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Discovery of the Earliest Rice Paddy in the Mixed Rice–Millet Farming Area of China

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Abstract: Neolithic rice remains were recovered from a mixed rice–millet farming area in China outside the original centers of rice farming. Whether the rice remains were the result of local cultivation or obtained through trade remains unclear. Rice paddy fields are direct evidence of local cultivation. In this study, phytolith samples from the Zhangwangzhuang site were analyzed. The discriminant function distinguished 17 of 30 samples in the suspected paddy field area as rice paddy fields with an average probability of 74%; The proportion of rice bulliform phytoliths with ≥9 scales indicated that rice (*Oryza sativa*) was still being domesticated and, moreover, six η-type phytoliths from broomcorn millet (*Panicum miliaceum*) were identified. These results suggested that the suspected paddy field at Zhangwangzhuang might be the earliest rice paddy field (ca. 6000 cal. BP) in northern China and that mixed farming was practiced here since the early Yangshao period. This study adopted discriminant analysis methods to discover ancient rice paddy fields, observed rice paddy fields outside the core rice origin area, and provided the earliest evidence regarding the development of mixed rice–millet farming in the upper Huai River region.

Keywords: phytolith; ancient rice paddy; the Zhangwangzhuang site; discriminant function; Yangshao cultural period

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1. Introduction

Rice was domesticated in the lower Yangtze region approximately 10,000 years ago [1] and eventually became one of the main food resources worldwide [2]. Paddy fields provide important evidence of the conscious human influence on rice growth and a key technological advance in rice domestication [3]. Moreover, the presence of paddy fields is direct evidence of local cultivation outside the centers of rice farming origins [4,5]. Therefore, it is of great significance to identify early rice paddy fields to measure the spread of rice farming beyond traditional rice farming areas and to study changes in the status of rice within the agricultural structure.

The agricultural structure in Neolithic China was comprised of rice (*Oryza sativa*) and millets (*Panicum miliaceum* and *Setaria italica*) in the Yangtze and Yellow River valleys, respectively [6–9]. The Huai River region is located between the Yellow and Yangtze Rivers and is considered a mixed rice–millet farming area [10,11]. Mixed rice–millet farming emerged in northern China no later than 7500 cal. BP, as demonstrated by plant remains from Zhuzhai [12] and Tanghu [13] sites. The earliest known evidence (~7300 to 6800 cal. BP) of mixed rice–millet farming in this region was found at the Shuangdun site in the middle reaches of the Huai River region [14]. However, the spatial and temporal limits on mixed rice–millet farming in the upper reaches remain unclear, primarily because no evidence of millet has been observed. Moreover, extensive rice remains have been recovered from outside the rice core origin region [15–20]. Whether these rice remains were cultivated locally or acquired through trade is controversial [21] since no ancient rice paddy fields have been reported in these areas.

The discovery of ancient rice paddy fields is primarily limited by the identification methods. One of the most prominent features of modern rice paddies is the emergence of an irrigation system with banks and canals, which is often used to identify rice paddy fields unearthed from archaeological sites [22–24]. However, it is difficult to identify paddy fields using this indicator alone, as ancient irrigation systems might have been undeveloped or could be poorly preserved. Fujiwara and Sugiyama [25] established a paddy identification standard of 5000 rice bulliform phytoliths in 1 g of dried soil. This standard has been used to identify Neolithic paddies in Shandong and Zhejiang Provinces [26,27]. The bulliform phytolith content left in the field is closely related to the harvesting process [28,29] and the age of the paddy soil [30]. Therefore, more reliable methods for identifying early rice paddies should be developed.

Recently, phytolith assemblages have been used to develop discriminant functions for identifying rice paddy fields that can effectively distinguish among wild rice fields, domesticated rice fields, and non-rice fields [31]. In this study, we collected samples from the Zhangwangzhuang archaeological site from the Yangshao cultural period (7000–5000 cal. BP). This is the first report regarding the observation and study of a Neolithic rice paddy in a mixed rice–millet farming area. The findings and identification of the rice paddy field are important for studying the development and spread of rice agriculture in China.

2. Materials and Methods

2.1. Materials

Zhangwangzhuang (33°34′6.17″ N, 113°39′18.65″ E, Figure 1) is situated in Wuyang County, Henan Province. From 2015 to 2018, more than 600 ash pits and approximately 60 house foundations were excavated by the Henan Provincial Institute of Cultural Heritage and Archaeology [32]. Abundant stone tools, bone artifacts, jade, and other cultural relics were unearthed, indicating that the Zhangwangzhuang site was occupied during the Yangshao cultural period (7000–5000 cal. BP) [33].

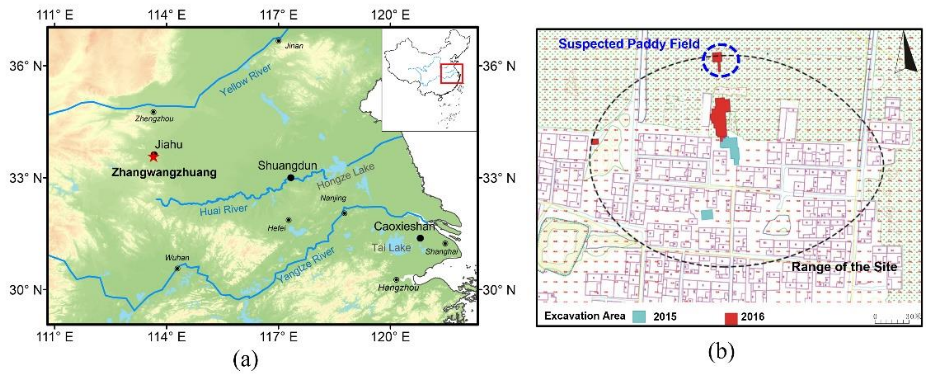

Figure 1. (**a**) Location of the Zhangwangzhuang site and other ancient paddy sites mentioned in this study; (**b**) and the excavation areas and suspected rice paddy at Zhangwangzhuang.

During the excavation in 2016, shallow circular pits with connected trenches and water plugging, which were suspected to be rice paddy fields, were observed along the river channel north of the site. At least two samples or three samples were collected from each suspected pit. For comparison study, we also collected some samples outside these pits to see the differences between in and out of these pits. In total, we collected 30 samples from this potential paddy field area for phytolith analysis. Detailed sampling information is shown in Figure 2 (context codes starting with K/H means pits and G means trench).

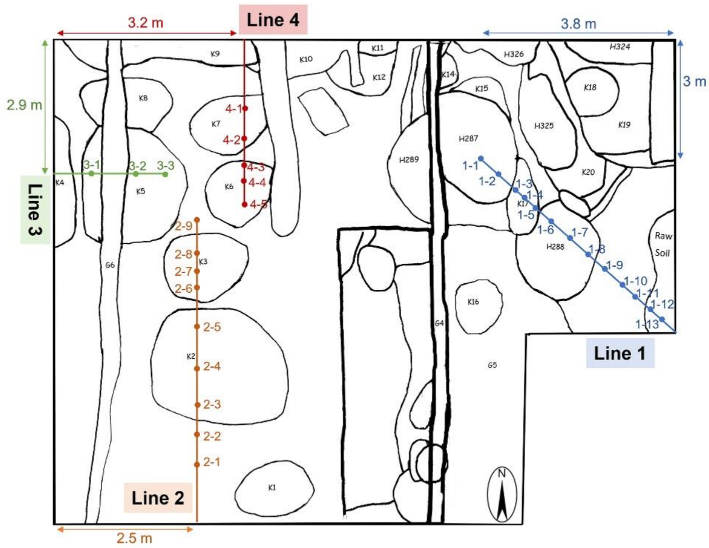

Figure 2. Samples collected from the suspected rice paddy field area. Line 1 is from the center of H287 to the raw soil area; Line 2, Line 3, and Line 4 are from the south, the west, and the north wall to the center, respectively.

In addition, we collected 35 samples from 23 archaeological contexts of ash pits (sample codes start with H) and house foundations (sample codes start with F) for phytolith analysis. Specifically, seven samples were collected from H507, three each from H375 and H356, two each from H369 and H38, and one sample from each of the other units. One charcoal sample was also collected from ash pit H507 and sent to Beta Analytic Inc. Laboratory for radiocarbon dating. The dating result was 5330 ± 30 BP (Beta567905), which was calibrated to 6106 ± 68 cal. BP using OxCal 4.4 [34] and the IntCal 20 atmospheric curve [35]. Systematic radiocarbon dating [33] was also performed at the site (Table 1), which suggests that the occupation of the early Yangshao period occurred around 6300–5600 cal. BP.

Table 1. AMS Radiocarbon dating results from the Zhangwangzhuang site (All dates are calibrated by OxCal v4.4.4, using the IntCal 20 Atmospheric curve).

Lab Code	Context No.	Dated Material	Conventional Radiocarbon Date (BP)	Calibrated Dates (2σ, BP)
Beta593414	F7	Charcoal	5380 ± 30	6283–6009
Beta592815	H38	Charcoal	5330 ± 30	6264–5999
Beta567905	H507	Charcoal	5330 ± 30	6264–5999
BA192651	F15	Charcoal	5105 ± 30	5924–5749
Beta593418	H35	Charcoal	5070 ± 30	5906–5741
Beta592816	F13	Charcoal	5050 ± 30	5904–5719
Beta593415	H14	Charcoal	4940 ± 30	5728–5596
Beta593413	H30	Charcoal	4910 ± 30	5715–5587

2.2. Phytolith Analysis

Phytoliths were extracted from the soil samples according to established methods [36,37] with minor modifications. Initially, approximately 2 g of each soil sample was weighed. Then, 30% H_2O_2 and 15% HCl were added to the samples to remove organic matter and carbonates. Next, the samples were subjected to heavy liquid flotation using $ZnBr_2$ (density, 2.35 g/cm^3) to separate the phytoliths, which were subsequently mounted on slides using Canada balsam.

After air drying, the phytoliths on the slide were counted and identified using a Leica microscope at 400× magnification. More than 400 phytolith particles were identified in each sample and recorded according to published references and criteria [38–44].

For the samples that contained rice phytoliths, the slides were scanned until 50 rice bulliform phytoliths with clear and countable fish-scale decorations were observed. This was performed to calculate the proportion of rice bulliform phytoliths with ≥9 fish-scale decorations [45,46]. Simultaneously, we also counted the rice bulliform phytoliths that did not have clear decorations.

A discriminant analysis of the phytolith assemblage was performed using SPSS version 22.0. We first calculated the percentage of the phytolith assemblages from Zhangwangzhuang and then placed the selected phytolith types into the discriminant functions [31]. Then, the discriminant functions presented three probabilities of each sample to the three different groups. The group with the highest probability is the predicted group membership of the ungrouped data. Therefore, the discriminant functions derived from modern samples were applied to the ungrouped data from Zhangwangzhuang to predict the group members.

3. Results

3.1. Phytolith Assemblages and Discriminant Analysis

Phytoliths were abundant in all 65 samples. Eighteen phytolith morphotypes were identified (Figure 3), including square, bulliform, smooth elongate, rectangle, acicular hair cell, rondel, reed bulliform, bilobate, and trapeziform sinuate. Six η-type phytoliths from broomcorn millet (*Panicum miliaceum*), two β-type phytoliths from barnyard grass (*Echinochloa* sp.) (in sample H343), and one phytolith from foxtail millet (*Setaria italica*) (in sample F16) were identified (Figure 4). The phytolith assemblages were then used for the discriminant analysis.

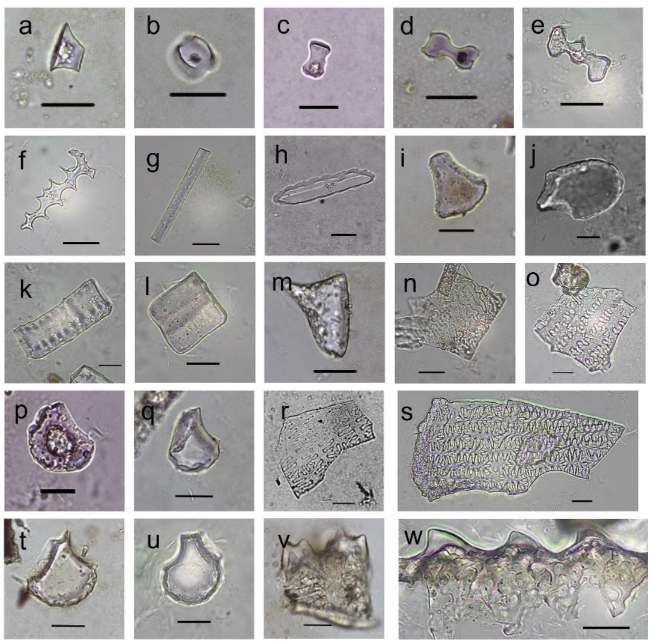

Figure 3. Phytoliths obtained from samples collected at Zhangwangzhuang: (**a**) Rondel; (**b**) short saddle; (**c**) long saddle; (**d**) bilobate; (**e**) multilobate; (**f**) sinuate elongate; (**g**) smooth elongate; (**h**) trapeziform sinuate; (**i**) bulliform; (**j**) reed bulliform; (**k**) rectangle; (**l**) square; (**m**) acicular hair cell; (**n**) barnyard grass; (**o**) foxtail millet; (**p**) rice bulliform without countable and clear fish-scale decorations; (**q**) rice bulliform with <9 fish-scale decorations; (**r**,**s**) broomcorn millet husk; (**t**,**u**) rice bulliform with ≥9 fish-scale decorations; (**v**,**w**) rice double-peaked (scale bar = 20 μm).

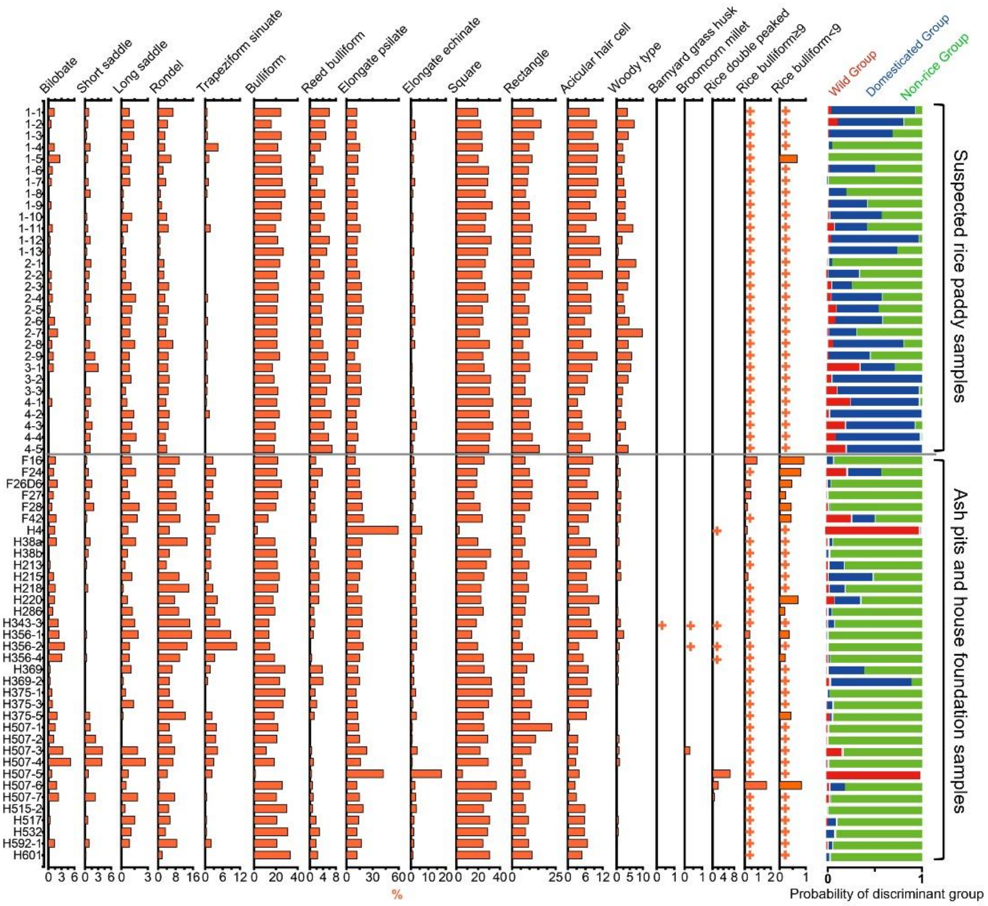

Figure 4. Percentages of the major phytolith types and results of the discriminant analysis at Zhangwangzhuang. Cross symbols indicate the presence of the phytolith types that were insufficient to count in the phytolith assemblage.

Among the 30 samples collected from suspected rice paddy fields, 17 were identified as domesticated paddy fields and 13 were identified as non-rice paddy fields (Figures 4 and 5). Among the 13 samples collected along Line 1, two samples from H287 (1-1, 1-2), one sample from K17 (1-3), one sample from G5 (1-10), and two samples from the raw soil layer (1-12, 1-13) were identified as domesticated rice fields. Among the nine samples collected along Line 2, one sample from K2 (2-4) and two samples from K3 (2-6, 2-8) were identified as domesticated rice fields. All three samples collected along Line 3 (3-1,3-2, 3-3) and all five samples along Line 4 (4-1, 4-2, 4-3, 4-4, 4-5) were identified with domesticated rice fields.

Among the 35 samples collected from ash pits and house foundations, 32 were classified as the non-rice group, two (H4, H507-5) were classified as the wild rice group, and one (H369-2) was classified as the domesticated rice group (Figure 5).

In addition, abundant double-peaked phytoliths from rice husks were found at H507, where phytoliths from barnyard grass were also found (Figure 4). A statistical analysis of the percentages of crop-related phytoliths in H507 indicated that the double-peaked phytoliths from rice husks accounted for approximately 78%, rice bulliform phytoliths from leaves accounted for approximately 19%, and the barnyard grass phytoliths accounted for less than 3% of the assemblage.

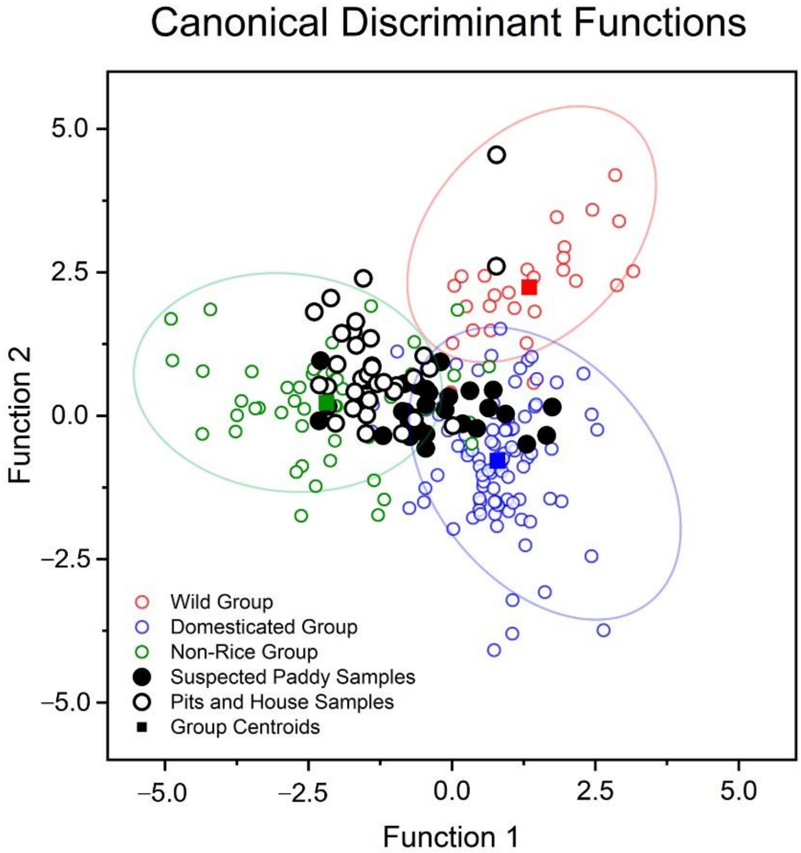

Figure 5. Discriminant results of the Zhangwangzhuang samples (black and white dots) in the context of modern rice paddy samples (colored dots) [31].

3.2. Rice Bulliform Phytoliths

All samples from Zhangwangzhuang contained sufficient rice bulliform phytoliths to identify their source areas as rice paddies. Approximately 70.7% of the identified rice bulliform phytoliths had clear and countable fish-scale decorations. We counted 50 phytolith particles with clear and countable fish-scale decorations and calculated the proportion of bulliform phytoliths with ≥9 fish-scale decorations (21.0 ± 8.0%; Figure 6). The average density of the rice bulliform phytoliths was 24,973 particles/g, with a minimum of 427 particles/g (1-12) and a maximum of 254,930 particles/g (F24, Figure 6).

In the samples from the suspected rice paddy field area (Figure 6), approximately 57.0% of the identified rice bulliform phytoliths had clear and countable fish-scale decorations. We counted 50 particles of phytoliths with clear and countable fish-scale decorations and calculated the proportion of bulliform phytoliths with ≥9 fish-scale decorations (16.2 ± 5.6%), with the lowest (7.8%) in s 2-9 and the highest (30.9%) in sample 1-8. The average density of the rice bulliform phytoliths was 12,539 particles/g, but individual sample densities varied widely. For example, the density of sample 1-12 (from raw soil) was only 429 particles/g and the density of sample 1-13 was 963 particles/g, whereas the density of sample K6 exceeded 10,000 particles/g and the density of sample 4-4 reached 82,680 particles/g. Thus, the density distribution of rice bulliform phytoliths varied (Figure 6).

In the ash pit and house foundation samples (Figure 6), approximately 85.0% of the identified rice bulliform phytoliths had clear and countable fish-scale decorations. We counted 50 phytolith particles with clear and countable fish-scale decorations and calculated the proportion of bulliform phytoliths with ≥9 fish-scale decorations (26.0 ± 7.6%), which was the lowest (10.5%) in sample H456-4 and the highest (38%) in sample H507-6. The average density of the rice bulliform phytoliths was 37,837 particles/g.

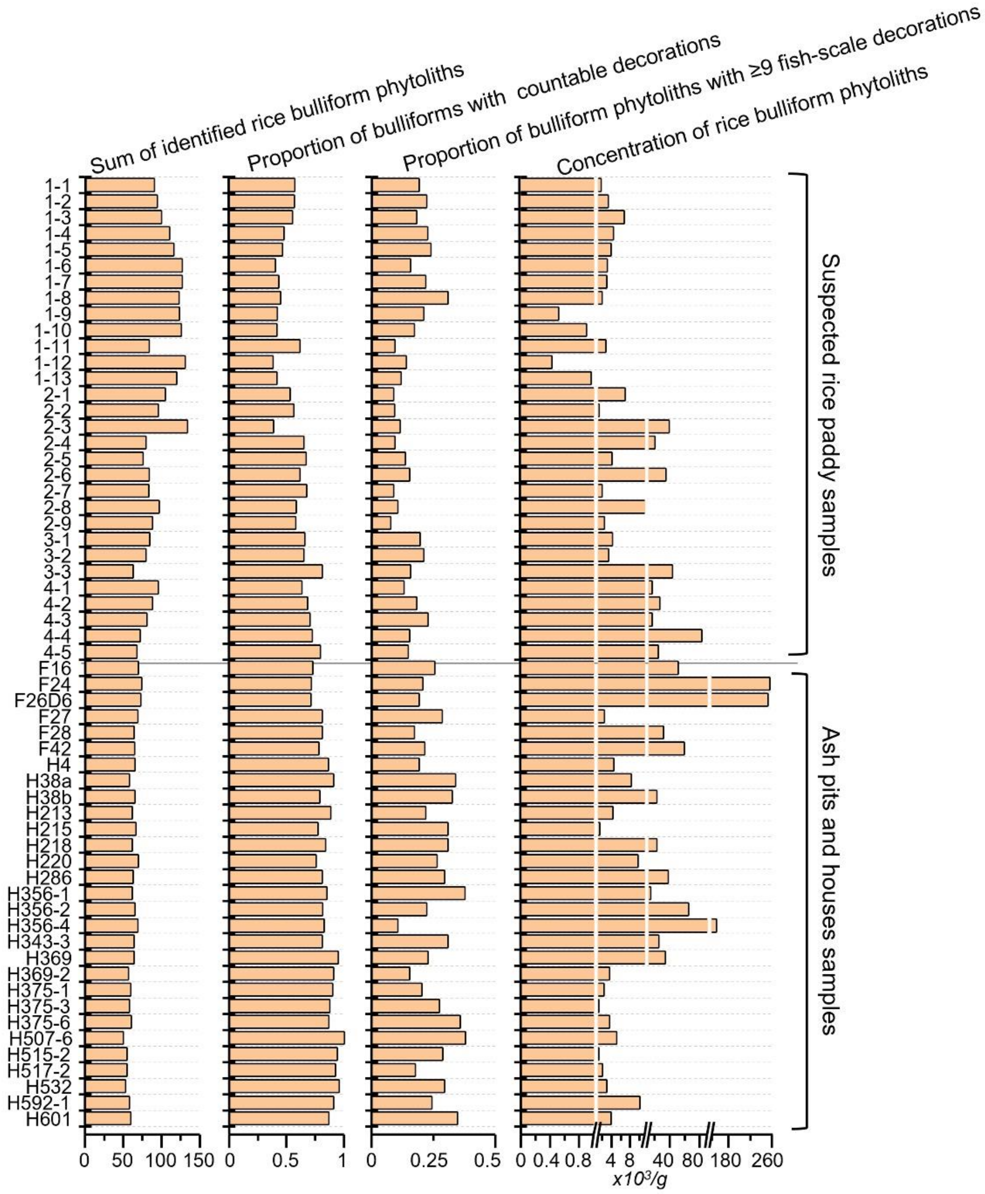

Figure 6. Results of rice bulliform phytoliths at Zhangwangzhuang.

4. Discussion

4.1. Identification of Rice Paddy Fields at Zhangwangzhuang

The discriminant function [31] of the phytolith assemblages distinguished 17 samples in the suspected paddy field area as rice paddy fields. The average probability of the 17 samples identified as domesticated rice paddy fields was 74%. The spatial distribution of these 17 samples indicated aggregation characteristics.

The first aggregation area was located around H287, where the average rice bulliform phytolith density was approximately 4000 grains (Figure 6) in three samples (1-1, 1-2, and 1-3), which is similar to the standard of 5000 grains. Thus, H287 could be a rice paddy field. The second aggregation area was located around the raw soil layer. The rice bulliform phytolith density in these three samples (1-10, 1-12, and 1-13) was fewer than 1000 grains (Figure 6). Therefore, although this was an aggregation area, it might have been located at the edge or transition area of a paddy field. The third aggregation area was located at K5, K6, and K7, where all eight samples were identified as domesticated paddy fields and two samples (2-6 and 2-8) from K3 were also identified as domesticated paddy fields. The rice bulliform phytolith density in this area was greater than 10,000 grains (Figure 6). Therefore, this area was likely the core area of the paddy fields. Based on the discriminant and density analyses of the phytolith assemblages, we identified the earliest known rice paddy field in a mixed rice–millet farming area in China. The preliminary structure of the field is shown in Figure 7.

Figure 7. Preliminary structural view of the rice paddy field identified at Zhangwangzhuang.

In addition, three samples from ash pits and house foundations were identified as rice paddies in the discriminant analysis. Samples H4 and H507-5 were misidentified as wild rice fields. These two samples were characterized by high proportions of sinuate elongate and smooth elongate phytoliths (Figure 4). This might have been the cause of the erroneous result. Sample H369-2 was also misidentified as a domesticated rice paddy field, likely due to the accuracy of the discriminant function.

Moreover, we found that the long saddle-type phytoliths commonly occurred in phytolith assemblages. This phytolith type is derived from Bambusoideae plants [38], indicating that plants of the bamboo subfamily could have grown around the Zhangwangzhuang site. The emergence of bamboo subfamily plants indicates a warm and humid environment consistent with that required for rice growth. The rice paddy fields at the Zhangwangzhuang site were dated to ca. 6000 cal. BP, which occurred during the Holocene climatic optimum period. Previous studies have shown that precipitation in this area during the Holocene peaked at approximately 6000 BP [47,48]. Therefore, the climate of the region was suitable for rice growth.

Based on the phytolith evidence, we believe that the Zhangwangzhuang site probably contains small fragments of rice paddy fields. The core paddy field area discovered thus far is smaller in size than the contemporary ancient rice paddy fields located in the lower Yangtze River region [22]. Approximately 6000 years ago, the ancient paddy fields at the Caoxieshan [49] and Chuodun sites [50] in the lower Yangtze River region were composed of various unit sizes, where a single unit could be as large as 10 m^2. In contrast, the size of the Zhangwangzhuang rice paddy field is much smaller. In addition, the currently excavated area is limited, and we have not yet fully revealed the details of the water management system at the Zhangwangzhuang site, including how the water was drained and how the water level in the paddy was maintained [4].

To sum up, more than half of the samples from the suspected rice paddy area at the Zhangwangzhuang site were determined as being rice paddy fields, suggesting that during the Yangshao cultural period, rice paddy fields likely appeared in the Huai River region; although, the paddy size was smaller than that in the Lower Yangtze River region at the same period. Further analysis of phytoliths demonstrated that the climate condition was beneficial to the development of rice paddy.

4.2. Rice Domestication Traits at Zhangwangzhuang

The proportion of rice bulliform phytoliths with ≥9 fish-scale decorations (wild rice = 17.46 ± 8.29%; domesticated rice = 63.70 ± 9.22%) can reflect the degree of rice domestication [37,46]. This indicator has not only been used to trace the domesticated rice origin to the beginning of the Holocene period [1,51], but has also been used to reconstruct Neolithic rice domestication in the lower Yangtze River region [52–55] and in the south [56–60]; this indicator has proven to be a reliable measure of rice domestication.

The proportions of rice bulliform phytoliths with ≥9 fish-scale decorations at the Zhangwangzhuang site varied in different units. Among the samples collected from suspected paddy field areas, the proportion was only 16.18 ± 5.63%. Among the samples collected from ash pits and house foundations, the proportion was 26.0 ± 7.6%, which is higher than that of the suspected rice paddy field samples. This might be because mature plants were selectively collected from the site and remained in the ash pits. Therefore, higher proportions of rice bulliform phytoliths with ≥9 fish-scale decorations would be observed in ash pits.

Phytoliths with clear and countable decorations in the suspected paddy fields accounted for only 57% of the total, whereas those in the pits and house foundations comprised approximately 85%. From these results, it can be inferred that the divergent preservation of the fish-scale decorations on rice bulliform phytoliths might be the reason for the different proportions of ≥9 fish-scale decorations between the suspected rice paddy fields and ash pits at Zhangwangzhuang. However, the exact mechanism remains unclear.

Nevertheless, the results obtained herein are indicative of the level of rice domestication at Zhangwangzhuang. The highest proportion (38%) of rice bulliform phytoliths with ≥9 fish-scale decorations was in the sample in which all the bulliform phytoliths had clear and countable scales. This sample might be more representative (when compared with modern standards) for measuring the level of rice domestication at Zhangwangzhuang. Based on the analyses of the rice bulliform phytoliths, we believe that the level of rice domestication at the Zhangwangzhuang site in the upper Huai River area during the Yangshao cultural period was higher than that of modern wild rice. However, the Yangshao period rice differs from modern domesticated rice. Thus, the rice was still being domesticated.

4.3. Mixed Rice–Millet Farming in the Upper Huai River Region

To date, the earliest agricultural evidence in the upper Huai River region is from the Jiahu site (9000–7800 BP), where abundant carbonized rice remains were observed and no millet remains were observed [61]. In the middle and lower regions of the Huai River, rice farming was also the sole farming type before 7000 cal. BP [62,63]. Mixed rice–millet farming emerged in the middle reaches of the Huai River region during ~7300 to 6800 cal. BP [14]; however, in the upper Huai River region, the evidence of mixed farming was late to ca. 5700–5000 cal. BP at the Hunanguo and Agangsi sites [64]. However, the gap between these periods hindered the study of when mixed farming began and how the agricultural structure shifted in the upper region.

The phytolith results from Zhangwangzhuang provide the earliest evidence of mixed millet and rice farming during the early Yangshao cultural period in the upper Huai River region. The presence of broomcorn millet phytoliths indicates that mixed rice–millet farming occurred approximately 6000 years ago, filling the evidence gap in the agriculture structure of this region. As for foxtail millet in this region, only one piece of foxtail millet phytolith without a typical Ω form was found in our study. We cannot discount the possibility that foxtail millet was being cultivated in this region at the time, because a recent study [32] of starch grain analysis from 54 pottery sherds and 13 stone tools at Zhangwangzhuang revealed that about 30% of the starch grains were from millets, and among the millet starches, foxtail millet accounted for 90% while broomcorn millet only accounted for 10%. The starch grains result indicated that foxtail millet is an important crop with broomcorn millet accounting for a small portion, while no rice starches were reported in the crop assemblage.

The controversy in the crop pattern reflected by phytoliths and starch grains might have resulted from the bias of different methods. In terms of phytolith, only phytoliths from the upper lemma and palea of millets could be retrieved and identified [41] in archaeological deposits, whereas phytoliths from leaves, stems, and glume cells of rice could be identified [45,65]; thus, in the phytolith-based agriculture structure, rice is the dominant crop rather than millets. As for the indicator of starch grain, critical progress has been made in the identification of millets [66] while barely any systematic study has been made on rice. Hence, the differences between the results of the two indexes could be greatly aggravated by these factors.

Overall, combing the phytolith and starch grain results, mixed farming, including rice, broomcorn millet, and foxtail millet, should have been present at the Zhangwangzhuang site during the early Yangshao period. Considering the potential bias involved with different micro-remains methods, the specific crop pattern at Zhangwangzhuang should be evaluated by a multi-index including a macro-remains study in the future.

5. Conclusions

Based on the discriminant analysis of phytolith assemblages, 17 of 30 samples in the suspected paddy field area at the Zhangwangzhuang site were identified as rice paddy fields with an average probability of 74%. The result demonstrated that the suspected rice paddy field at Zhangwangzhuang is likely to be the earliest known rice paddy field in northern China and can be dated to ca. 6000 cal. BP. The surrounding environment and the general climatic conditions were favorable for the development and management of rice paddy fields. Further analysis of the crop phytoliths suggested that rice and millet mixed farming occurred in the upper Huai River region as early as the early Yangshao cultural period and the proportion of rice bulliform phytoliths with ≥9 scales indicated that rice was still in the process of domestication.

This study adopted new methods to identify ancient rice paddy fields and is the first application of phytolith assemblage discriminant functions at an archaeological site. We revealed the existence of a new rice paddy field outside the core rice origin area and provided new evidence for the development of mixed millet and rice farming in China.

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