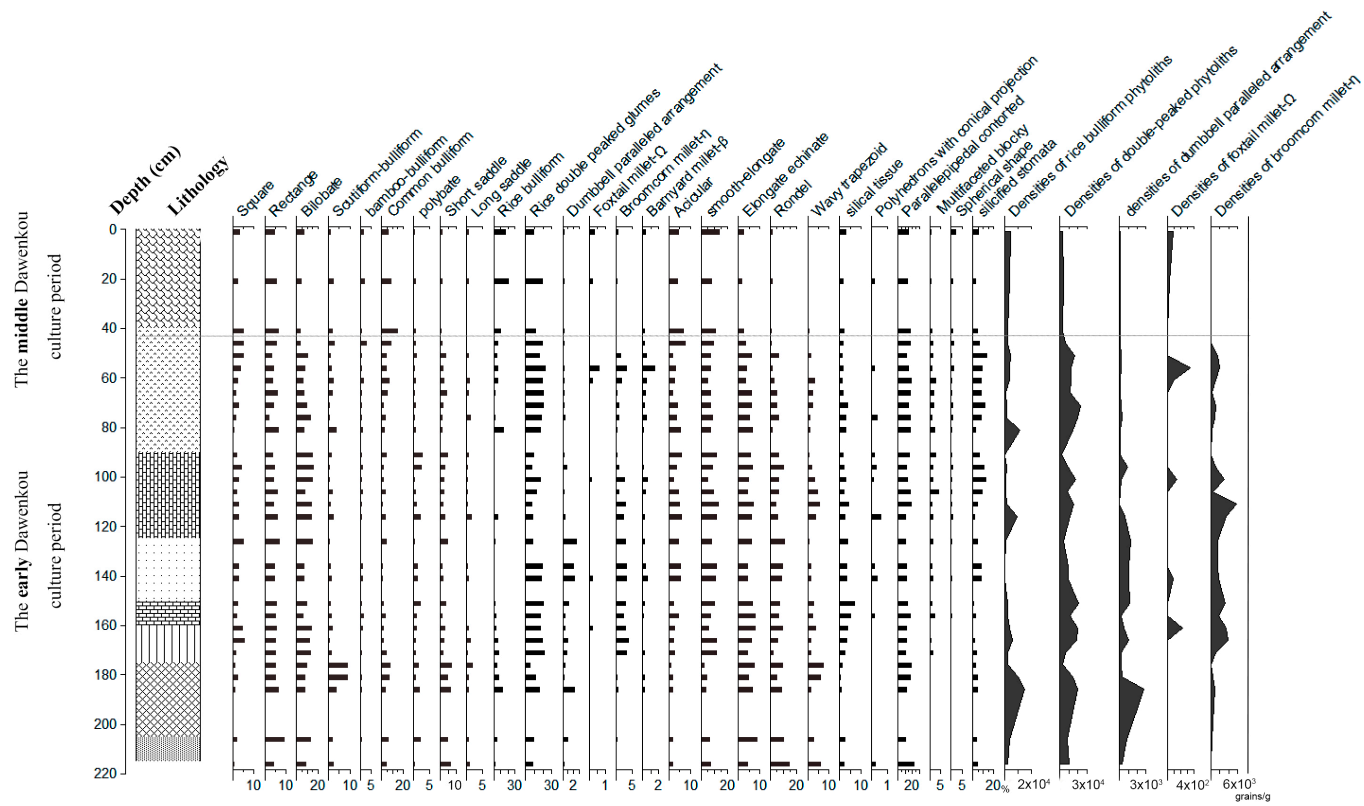

Figure 10. Percentage diagram of main phytoliths found from the profile of the Wanbei site.

A total of 5873 phytoliths were counted from 12 samples belonging to the late Dawenkou culture period. The phytolith assemblages were characterized by a high proportion of smooth elongate cells (28.49%), followed by silicified stomata (10.1%), rondel short cells (8.07%), bilobate short cells (7.28%), cuneiform bulliform cells (6.04%), elongate echinate long cells (5.59%), double-peaked glume cells (5.36%), and others (Figure 6) (Table S1). In phytolith assemblages, a total of 314 double-peaked phytoliths (for a ubiquity of 91.67%), 28 rice bulliform phytoliths (for a ubiquity of 83.33%), 10 bilobate short cells with scooped-end paralleled arrangements (for a ubiquity of 66.67%), 5 Ω-type undulations (for a ubiquity of 8.33%), and 13 η-type undulations (for a ubiquity of 41.67%) were recovered. The estimated average concentrations of these phytoliths were 7292.43 grains/g, 538.98 grains/g, 217.56 grains/g, 107.45 grains/g, and 226.56 grains/g, respectively. Statistics for these crop seed phytoliths show that rice, foxtail millet, and broomcorn millet comprised 94.58%, 1.51%, and 3.91% of the total crops, respectively (Figure 7) (Table S5). A total of 298 rice bulliform phytoliths with clear fish-scale decorations and 12 η-type undulations were encountered through the fast scanning of multiple slides. The results show that the proportion of rice bulliform phytoliths with ≥9 fish-scale decorations and ηIII-type undulation was 45.14 ± 4.22% and 33.33% (Figures 8 and 9) (Tables S5 and S7).

3.2.2. Phytoliths from the Profile

A total of 15,944 phytoliths were found from the samples from layers 17 to 11 that were dated to the Early Dawenkou culture period. The phytolith assemblages were dominated by double-peaked glume cells (14.62%), parallelepipedal contorted cells (14.61%), bilobate short cells (9.84%), smooth elongate long cells (8.11%), rondel short cells (6.18%) and silicified stomata (5.91%), followed by elongate echinate long cells (5.54%), rectangular cells (5.03%), rice bulliform cells (4.19%), cuneiform bulliform cells (3.81%), and others (Figure 10) (Table S2). A total of 2354 double-peaked glume cells (for a ubiquity of 100.00%), 659 rice bulliform phytoliths (for a ubiquity of 100.00%), 98 bilobate short cells with scooped-end paralleled arrangements (for a ubiquity of 96.43%), 8 Ω-type undulations (for a ubiquity of 17.86%), and

260 η-type undulations (for a ubiquity of 85.71%) were recovered. The estimated average concentrations of these phytoliths were 11,941.84 grains/g, 3472.81 grains/g, 492.31 grains/g, 32.68 grains/g, and 1446.83 grains/g, respectively (Figure 10) (Table S4). Statistics for these crop seed phytoliths show that rice, foxtail millet, and broomcorn millet comprised 89.78%, 0.31%, and 9.92% of the total crops, respectively (Figure 7). A total of 1297 rice bulliform phytoliths with clear fish-scale decorations and 103 η-type undulations were encountered through the fast scanning of multiple slides. The results show that the proportion of rice bulliform phytoliths with ≥9 fish-scale decorations and ηIII-type undulation was 66.39 ± 7.53% and 40.78% (Figures 8 and 9) (Tables S6 and S7).

A total of 1229 phytoliths were found from the samples from layer 10 dated to the middle Dawenkou culture period, including rice bulliform cells (18.77%), double-peaked glume cells (14.49%), parallelepipedal contorted cells (13.52%), smooth elongate long cells (10.46%), bilobate short cells (5.72%), acicular cells (4.07%), rectangular cells (4.96%), silicified stomata (4.01%), elongate echinate long cells (2.04%), and others (Figure 10) (Table S2). Among them, we recovered a total of 179 double-peaked glume cells (for a ubiquity of 100.00%), 231 rice bulliform phytoliths (for a ubiquity of 100.00%), 2 bilobate short cells with scooped-end paralleled arrangements (for a ubiquity of 100.00%), 3 Ω-type undulations (for a ubiquity of 100.00%), and 4 η-type undulations (for a ubiquity of 100.00%). The estimated average concentrations of these phytoliths were 2914.71 grains/g, 3945.36 grains/g, 34.99 grains/g, 56.04 grains/g, and 77.09 grains/g, respectively (Figure 10) (Table S4). The statistics for these crop seed phytoliths show that rice, foxtail millet, and broomcorn millet comprised 96.24%, 1.61%, and 2.15% of the total crops, respectively (Figure 7). The proportion of 103 rice bulliform phytoliths with ≥9 fish-scale decorations encountered through the fast scanning of multiple slides was 73.65 ± 8.98% (Figures 9 and 10) (Tables S6 and S7).

In sum, when combining the results from both the ash pits and profile, the paleoethnobotanic data at the Wanbei site demonstrated the following trends. The proportion of rice increased from 90.26% to 94.3% and then up to 94.58% in total, while that of broomcorn millet decreased from 9.34% to 4.24% and 3.91% during the early, middle, and late Dawenkou culture periods. Similarly, foxtail millet was present in the early Dawenkou culture period in the smallest proportion (0.40%), but increased to 1.46% and 1.51% between the middle and late Dawenkou culture periods (Figure 10). The proportions of rice bulliform phytoliths with ≥9 fish-scale decorations from both ash pits and the cultural profile at Wanbei reached 66.4% ± 8.98% (n = 1689) and 58.95% ± 11.9% (n = 964) during the early and middle Dawenkou culture periods, and then decreased to 45.14% ± 4.22% (n = 298) during the late Dawenkou culture period (Figure 7) The morphometric analysis of broomcorn millet phytoliths show that the percentage of ηIII patterns was 40.78% (n = 103), 40% (n = 80), 33% (n = 12) during the early, middle, and late Dawenkou culture periods (Figure 8).

4. Discussion

4.1. Multicropping Pattern at Wanbei

According to the results of the phytolith analyses presented in this paper, the multicropping pattern of combining rice, broomcorn millet, and foxtail millet emerged in the middle and lower Huai River Valley between 5720 cal. BP and 4426 cal. BP, a fact that is also supported by evidence from carbonized plants drawn from the Wanbei site [38]. Additionally, the data (Figures 6, 7 and 10) show that rice always dominated all other crop types, and that both broomcorn millet and foxtail millet, in turn, appeared in lower proportions. With time, the proportions of rice and foxtail millet increased slightly, while the proportion of broomcorn millet decreased gradually. The proportion of foxtail millet did not exceed that of broomcorn millet, suggesting that broomcorn millet was more significant than foxtail millet at the Wanbei site.

This multicropping pattern was a special mode of agriculture in prehistoric China that benefited from the spread of rice and millet farming. The model of multicropping first appeared in the Haidai region [62,63] in the upper reaches of the Huai River Valley [64–66] as early as ca. 7800 and 8000 BP. Subsequently, it developed quite rapidly [16,67,68], with millet emerging as the dominant crop, followed by rice. Previous studies indicated that rice was the dominant crop and that broomcorn millet was present first, but less prevalent at the site of Shuangdun in the middle and lower Huai River [27]. Then, the status of rice in this pattern decreased to the same level as, was slightly higher than, and was lower than that of millet at the archaeological sites of this region during the late Dawenkou culture period [16,31,33,37]. As mentioned above, the multicropping pattern at the Wanbei site was dominated by rice, followed by broomcorn millet and foxtail millet. This is not only different from contemporaneous sites in the Haidai region [68] and the upper reaches of Huai River Valley [67], but also different from the local Neolithic sites [16,31–33,37], suggesting a spatiotemporal variation in cropping patterns.

Previous studies indicated that rice farming first extended to the middle and lower Huai River Valley at the latest during the Shunshanji culture period [16,24–35]. The expansion of these practices subsequently continued during the Shuangdun culture period, in phase II of the Houjiazhai site, and throughout the early Dawenkou culture period [24–26,29,35], and then appeared again at several late Dawenkou cultural sites (ca. 5000 BP), Longshan, and other ancient cultural sites discussed in the literature [30–34,37]. The discoveries of rice at Wanbei prove that rice consistently constituted an important proportion of food production in this region, at least until the Shang Dynasty. The early record of millet in the middle and lower Huai River Valley was recovered from the Yuchisi, Yangpu, and Jinzhai sites during the late Dawenkou culture period [31–33,37]. Subsequently, the phytoliths, starch granules of millets, and miliacin were recovered from Shuangdun, Houjiazhai, and Yuhuicun sites, respectively [27,28,36], suggesting that millets had spread to this region as early as the Shuangdun culture period. The discoveries of broomcorn and foxtail millets at Wanbei, together with millet starch granules from phase II of the Houjiazhai site [26], indicate that millets spread here again during the early Dawenkou culture period, and at least lasted until the end of Neolithic age [16]. These early millet records in this region are earlier than those found in southern China, e.g., Baitoushan, Tanshishan, Zhuangbianshan sites (ca. 5500 cal. BP) [69]; Huangguashan, and Pingfengshan sites in Fujian Province (4000–3500 cal. BP) [17]; and Jingshuidun site in Southern Anhui Province (2667–2568 cal. BP) [70]. The findings raise the following question: did crop communications ever occur between north China, the middle and lower Huai River Valley, and even southern China, mapping a possible route for the southward spread of millets during the middle and late Holocene?

4.2. Domestication of Rice and Millets

Multiple pieces of evidence indicate that the earliest domestication of rice can be dated back to ca. 10,000 BP in the middle and lower Yangtze River Valley [8,71–73]. In the middle and lower Huai River Valley, the earliest rice remains with early domestication traits were recovered from Shunshanji cultural sites [18,23]. The data of our phytolith analysis show that the proportions of rice bulliform phytoliths with ≥9 fish-scale decorations during the early and middle Dawenkou culture periods were slightly higher than those in modern domesticated rice paddy samples of 57.6% ± 8.7% [74] (Figure 8), which are considered the distinct morphological feature of domesticated rice. The result is confirmed by the judgments from the analyses of charred rice at Wanbei [38]. The morphologies of rice spikelets and morphometric analysis of rice granules at Wanbei also show that rice during the Dawenkou culture period was of the domesticated *japonica* variety [38]. This result is generally consistent with the interpretations from Gongzhuang site [30] and layer 4 (ca. 5500 BP) of Longqiuzhuang site in Gaoyou City, Jiangsu Province, where the rice remains were present with the fixed traits of the *japonica* type and large grain size [35].However, the proportion of rice bulliform phytoliths with ≥9 fish-scale decorations during the late Dawenkou culture period decreased to 45.14% ± 4.22% (n = 298). The presence of a lower proportion might imply that the process of rice domestication went backwards at the site, which also happened in the lower Yangtze River Valley ca. 7.0 ka BP [75]. The reasons for the slowing down of the domestication process here remain unclear. This is an area in need of greater research, although factors such as the location and number of samples cannot be ignored [76]. In addition, it is a pity that few individual double-peaked glume cells with five distinguishable parameters developed by Zhao et al. [46] that were successfully measured were encountered as being available for further morphometric analysis, although double-peaked glume cells were abundant in this paper.

When compared with the level of these cells at other sites (i.e., Shunshanji, Hanjing, Xuenan Shuangdun, Yuhuicun, Gongzhuang), in this region [18,22,23,27,29,30], the data in Figure 8 show that the proportions of rice bulliform phytoliths with $\geq$9 fish-scale decorations gradually increased from the Shunshanji culture period and Shuangdun culture period to the Dawenkou culture period as a whole, but decreased at Wanbei during the late Dawenkou culture period. This trend suggests that rice was under selective pressure of domestication since it demonstrated 8.5 ka BP and closely resembled the modern domesticated variety during the early and middle Dawenkou culture periods, although the process of rice domestication might have regressed regionally during the late Dawenkou culture period in the middle and lower Huai River Valley.

Microfossil evidence from the Cishan, Nanzhuangtou, and Donghulin sites in the North China Plain indicate that domestication of broomcorn millet and foxtail millet may also have occurred as early as ca.10,000 BP [6,77]. However, the domestication rate of the earliest millet remains recovered from Shuangdun cultural sites in the middle and lower Huai River Valley remains unclear [27,28,36]. Our morphometric analysis of broomcorn millet phytoliths show that the percentages of ηIII patterns were all higher than in modern domesticated broomcorn millet [40] (Figure 9). Unfortunately, the phytoliths of foxtail millet encountered in samples at Wanbei were all fragmented, meaning that further morphometric analysis could not be conducted successfully. According to Cheng et al. [38], the morphometric characteristics of charred broomcorn millets (n = 18) and foxtail millets (n = 27) recovered from the Wanbei site were consistent with the modern domesticated ones [78]. Taken together, it is believed that broomcorn millet and foxtail millet with domesticated traits occurred at the Wanbei site throughout the Dawenkou culture period.

4.3. Cropping Pattern Response to Climatic Environment and Cultural Exchange at Wanbei

The development and evolution of agriculture, especially in prehistoric times, is closely linked to climatic and environmental changes around the world [3–5]. Previous studies indicated that climate change played a critical role in the selection of millet species for domestication in northern China and in the spatial–temporal variation of cropping patterns in Neolithic China [3,5]. Alternatively, the evolution of agricultural patterns was also significantly influenced by cultural exchange. Southern and northern cultural exchange involved the transfer of millets and rice in Neolithic China, which transformed the prehistoric evolution of dualistic-structure mixed farming in Neolithic China [14]. The trans-Eurasian exchange in prehistory greatly promoted food globalization [79–81]. Specifically, the formation of cropping patterns and their spatiotemporal variations in some regions were usually affected by both the climatic environment and cultural exchange. Li et al. [82] proposed that climatic conditions in the Hutuo River Valley, Sushui River Valley and some parts of Henan Province led people to develop foxtail and broomcorn millet, and that cultural exchange with external societies also influenced the formation of different crop patterns.

The results presented at the Wanbei site indicate that rice was the principal crop during the Dawenkou culture period. Rice is a typical thermophilous and hygrophilous plant, needing a warm and humid climate. Pollen analysis from the Qingfeng section, Jianhu, Jiangsu Province, China, revealed that the percentages of subtropical deciduous broadleaved trees and aquatic plants clearly increased between 8500 BP and 3700BP, suggesting a warm and wet climate [83]. Additionally, the Holocene climate change recorded by the Xiangcheng loess section in Henan Province in the northwest Huai River basin showed that the climate was humid during the period between 5800BP and 4500 BP [84]. These similar records were also observed in the pollen and charcoal analyses from the nearby region, where pollen and charcoal records in the Taihu Lake basin indicate an increase in summer precipitation coincident with the Holocene summer insolation maxima between 7900 BP and 4400 BP [85]. Moreover, zooarchaeology research at the Wanbei site shows that several samples of Elaphurus davidianus, which is a typical thermophilous and hygrophilous animal, were present, which also suggests that the climate during the Dawenkou culture period was warmer and wetter than today [55]. The warm and humid environment offered adequate hydrothermal conditions for rice cultivation. Previous studies confirmed that the occurrence of rice cultivation was consistent with the initiation of the Holocene optimum in the Huai River basin [86]. Hence, we believe that the suitable climatic environment probably enabled the population to focus on the development of rice farming at the Wanbei site.

As discussed before, broomcorn millet and foxtail millet were important crops of the Wanbei site, although they occupied a lower position in the multicropping pattern. Broomcorn millet and foxtail millet were staple crops of the Haidai region during the Neolithic age [62,68,87–89]. It is clear that the material culture at Wanbei between the years 5720 cal. BP and 4426 cal. BP belonged to the Dawenkou culture, whilst having some cultural factors of the Songze culture (6000–5300 BP), in terms of analysis of the assemblages and production of pottery, stone artifacts, and the tomb system recovered from the Wanbei site [51,53]. In addition, comparative analyses of shape and decoration show that some painted potteries recovered from the phase II of the Houjiazhai site in Anhui Province were originally related to the Dawenkou culture. Recent starch analysis indicate that broomcorn millet, and foxtail millet were also present at the phase II of Houjiazhai site during this time [26]. These findings suggest that cultural exchange and communication did exist between the Haidai region in the north and the Huai River Valley during the Dawenkou culture period, which probably promoted the spread of millet farming. Hence, we suggest that the occurrence of millet farming at the Wanbei site was probably due to human introduction with the development of cultural exchange between Haidai region and middle and lower Huai River Valley.

5. Conclusions

The phytolith evidence discussed from the Wanbei site, together with radiocarbon dating, verifies that multi-cropping patterns occurred in the middle and lower Huai River Valley between 5720 cal. BP and 4426 cal. BP. Rice was always used as the staple crop, with the proportion of its cultivating increasing slightly. Broomcorn and foxtail millet also appeared only in lower proportions in situations that saw the proportions of broomcorn millet decrease, while the incidence of foxtail millet slightly increased throughout the period. Morphometric analysis of phytoliths indicate that rice assigned to the early and middle Dawenkou culture periods was the domesticated variety, but that the rate of domestication during the late Dawenkou culture period might have fallen to a lower level. Broomcorn and foxtail millet fell within the range of variation of the domesticated types between 5720 cal. BP and 4426 cal. BP. Finally, the fact that the flourishing development of rice faming corresponded with the warm and wet climatic environment, while the occurrence of millets was closely linked to the cultural exchange and communication between the Haidai region and the middle and lower Huai River Valley during the Dawenkou culture period, suggest that both the climatic environment and cultural exchange influenced the formation of the multicropping patterns at Wanbei. The findings in this paper can provide new references to use in the clarification of the spatiotemporal route of the southward spread of millet agriculture and assist scholars in understanding human adaptation strategies in central-eastern China during the Holocene.

It should be pointed out that more work is needed to complete the picture of crop patterns and human adaption at the Wanbei site in the Dawenkou culture period due to the limited materials and methods available for use in this study. A greater variety of types of methods will be needed in future studies, such as pollen analysis and starch analysis.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land12061158/s1, Table S1: The number, concentration, and percentage of various types of phytoliths in the ash pits of the Wanbei site; Table S2: The number, concentration, and percentage of various types of phytoliths in the profile of the Wanbei site; Table S3: The number and the average proportion of crop seed phytoliths in the ash pits at the Wanbei site; Table S4: The number and the average proportion of crop seed phytoliths in the profile at the Wanbei site; Table S5: The number of fish-scale decorations of rice bulliform phytoliths in ash pits at Wanbei site; Table S6: The number of fish-scale decorations of rice bulliform phytoliths in the profiles at Wanbei site; Table S7: The number of ηIII pattern phytoliths in ash pits and profiles at the Wanbei site.

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