Neolithic cultivation of water chestnuts \((Trapa L.)\) at Tianluoshan (7000-6300 cal BP), Zhejiang Province, China

Yi Guo\(^1\), Rubi Wu\(^1\), Guoping Sun\(^2\), Yunfei Zheng\(^2\) & Benjamin T. Fuller\(^3\)

Water chestnuts \((Trapa)\) are frequently recovered at Neolithic sites along the Lower Yangtze River Valley and have been important components of the diets of prehistoric people. However, little systematic research has been conducted to determine their cultural and dietary importance. Excavations at the Tianluoshan site produced large quantities of well-preserved specimens, which provide an excellent collection for studying morphological changes with time. Using modern wild and domesticated water chestnuts \((n=447)\) as a reference, we find Neolithic samples \((n=481)\) at Tianluoshan are similar in shape but smaller in size compared to the domesticated species \(Trapa bispinosa\). In particular, the Tianluoshan water chestnuts have bigger seeds than the wild species \(Trapa incisa\). Further, water chestnuts diachronically increased in size at the Tianluoshan site with significant differences \((one-way, ANOVA)\) observed for length \((p=7.85E-08)\), height \((p=3.19E-06)\), thickness \((p=1.2E-13)\), top diameter \((p=5.04E-08)\) and bottom diameter \((p=1.75E-05)\) between layers 7 \((6700-6500 \text{ cal BP})\) and 6 \((6500-6300 \text{ cal BP})\). These results suggest that water chestnuts were actively selected based on size \((big)\), shape \((full fruit, two round horns, wide base, etc.)\) and were an important non-cereal crop to the agricultural practices at the Tianluoshan site.

The water chestnut \((Trapa L.)\) is an edible plant that grows widely in Eurasia, Africa, North America and Australia\(^1\). In China, this plant is mostly distributed in the subtropical region of the Yangtze River drainage basin\(^3\). Water chestnuts have a long history of utilization\(^6\), and the early use of water chestnuts for human consumption is found at many locations across China. Currently, there are 21 Chinese Neolithic sites where water chestnuts have been discovered \((Table \ 1)\). This indicates that water chestnuts were one of an important number of foods for the ancient people of China, especially for the inhabitants of the Middle and Lower Yangtze River Valleys\(^8\). In addition, rice remains are normally found associated with the water chestnuts\(^8\), suggesting that the production and utilization of water chestnuts share common characteristics with rice agricultural systems.

Due to a lack of systematic research on Chinese water chestnuts, there are many questions associated with the timing, places and processes by which water chestnuts were domesticated as well as its importance in the diets of prehistoric people\(^8\)\(^-\)\(^12\). In the past, many scholars have identified water chestnuts as a wild food that was gathered, rather than actively selected for cultivation\(^13\)\(^-\)\(^14\). This was certainly the case for many Neolithic sites. For example, the more than 7000 pieces of water chestnuts unearthed at the Jiahu site \((9000-7800 \text{ cal BP}, \text{ Jiahu Culture})\) are associated with the wild variety and are believed to have played an important role in the gathering economy of these people\(^15\)\(^-\)\(^16\). However, at the Qucheng site \((7000-5500 \text{ BP}, \text{ Majiabang Culture})\) water chestnuts are similar in shape but smaller in size to the modern domesticated Nanhu water chestnuts which are the primary variety cultivated in Jiaxing City\(^8\). In addition, water chestnuts from the Fujiaoshan site \((6500-4500 \text{ cal BP}, \text{ Hemudu Culture})\) are regarded as domesticated water chestnuts\(^7\).

The Tianluoshan site \((7000-5800 \text{ cal BP})\) is located in Yuyao City, Zhejiang Province, China, and is about 120 km southeast from the modern city of Hangzhou \((Fig. \ 1a)\). It was an important site of the Hemudu Culture,
where plant, animal and human remains were recovered. Since 2004, eight cultural levels were excavated, and in the lower part of the site below layer 6, the artifacts are sealed in a waterlogged and anaerobic environment that results in exceptional preservation of organic material. Abundant plant remains have been recovered such as: rice (Oryza rufipogon/sativa), water chestnut (Trapa bispinosa), acorn (Quercus spp. (sensu lato)), foxnut (Euryale ferox), peach (Prunus persica), bottle gourd (Lagenaria siceraria), etc. Many of the water chestnuts found during the excavation are fragments that represent refuse from human consumption with a comparatively small number of intact specimens. However, in pits where the water chestnuts were stored, they were found completely intact. This large number of waterlogged and well-preserved water chestnuts recovered from the different cultural layers at Tianluoshan (Fig. 1e) permits the investigation of how these plants may have been selected for advantageous traits for human consumption through time.

Table 1. Summary of Neolithic sites in China that have found prehistoric water chestnuts remains. Note: ★ = uncalibrated age as original dating information was not available.

| No. | Site         | Species                  | Archaeological Culture | Age (cal BP) | City, Province | Comments | References |
|-----|--------------|--------------------------|------------------------|--------------|---------------|----------|------------|
| 1   | Jiahu        | †                        | Jiahu                  | 9000-7800    | Wuyang, Henan | more than 7000 pieces | 15,16     |
| 2   | Bashidang    | †                        | Pengtoushan            | 8000-7500★   | Lixian, Hunan | 150 half-fruit   | 53,54     |
| 3   | Chengtoushan | Trapa maximowiczii Korsch | Pengtoushan            | 6500-4800★   | Lixian, Hunan |          | 13        |
| 4   | Kuahuqiao    | T. bicornii Osbeck var. bicornis, T. quadrissipina Roxb. | Kuahuqiao            | 8000-7000    | Xiaoshan, Zhejiang |          | 41,42     |
| 5   | Xianun       | †                        | Kuahuqiao              | 8000-7000    | Xiaoshan, Zhejiang |          | 41,42     |
| 6   | Hemudu       | Trapa bispinosa Roxb.    | Hemudu                 | 7000-5800    | Yuyao, Zhejiang | shells    | 55        |
| 7   | Tianluoshan  | Trapa bispinosa Roxb.    | Hemudu                 | 7000-5800    | Yuyao, Zhejiang |          | 18        |
| 8   | Fujiashan    | †                        | Hemudu                 | 7000-5800    | Ningbo, Zhejiang |          | 17        |
| 9   | Majiabang    | Trapa acorns Nakano      | Majiabang              | 7000-5800★   | Jiaxing, Zhejiang |          | 8         |
| 10  | Luqiajiao    | †                        | Majiabang              | 7000-5800    | Tongxiang, Zhejiang |          | 11        |
| 11  | Xingqiao     | Trapa maximowiczii Korsch | Majiabang              | 7000-5800★   | Tongxiang, Zhejiang | 13 horns, average length 13mm, carbonized | 56        |
| 12  | Qiucheng     | Trapa acorns Nakano      | Majiabang              | 7000-5800★   | Wuxing, Zhejiang |          | 8         |
| 13  | Caoxieshan   | Trapa acorns Nakano      | Majiabang              | 7000-5800    | Wuxian, Jiangsu | stems and fruits | 57        |
| 14  | Longquzhuan  | †                        | Longquzhuan            | 7000-5500    | Gaoyou, Jiangsu |          | 58-60     |
| 15  | Yuhuzhai     | †                        | Banpo and Shijia Periods | 6500-5500 | Xi’an, Shaanxi |          | 14        |
| 16  | Choudun      | †                        | Majiabang to Maqiao    | 6300-3300    | Kunshan, Jiangsu |          | 13        |
| 17  | Longnan      | †                        | Songze to Liangzhu     | 5360-4760    | Wujing, Jiangsu |          | 61        |
| 18  | Bianjiashan  | †                        | Liangzhu               | 5300-4200    | Yuhang, Zhejiang |          | 62        |
| 19  | Qingduan     | †                        | Liangzhu               | 5300-4200    | Hai’an, Jiangsu |          | 8,63      |
| 20  | Qianshanyang | T. acorns Nakano, T. maximowiczii Korsch., T. quadrissipina Roxb. | Qianshanyang          | 4400-4200    | Wuxing, Zhejiang |          | 65,66     |
| 21  | Guangfulin   | Trapa bispinosa Roxb.    | Guangfulin             | 4200-4000    | Shanghai    | charred fruits, flesh and pieces of shells; 360 fragments | 66,67     |

Table 1. Summary of Neolithic sites in China that have found prehistoric water chestnuts remains. Note: ★ = uncalibrated age as original dating information was not available.
Results

All sample information and measurements are listed and summarized in the Supplementary Tables 1 and 2. Comparison of the waterlogged and preserved samples (see Methods section below) from pit H69 (layer 6) found no statistical differences for the five measured parameters except for the top diameter ($p = 0.017$, one-way ANOVA), which was larger in the preserved specimens (Table 2). This suggests that caution should be applied in the interpretation of this parameter. However, the effects of preservation were not significantly different for the other measurements and the two groups were treated equally. The water chestnut measurements are grouped according to archaeological layer in Table 3, and are found to increase in size from layers 8 to 6. No statistical differences were found between the measurements of layers 8 and 7. However, significant differences (one-way, ANOVA) were observed for length ($p = 7.85 \times 10^{-8}$), height ($p = 3.19 \times 10^{-6}$), thickness ($p = 1.2 \times 10^{-13}$), top diameter ($p = 5.04 \times 10^{-8}$) and bottom diameter ($p = 1.75 \times 10^{-5}$) between layers 7 and 6.

In terms of shape characteristics (Table 4) (classification methods can be found in the Method section), the majority of the Tianluoshan water chestnuts (~77%) belong to Type III. They have a relatively large size in comparison to the other types, and have the shape of an inverted triangle (Fig. 2a). The fruits are plump and the shoulder horns are short, round and not spinous. The beak is not distinct and the base connected to the stem is wide. The Type II specimens (~20%) have the shape of a diamond and possess a big crown and neck. In addition, few Type II specimens possess mastoids on their abdomen. The two shoulder horns point horizontally or at a slight angle upwards and have short, sharp and hard tips (usually together with big horns). The Type I water chestnuts or the wild variety are found in the smallest numbers (~4%) and are generally smaller in size with a narrow-inverted-triangle shape and a crown on the top. The shoulder horns slant upward and have hard tips while the base is generally shorter than the Type II samples. Most of the Type I specimens have mastoids on their abdomen, and bases that are similar to those of Type II.

Discussion

Water chestnuts have a long and stable presence in the archaeobotanical assemblage at Tianluoshan. The large quantities of intact water chestnuts from storage pits, as well as the broken pieces from human consumption, reflect the important role that this plant played in the human diet.

Diachronic increases in the size of the Tianluoshan water chestnuts from layers 8 to 6 are shown in Fig. 3. These archaeological specimens are smaller than the modern domestic types but remarkably bigger than the modern wild types. In terms of shape, Type III (full fruit, two round horns, wide base, etc.) occupy the dominant position at Tianluoshan for at least 700 years. Comparing the Neolithic water chestnuts with the modern Chinese varieties, specimens at Tianluoshan are relatively similar in shape with the domesticated species *Trapa bispinosa* Roxb., but distinctly different from the wild species *Trapa incisa* Steh. and Zucc. (Fig. 4).

According to modern botanical research genetic polymorphisms are found in water chestnuts, and they are capable of generating new variants in the wild. In the absence of human intervention, they will not consistently produce the same size and shape of fruit if subjected to variable and/or unfavorable growing conditions. For example, in order to maintain the desirable traits of the Nanhu water chestnuts (a highly domesticated species without sharp horns), modern farmers need to accomplish a series of activities at specific growing times such as: picking the water chestnuts, selecting the good ones for conservation and sowing, maintaining and cleaning the
Table 2. Results of one-way ANOVA on Neolithic water chestnuts conserved in two ways (unit: mm) Note: a,b are used to show the outcome of the one-way ANOVA, the same letter under the same column means no significant difference.

| Layer | Time (cal BP) | Length | Height | Thickness | Top Diameter | Bottom Diameter |
|-------|---------------|--------|--------|-----------|--------------|-----------------|
| H69 Waterlogged | 6500-6300 | 262 ± 1.46 | 16.90 ± 2.17 | 13.60 ± 2.70 | 6.48 ± 0.91 | 11.17 ± 2.57 |
| H69 Preserved | 6500-6300 | 52 ± 1.44 | 17.48 ± 2.34 | 13.74 ± 2.73 | 6.83 ± 1.20 | 11.73 ± 2.80 |

Table 3. Results of one-way ANOVA on Neolithic water chestnuts summed by layers (unit: mm). Estimated ages of the layers are based on radiocarbon dates from Wu et al. and Jin et al. Note: a,b,c are used to show the outcome of the one-way ANOVA, the same letter under the same column means no significant difference.

| Location | Type I (Wild) N (%) | Type II (Intermediate) N (%) | Type III (Domesticated) N (%) | Sum of Samples |
|----------|---------------------|-----------------------------|-----------------------------|----------------|
| T104 Layer 8 Preserved | 2 (28.6%) | 5 (71.4%) | 0 (0%) | 7 |
| T206 Layer 8 Preserved | 3 (7.9%) | 4 (10.5%) | 31 (81.6%) | 38 |
| T205 Layer 7 Waterlogged | 4 (5.5%) | 12 (16.4%) | 57 (78.1%) | 73 |
| T305 Layer 7 Waterlogged | 3 (6%) | 11 (22%) | 36 (72%) | 50 |
| H69 Layer 6 Waterlogged | 3 (1.1%) | 54 (20.7%) | 204 (78.1%) | 261 |
| H69 Layer 6 Preserved | 2 (3.8%) | 7 (13.5%) | 43 (82.7%) | 52 |
| Total | 17 (3.5%) | 93 (19.3%) | 371 (77.1%) | 481 |

Table 4. Distribution of the shapes of the Neolithic water chestnuts at Tianluoshan.

Since the majority of the Tianluoshan water chestnuts unearthed from layer 8 already show a similar type with *Trapa bispinosa*, while only a minority are approximately close to *Trapa incisa*, this suggests that the domestication of water chestnuts in this region had commenced sometime earlier than approximately 7000 years ago. Thus, the Tianluoshan water chestnuts were already in the process of domestication but had not yet reached the modern version in terms of size and shape of the domesticated species. So far among the sites of the Shangshan Culture (11000–8600 cal BP), which is one of the oldest Neolithic cultures discovered in the Lower Yangtze River Valley, only starch grains of water chestnuts have been found. However, the macro-remains of water chestnuts have been recovered at the Kuahuqiao site (8000–7000 cal BP) (Fig. 1b,c). Future work is planned to investigate the size and shape of the water chestnuts from Kuahuqiao, and these results will be compared to those of Tianluoshan to better understand the timing and the process of water chestnut cultivation and management in the Lower Yangtze River Valleys of China.
Conclusions
In spite of being previously considered as a wild dietary resource that was gathered during the Neolithic, the water chestnuts at Tianluoshan demonstrate that they were already under intensive domestication and cultivation by approximately 7000 BP. This finding supports the view that Neolithic humans had a good command and understanding of natural resources such as the growth cycles and requirements of various plant species. These findings at Tianluoshan support past archaeobotanical research from other parts of the world that agricultural intervention was applied to a series of plant resources, rather than to cereals only. Thus, humans had well-adapted and developed subsistence strategies based on local environmental and climate conditions. This viewpoint is now being recognized by more scholars in China, and contributes to a deeper understanding of how non-cereal plants were influenced by human activity and selection in the Lower Yangtze River Valleys of China.

Methods
Two types of methods were used to collect the water chestnuts at Tianluoshan. 1) In storage pits, the majority of water chestnuts were preserved intact and hand shovels were used to excavate and collect the remains. 2) In the cultural layers, the water chestnut remains were generally husk fragments. However, after manually washing the soil, some complete water chestnuts were selected from the other botanical remains with the use of a mesh screen (0.34 mm).

Figure 2. (a) Photographs that represent the three general shapes of classification for Type I (wild), Type II (intermediate) and Type III (domestic) water chestnuts. (b) Photographs depicting the specific regions of the water chestnut based on the work of Wang et al. (c) Diagram showing the measurement locations of the water chestnuts. L: length; H: height; TD: top diameter; T: thickness; BD: bottom diameter.

Figure 3. The relationship between length and height of Neolithic Tianluoshan and modern water chestnuts from China.
Complete or nearly complete water chestnuts (n = 481) from five different excavated grids (layers 6 to 8) of the Tianluoshan site were collected and measured with an electronic digital caliper (brand: Guanglu, range: 0–200 mm) to two significant figures (Fig. 2a,b). Since most of the Neolithic water chestnuts do not have obvious necks and humps, which are diagnostic characteristics of modern species, we decided to take measurements of length, height, thickness, top diameter and bottom diameter49–51 to quantify the shapes and sizes of the specimens (Fig. 2c).

The majority of the Neolithic samples (n = 384) were preserved in their original waterlogged condition. However, some of the water chestnuts (n = 97) were previously conserved in a solution of trehalose and water according to the protocol of Nagahama et al.52. In order to investigate possible differences related to these preservation conditions between waterlogged (n = 261) and trehalose preserved water chestnuts (n = 52), measurements from both types of samples from pit H69 (layer 6) are directly compared. In addition, eight different modern water chestnuts (n = 447) were also measured including three wild varieties (n = 268) and five domesticated types (n = 179) (Fig. 3). One of these wild populations grows freely inside of the Hemudu site park (~7 km from Tianluoshan), and the other two are from Hubei Province and Shandong Province. The domesticated species were purchased from markets in Yuyao, Jiaxing and Hangzhou, modern cities located in eastern and northern Zhejiang Province.

Water chestnuts were also sorted into three different shape classifications. These were characterized as: Type I (wild), Type II (intermediate) and Type III (domesticated) (Fig. 2a)1,49–51. The classification system developed here was based on past research which found that the size of the fruit is an extremely important criteria when classifying water chestnuts49,50. In addition, the shape and number of horns2,49,50, the existence and height of the mastoid50 and the shape of fruit27,31 can all function as features to separate water chestnuts into different groups.

First, the water chestnuts at Tianluoshan were placed into two groups according to the size of the fruit. The first group (containing Type I and II specimens) is smaller in size, with an average length of less than 30 mm. In addition, the Type I and II water chestnuts display certain wild type characteristics, such as comparatively sharp horns (defense against predators and to help the water chestnuts insert into the bottom of lakes for reproduction), a short bottom diameter (allowing it to break from the stem easier), and a bigger crown (Fig. 2a–c). In contrast, the second group is composed of the Type III specimens, and these are bigger in size with the majority of samples longer than 30 mm. Further, the Type III water chestnuts display certain domesticated features such as relatively shorter, wider and rounded horns, a wide bottom diameter and smaller or not obvious crowns (Fig. 2a–c).

After this initial classification, some additional differences in the first group suggest that they could be further divided into two additional types: Type I (wild) and Type II specimens. This was based on the work of Kadono27 who pointed out that the shape of the fruit is a critical feature when classifying *Trapa* and Wan51 who argued that the mastoid plays an important role in the classification of water chestnuts. Visual observation of the water chestnuts in the first group found that some of the samples had horns that slant upward, making the whole water chestnut a narrow inverted triangle shape (Fig. 2a (wild)). In addition, these specimens have mastoids on their abdomen. As these characteristics are quite similar to the modern wild water chestnuts collected in this paper, these specimens were classified as Type I (wild). The rest of the samples were observed to have horizontal horns, a diamond shape and few mastoids on their abdomen. These specimens display differences compared to the modern wild varieties, but have not reached the shape and size of the domesticated samples. Therefore, these specimens were classified as Type II or and intermediate stage of development.

Data availability. All data generated or analysed during this study are included in this published article (and its Supplementary Information files).

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Author Contributions
Y.G., R.W. and B.T.F. designed the research and analyzed data. R.W. performed the measurements. G.S. and Y.Z. provided materials and resources. Y.G., R.W., G.S., Y.Z. and B.T.F. wrote the paper.

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