Supplemental Notes

Supplemental Note 1. “Hoe” and “shovel” refer to the variable means of hafting finished tools. A hoe is hafted with its blade affixed perpendicular to the handle with its cutting edge being at the right angle to the shaft. A shovel is hafted with its blade affixed extending off the end of and its axis in line with the handle.

Supplemental Note 2. We employed a cone penetrometer, Beijing Eco-Agriculture Science and Development Co. ECA-YL01, to measure PR in the fields. Before each experiment, the soil penetration resistance value was measured at five to ten loci per experimental plot, each to a depth of 15 cm in rice fields, or 10 cm in the harder, non-agricultural fields, at depth intervals of 3–5 cm. For example, at Locus 1 in Plot 1, force was measured at depths of 5, 10, and 15 cm.

Supplemental Note 3. We measured soil water content in the Archaeometric Lab at the Zhejiang Provincial Institute of Cultural Heritage and Archaeology in Hangzhou, and the Soil Particle Size Laboratory of the College of Geographical Sciences, Fujian Normal University in Fuzhou. In these labs, 15–20 grams of soil from each sample were weighed, then oven-dried for up to 12 hours at a temperature of 100°C until they reached their “constant weight.” Values of gravimetric water content were then calculated as the ratio of weight lost to the constant weight.

Supplemental Note 4. Wet sieving was employed to measure sand fraction and laser diffraction for silt and clay. Soil samples (approximately 100 grams each) were ground finely enough to pass through a 2000 μm (2 mm) screen for the gravel fraction. In our samples, the gravel fraction includes all hard particles that could not pass through the 2000 μm screen, including not only regular gravels but small ceramic fragments and burned clay as well. Carbonates and organic matter were then removed by chemical processing from 25 g of the < 2000 μm sub-samples, and then the sand fraction (consisting of particles of 63–2,000 μm in size) was separated from clay and silt by means of chemical solution, physical disaggregating equipment, and finally mesh sieves of 63 μm.

Supplemental Note 5. An ideal method for estimating the energy costs of aerobic activities is measuring oxygen consumption; however, instrumentation for measuring oxygen consumption is expensive and impractical to use in the fields where our digging experiments were conducted. Alternatively, the heart rate-based caloric consumption calculation employed in our study was suggested by University of Arizona biological anthropologist David Raichlen whose research focuses on human energetics. The linear correlation between heart rate and oxygen consumption related to aerobic activities allows calculation of energy cost (i.e., calories burned). Because heart rates may also be influenced by other factors, such as emotional state and body temperature, strategies were employed to minimize these effects. For instance, each paired experiment was usually finished within a relatively short period of time so that the subject's body temperature and emotional state were maintained as closely as possible. Distractions that might potentially affect the participant's emotional state (e.g., the presence of others who might comment negatively on his capabilities and ridicule them) were removed before each experiment. During activity, the operators' heart rates were recorded with a Polar® RS800CX monitor every five seconds. In the end, these data were migrated into a Polar software package and calories burned were automatically calculated based on the operator's heart rates with respect to sex, age and body weight. In order to obtain a practical sense of energy costs, several operators' energy expenditures for normal walking or casual activities as well as for digging with iron hoes or tilling with iron shovels were also measured, and these were compared to energy costs for digging with stone and bone shovels (Supplemental Table 1). For instance, 1000 kcal could support Operator 13 walking 8.5 hours, excavating .57 m^3 of soil with a stone shovel, .23

m^3 with a bone shovel, or 2.75 m^3 with an iron hoe in Field VII. In Field VI, he could excavate .65 m^3 with a stone shovel or .28 m^3 with a bone shove.

Supplemental Note 6. The tool's worn-down area, rather than the worn-down mass or weight lost, was used in the calculation of implement cost, because the latter two measurements were either impractical to acquire or unreliable. The worn-down area was measured by two-dimensional morphological differences before and after use through superimposing the scanned images of before and after use and delineating areas worn down with Adobe Photoshop®.

Supplemental Note 7. In the pilot experiments, Operators 5 and 6 repeated paired experiments four times respectively and tilled 72 m^2 in total in the field to an average 10 cm-depth. Although the stone implement worked slightly better than bone in time-economy (although energy consumption was not yet clear) of digging in most of their paired experimentation, both Operators 5 and 6 expressed their preferences for bone implements for its "sharpness."

Supplemental Note 8. The paired experiments of bone and stone implements undertaken by Operator 6 were conducted on different days in two plots where soil penetration resistance differed significantly. The average soil penetration resistance in the plot where the stone implement was used was harder than where the bone variant was used (12.7 vs. 8 kg/cm^2). Operator 21 started his paired experiment with the bone implement and noticed edge damage resulting from occasionally impacting small rocks; consequently, when he dug with the stone implement he tried as best he could to avoid edge damage, which he believed was what the authors wanted. His adjusted behavior no doubt led to higher time and energy investments for completing a unit plot of digging than if he had acted more spontaneously.

Supplemental Note 9. Additional experiments conducted in Field VI comparing digging efficiency of a stone shovel and a stone hoe illustrated that a stone hoe works significantly better than a stone shovel, with mean differences of .71 hr/m^3, and 698 kcal/m^3, $W = 4$, $Z = 7.5$, $p = .0313$, $n = 5$ (Supplemental Table 2). Qualitative comments from the operators highlighted the stone hoe's time and energy efficiency and greater impact ability.

Supplemental Note 10. Calculation of this figure proceeded in the following way. Applying the equation of Bone Attrition Rate = 4.409238 + .0795057*PR*Sand (Figure 7), the wear rate of scapular spades penetrating the ground (with an average sand fraction of 22 percent and a PR value of 5.5 kg/m^2) is estimated at 4.409238 + .0795057*5.5*22=14 cm^2/m^3. With 120 cm^2 of potential area that could be worn down from the working edge (see section of "use-lives" of bone spades for detailed discussion), the consequent use-life of a scapular spade is estimated at 120/14=8.6 m^3.

Supplemental Note 11. Calculation of this figure proceeded in the following way. Applying the equation of Bone (hr/m^3) = $.3244^{.1448*PR}$ (Figure 3), it would have taken $.3244^{.1448*5.5}$ = .72 hour to loosen 1 m^3 of soil, and so to loosen 8.6 m^3 it would have taken .72*8.6=6.2 hours.

Supplemental Note 12. Calculation of this figure proceeded in the following way. First, with the equation of Attrition rate = -.240143 + .1097619*PR (Figure 5), bone spade's attrition rate is estimated at -.240143 + .1097619*3 = .089. Then, with 120 cm^2 of potential area that could be worn down from the working edge (see section of "use-lives" of bone spades for detailed discussion), one single bone spade could have excavated 120/.089=1348.31m^3 of rice field, or tilled 13,483.1 m^2 of rice field to a 10-cm depth. Finally, tilling 6.3 ha (i.e., 63,000 m^2) of rice fields (Zheng et al. 2009) to a 10-cm depth would have exhausted 63,000/13,483.1= 4.7 bone implements.

Supplemental Note 13. Calculation of this figure proceeded in the following way. First, with the equation of Bone attrition rate = 4.409238 + .0795057*PR*Sand (Figure 7), bone spade's attrition rate is estimated at 4.409238 + .0795057*4.5*.08=4.44. The PR (penetration resistance) value applied in this calculation, .08, is an average value of 13 measurements in the Hemudu rice fields. With 120 cm^2 of potential area that could be worn down from the working, one single bone spade could have excavated 120/4.44=27.04m^3 of rice field, or tilled 270 m^2 of rice field to a 10-cm depth. Finally, tilling 6.3 ha (i.e., 63,000 m^2) of rice fields to a 10-cm depth would have exhausted 63,000/270 = 233 bone implements.

Supplemental Note 14. Calculation of this figure proceeded in the following way. First, with the equation of time cost with bone spades for digging activities, Bone (hr/m^3) = $.3244^{.1448*PR}$ (Figure 3), a person with a bone spade could have used $.3244^{.1448*3}$ = .5 hours to till 10 m^2 of field to a 10-cm depth when soil PR value was 3. Therefore, within assuming five working hours each day, one person could have till 100 m^2. To complete tillage of the 6.3 ha of rice fields would have taken 30 people 63,000/30/100 = 21 days.

Supplemental Note 15. The source of the pure yellowish clay is unknown and we plan to investigate the source in the near future. For the convenience of demonstrating how our experimental results can be applied to estimate time, labor, and implement assumption for constructing massive earthen projects, we assume that it is the Xiashu Loess that is commonly distributed in the area. Calculation of these figures proceeded in the following way. First, with the equation of time cost with stone spades for digging activities (Figure 3), Stone (hr/m^3) = $.4063^{.1024*PR}$, a person with a stone spade could have used $.4063^{.1024*22.6}$ = 4.1 hours to dig out 1 m^3 of Xiashu Loess. Therefore, within assuming five working hours each day, a worker could have excavated only 1.22 m^3 of soil. Two hundred people equipped with stone spades could have excavated 243 m^3 of soil per day. To procure 1,380,000 m^3 of soil, it would have taken these 200 people 1,380,000/243=5,679 days, i.e., almost 15.6 years to accomplish.

Supplemental Note 16. Calculation of this figure proceeded in the following way. First, with the equation of stone's attrition rate = .0494806 + .3161917*PR (Figure 6), stone spade's attrition rate is estimated at .0494806 + .3161917*22.6=7.2. Then, with 120 cm^2 of potential area that could be worn down from the working edge (see "use lives" of bone spades for detailed discussion); a single stone spade could have excavated 120/7.2=16.7m^3 of Xiashu Loess. Finally, 1,380,000 m^3 of Xiashu Loess would have exhausted 1,380,000/16.7 = 82,635 stone implements.

Supplemental Table 1. Activities Supported by 1000 kcal.

ID	Walk (hr)	Casual act. (hr)	Regular digging (m³)																		Tillage (m²)								
			Field I		Field II		Field III		Field IV			Field V		Field VI				Field VII			Field II		Field III		Field IV			Field V	
			Ss[1]	Bs[2]	Ss	Bs	Ss	Bs	Ss	Bs	Is[3]	Ss	Bs	Ss	Bs	Sh	Ih	Ss	Bs	Ih[4]	Ss	Bs	Ss	Bs	Ss	Bs	Is	Ss	Bs
13	8.47								1.21	1.3				.7	.3			.6	.2	2.8					23	29			
15	6.25													.6	.3			.3	.1										
16	9.62													.3	.3	.6	1.3	.3	.2	1.3									
17	7.3													.4	.3	.6	1.3												
18	6.9													.4	.2														
2		3.77	6.16	7.35	7.3	5.77						2.8	2.2								53	50						35	29
19		4.54			7.1	8.71						3.2	2.4								67	59						48	42
4	7.04		11.1	10.2																									
5	11.6		7.91	10.5	7.2	5.79	6.7	5				7.8	4.1								69	71	67	53					
6		4.74, 6.8	9.41	10	7.6	5.93	2.8	3.8				2.7	3.2								83	67	33	42				46	46
7	5.13						5.1	5.3															53	56					
8									2.19	2.2	7.8														38	53	111		
10									3.61	2.7	4.4														43	42	63		

Note: Operator 2's casual activities included carrying several modern and experimental tools while talking and walking; Operating 19's included carrying two experimental bone and stone digging tools while walking; Operator 6's included talking and smoking at rest and slow walk in summer for 4.74 hours, and slow walk, talking, and driving a motorcycle in winter for 6.8 hours.

[1] Ss = stone shovel

[2] Bs = bone shovel

[3] Is = iron shovel

[4] Ih = iron hoe

Supplemental Table 2. Time and Energy Expenditures of Stone Hoes and Shovels Digging in Field VI.

ID	**Age**	**Imple-ment**	**Area (m^2)**	**Dep. (cm)**	**Time (sec.)**	**Energy (Kcal)**	**Energy-eco. (kcal/m^3)**	**Time-eco. (hr/m^3)**	**Pref.**
13	61	Ss[1]	.6	2.8	262	26	1548	4.33	Sh*[1]
		Sh[2]	.6	2.9	212	20	1149	3.38	
16	73	Ss	.6	4	543	80	3333	6.28	Sh*[2]
		Sh	.6	3.2	389	34	1771	5.63	
17	75	Ss	.6	2.5	398	40	2667	7.37	Sh*[3]
		Sh	.6	2.5	374	24	1600	6.93	
19	59	Ss	.6	4.7	436	35	1241	4.29	Ss*[1]
		Sh	.6	5.3	390	29	912	3.41	
20	73	Ss	.6	4.6	404	35	1268	4.07	Ss*[1]
		Sh	.6	2.2	164	15	1136	3.45	

Note: Reasons for implement preferences: Sh*1 = more efficient; if hafted with a longer handle, would be more comfortable and definitely better than the shovel; Sh*2 = great impact; Sh*3 = labor-saving. Ss*1 = longer handle, otherwise, no difference between the shovel and the hoe.

[1] Ss = stone shovel

[2] Sh = stone hoe