

**Archaeobotanical investigations on the role of
agriculture in social changes: case studies of the
Central Plain and Haidai Region, China, from
the Late Neolithic to the Early Bronze Age**

Dissertation in fulfilment of the requirements for

the doctoral degree

at the Faculty of Arts and Humanities

at Kiel University

in Kiel.

submitted by

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Kiel, 2021

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Date of the oral examination: June 30, 2021

Approved for printing by the second Vice Dean: July 19, 2021 by
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ABSTRACT

The long-term response of ancient societies and agriculture to climate change has been a matter of global debate. In the Central Plain and Haidai Region of China, the period from the Late Neolithic to the Early Bronze Age (ca. 2400-1046 cal. BCE) was important for both cultural evolution and climatic change. Culturally, the chiefdom-like Late Neolithic Longshan culture (2400-1800 cal. BCE) showed the trend of collapse around 2100/2000 cal. BCE in the East-Haidai and around 1800 cal. BCE in the West-Haidai whereas the Longshan and Xinzhai cultures (2300-1750 cal. BCE) in the Central Plain exclusively stepped into a state-level new era around 1750 cal. BCE. Paleoclimatically, this period witnessed several climatic fluctuations, especially the profound cool and drought event occurring around 2200 BCE. The remarkable decline in the rainfall and temperature after the 2200 BCE climatic event clearly affected natural conditions for agriculture and directly impacted a society's ability to produce stable grain yields. This circumstance is apparently a limiting factor for social development in given regions. However, there is no simple correlation between climatic deterioration and social collapse. In the case of this research, the earliest states emerged in the Central Plain when environmental factors appear to be less than optimal. Such a case dictates that it is of great value to re-assess the relationship between social transformations and climatic changes. In this Ph.D. project, agriculture has been chosen to re-evaluate the social evolution of these Late Neolithic societies since it can reshape societies by adjusting and overcoming environmental constraints and potentials.

In previous archaeobotanical investigations, the West-Haidai and the East-Haidai have always been studied in a package and described as the social collapse synchronously occurred in the Yueshi period (1800-1450 cal. BCE). This idea leads to the theory that this social change is due to the decline of Longshan rice farming after the 2200 BCE climatic event. However, the social collapse actually occurred earlier in the East-Haidai, more importantly, rice farming was not the only agricultural form during the Longshan period. Meanwhile, the unique multi-cropping system in the Central Plain has been considered as one of the main reasons for the cultural prosperity in the Erlitou period (1750-1550 cal. BCE). However, in this hypothesis, the environmental factor has been overlooked. In a period of environmental deterioration with a cooler and drier climate, rather than water-requiring crop species, a shift to drought-tolerant crop species such as the preferences of millet (*Setaria italica*, *Panicum miliaceum*) dry farming during the

Yueshi period in the West- and East-Haidai is expected. Thus, agriculture behind the rise and demise of Neolithic cultures in China remains open for discussion. Given these conditions, the agricultural conditions in these regions have been revealed with a compilation of previous archaeobotanical data covering the Late Neolithic and the Early Bronze Age, and an analysis of new samples from the Xinzhai site of the Xinzhai period (1850-1750 cal. BCE) in this project. The results are presented in the form of a cumulative dissertation composed of four papers.

Rather than ranging broadly overview of the whole Central Plain, a case study of the crop water management and the crop processing method in the Xinzhai settlement is presented in the first two contributions. It shows that the settlement formed an irrigated wet rice farming and a rainfed millet dry farming. This result is further used to interpret the concentration of rice in central settlements: due to the extra inputs of labour and time in irrigation, rice became a prestige food and closely related to elites and regional centres. Meanwhile, the processing of crops was organized on small units of household which is of distinctive difference with the other Xinzhai period sites. This diversification in the social organization with some sites keeping the communal organization but some shifting to households is different from the unified communal organization in the Yangshao period (5000-2500 cal. BCE) but similar to the pattern in the Longshan (2300-1900 cal. BCE) and Erlitou-Shang periods (1750-1046 cal. BCE). The third paper serves as a regional overview of archaeobotanical data in the Central Plain. While entering the Early Bronze Age, the Erlitou societies developed a similar agricultural system with the Xinzhai period but a change of an abrupt increase of wheat occurred since the Early Shang period (1550-1300 cal. BCE). This consistency and change in agriculture can be interpreted through the practice of irrigation. The last paper acts as a comparative study of agriculture between the West- and East- Haidai. Unlike the agricultural technique in the Central Plain, the different social transformations while facing huge climatic changes are attributed to the specific resilience of rice farming and millet farming. Furthermore, different agricultural strategies such as population migration to new ecological areas and agricultural extensification to maintain crop production also contributed to the social changes. To sum up, a diverse but very important role of agriculture can be proposed underlying the social changes during the Late Neolithic to the Early Bronze Age in this Ph.D. research.

ACKNOWLEDGEMENT

I would like to express my greatest gratitude to all those people who have helped to accomplish this doctoral dissertation. First, I am grateful to my first supervisor Prof. Wiebke Kirleis. It has always been a great pleasure to discuss my papers with her. With her broad views of world Archaeobotany and Palaeoecology, I can interpret my own database from a broader perspective. I am also very grateful to Prof. Johannes Müller. With his generous agreement to be my co-supervisor, I finally manage to pursue a doctoral degree in Germany. Second, I want to express my gratitude to Prof. Guiyun Jin at Shandong University. She gave me great supports during my doctoral study. She has always shared the most frontier research papers with me and it helped me build a solid archaeological background. Moreover, I wish to thank my colleagues with whom I could discuss and share ideas. Dr. Marta Dal Corso has discussed phytolith with me from sampling to lab processing and to the final interpretation. She patiently read the draft of my paper, gave many inspiring comments, and helped me to arrange an academic paper in a more scientific way. PD Dr. Mara Weinelt has generously contributed many constructive comments to the Paleoenvironmental background of this research. The methods used in this paper have been discussed with Dr. Jutta Kneisel (CA, Oxcal program), Stefanie Schaefer (CA), Dr. Anna E. Reuter (RI Index), Robert Hoffman (Oxcal program), Dr. Ingo Feeser (Countpal program), especial thanks to Jutta, she has been very patient and helpful with the data interpretation. Dr. Helmut Kroll, Yasmin Dannath, Dr. Wanli Lan helped in the identification of macro-botanical remains and shared many plant-ecological information. This dissertation would not be possible without the new samples provided by Dr. Chunqing Zhao from the Xinzhai team, the Institute of Archaeology, Chinese Academy of Social Sciences in China. Dr. Weihong Wu, Huadong Zhu (Anhui University), Honghong Wei (Archaeological Institute of Zhengzhou), Guangxiang Geng (Xinyang Museum), and the year 2016- archaeological students in Anhui University have offered great help in the collection of samples. Besides, the writing of this dissertation was financially supported by the Chinese Scholarship Council (CSC201706220058) and the China National Natural Science Foundation (41771230), and research facilities were provided by the Graduate School of Human Development in Landscapes (GSHDL) (until October 31, 2019) and the Young Academy of the Cluster of

Excellence ROOTS (EXC 2150) (from October 31, 2019) at Kiel University.

I also want to thank my friends and colleagues with whom I had lots of enjoyable time and overcame my anxieties while facing the Ph.D. crisis: Wenjuan Huo, Anna Wierzgon, Tanja Reiser, Peng Cao, Sonja Filatova, Hong Cuc Bui, Vio Con, Si Wang. Also, thanks for the accompany of Möwen (seagulls), everyday morning they kindly woke me up with their beautiful voice and only left until they made sure that I would not oversleep. Last but not least, I would like to thank all my beloved family members, particularly my parents and fiancé, who have been supporting me all the time in any possible way.

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1. Introduction

1.1 Research area and research timeframe

Research area of the Central Plain and the Haidai Region

The main aim of this research is to investigate the role of ancient agriculture in social transformations within a relatively broad timeframe from the Late Neolithic to the Early Bronze Age (ca. 2400-1046 cal. BCE) in the Central Plain and the Haidai Region of China (Fig. 1.1.1). The reason behind this topic is several important social changes were recorded in these regions during this period. In the Central Plain, particularly its core region-the Zhengluo Region, it is expressed as the emergence of the earliest urban centers around 1750 cal. BCE (Chang 1986, 1999; Liu and Chen 2012; Zhang 2017a; Han 2019a,b). In the Haidai Region, the social change is marked by the collapse of Longshan culture around 2000 cal. BCE in the East-Haidai and around 1800 cal. BCE in the West-Haidai (Liu and Chen 2012; Luan 2016; Han 2019a,b). However, we know surprisingly little about the role of agriculture underlying these social changes. Although China is well known for its rich historical documents, the earliest document is in the Shang period presenting in the form of inscriptions on bones or tortoise shells, therefore, the reliable recording of earliest China started from the Shang period whereas the Late Neolithic and Erlitou (Xia) period almost remain in blanks (Chang 1981; Boltz 1986; Keightley 1996). Besides, although Paleoclimatic change has long been a focus of attention in Chinese archaeology, the study of correlations among agriculture, environmental change, and the societal response has met with frustrations. Moreover, since our understanding of the Late Neolithic- the Xinzhai period (1850-1750 cal. BCE) -in the Central Plain is insufficient, it is still unclear why the earliest state only initially emerged from a limited region in the Central Plain, but not multiple states simultaneously developed over many regions such as the Haidai Region. It is, thus, of great value to understand the interaction of agriculture and environmental conditions underlying these social changes.

The “Central Plain Cultural Region” and “Haidai Cultural Region” or simply the “Central Plain” and “Haidai Region” in an abbreviated way are definitions from an archaeological perspective (Yan 1987; Gao and Shao 1984). Geographically, the Central Plain is situated in the Middle Yellow River and occupies a pivotal central

1.Introduction

position that can be connected with surrounding cultures from all directions (Zhang 2007; Cao 2012; Liu and Feng 2012). The Haidai Region is located on the Lower Yellow River along the east coast of China and it was (and still is) an important traffic point connecting China and the other East Asian cultures through the sea road (Chen 1989; Yan 1989; Luan 2005; Ahn 2010). As cultural definitions, their distribution areas varied during different periods. On their peaks, the Central Plain covers parts of modern Shaanxi, Shanxi, Hebei provinces and the whole Henan province (Yan 1987; Su 1991,1999; Li 2008) and the Haidai Region includes the whole modern Shandong province, the northern parts of Jiangsu and Anhui, eastern Henan, south-eastern Hebei and the southern part of the Liaodong Peninsula (Shao and Gao 1984; Shao 1989; Luan 1997) (Fig. 1.1.1).

In this research, the Central Plain is limited to the core region- the Zhengluo Region -covering the modern central and western Henan province. The West-Haidai and East-Haidai are divided by a line drawn by the Wei River, the Yi mountain, and the Meng mountain spanning from northeast to southwest. The East-Haidai covers the modern northern Anhui, the northern Jiangsu, and the eastern Shandong. The West-Haidai includes the modern southern Liaodong Peninsula and the western Shandong. Because the eastern Henan has more cultural communication with the region of West-Haidai during the Longshan and Yueshi periods (Luan 1992), thus, also belongs to the West-Haidai in this project.

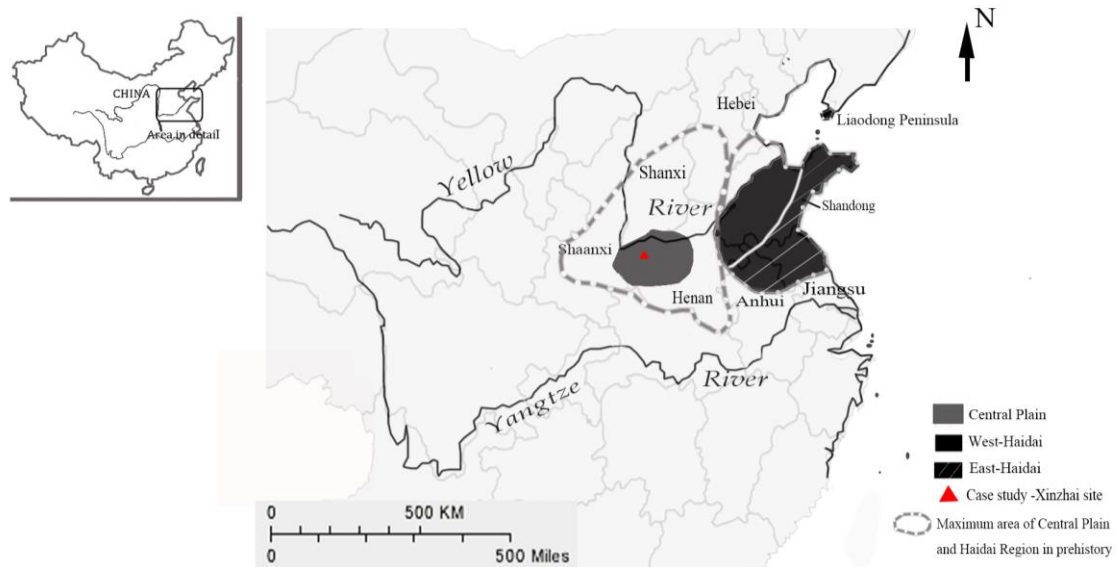


Figure 1. 1. 1 Location of the Central Plain and the Haidai Region (modified from Yan 2015)

Research timeframe from the Late Neolithic to the Early Bronze Age (2400/2300-1046 cal. BCE)

The Late Neolithic to the Early Bronze Age was a transitional period in ancient China during which complex chiefdom societies developed into state-level societies (Chang 1986, 1999; Liu 2005; Liu and Chen 2012; Zhang 2017a). Although with different voices (e.g. Li 1997; Xu 1999; Allan 1984, 1991; Bradley 1999; Keightley 1983; Linduff 1998; Railey 1999; Thorp 1991; Trigger 2003)¹, most Chinese scholars and some western Sinologists favored the opinion that the establishment of the Xia dynasty (ca. 2100-1600 BCE) symbolized the emergence of the earliest state (also the first city or urban center) in China, and that the material remains of this dynasty are represented by the Erlitou site which is regarded as the capital of Xia (e.g. Zhao 1987; Du 1991; Song 1991; Wang and Bu 1998; Child-Jonson 1998; Chang 1999; Liu and Xu 2007; Xu 2012; Han 2015). The Late Neolithic Longshan period started approximately in the end of the 3rd millennium BCE covering 2300-1900 BCE in the Central Plain and 2400/2300-1800 BCE in the Haidai Region (Luan 2016; Han 2019a,b) (Table 1.1.1).

Table 1. 1. 1 Chronology of the Late Neolithic to the Early Bronze Age in the Central Plain and the Haidai Region

	Haidai Region			Central Plain			References
	Cultures	Phases	Chronology (cal. BCE)	Cultures	Phases	Chronology (cal. BCE)	
Late Neolithic	Shandong Longshan	Early	2400/2300-2100/2000	Henan Longshan	Early	2300-2100	Luan 2016; Han 2019a,b
		Late	2100/2000-1800		Late	2100-1900	Luan 2016; Han 2019a,b
				Xinzhai		1850-1750	Zhao and Zhang 2010
Early Bronze Age	Yueshi		1800-1450	Erlitou		1750-1550	Zhao and Zhang 2010
	Shang/	Early	1550-1300	Erligang	Early	1550-1300	Fang 1998, 2013
	Zhenzhumen	Late	1300-1046	Yinxu	Late	1300-1046	Fang 1998, 2013

¹ Some Chinese archaeologists and historians suggest that the early state emerged during the Longshan period or even earlier (Li 1997; Xu 1999); many Sinologists in the west question the historical relationship between the archaeological remains known as the Erlitou culture and the legendary dynasty of the Xia and some doubt the existence of Xia at all (Keightley 1983; Allan 1984,1991; Thorp 1991; Linduff 1998; Bradley 1999; Railey 1999; Trigger 2003).

1.2 Archaeological setting of this research

Cultural prosperity in the Late Neolithic Longshan period (2400/2300-1900/1800 cal. BCE)

Archaeological information in the Central Plain as well as in the Haidai Region is well revealed (Fig. 1.2.1). Around 2300 BCE, most parts of the Middle and Lower Yellow River region stepped into the late Neolithic Longshan culture with few previous archaeological cultures embedding among them such as the Late Dawenkou culture (3000-2400 cal. BCE) in the Haidai Region (Yan 1981,1993) (Fig. 1.2.2a). The Longshan culture is believed to be the most flourishing culture with an abrupt increase in the number of site and population (Guojia 1991, 2007). It forms a highly complex chiefdom-like society with several cultural traits such as the practice of a possible writing system, the use of copper and bronze for making small implements and ornaments, the advanced fast-speed wheel skills in pottery making, the built of town walls, the widespread of violence and warfare between settlements on a regional scale, the presence of social hierarchies in burial configurations and so on (Chang 1999; Liu 1996, 2005; Liu and Chen 2006; Liu et al. 2019).

This period is also well known as one of the earliest episodes of global food expansion (Jones MK et al. 2011; Boivin et al. 2012; Liu and Jones 2014; Jones H et al. 2016; Liu et al. 2017, 2019). It is associated with the increasing interaction among different groups in Eurasia with the introduction of wheat *Triticum aestivum*, barley *Hordeum vulgare*, sheep *Ovis* sp., goat *Capra* sp., and bronze metallurgy to China and also local Chinese millet *Panicum miliaceum* to the west (Zhao 2009, 2015; Jones MK et al. 2011; Betts et al. 2014; Liu and Jones 2014; Liu et al. 2017, 2019; Zhang 2017b; Long et al. 2017, 2018). In the research area of this project, some of these trans-Eurasia exchange/migration network elements have been quickly accepted within a short period, but many have been consciously chosen either abandoned or delayed for some reasons. In the Central Plain, domesticated sheep occurred during the Longshan period (Yuan et al. 2009; Yuan 2010) while wheat might first appear in the Erlitou period (Zhao 2009; Zhao and Liu 2019). In the Haidai Region, wheat and sheep both appeared in the Longshan period (Jin 2009). Many disputes exist with barley. It has been suggested only appear in

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eastern China until 900 BCE (Liu et al. 2017), although barley grains have been recorded in many Longshan contexts in both Central Plain and Haidai Region (Jin 2009; Guo and Jin 2019; An et al. after revision, under review). To summary, during the occupation of the Longshan period, these two regions developed highly complex societies and interacted with western cultures on different scales.

Besides, before shifting to the Bronze Age, the Central Plain was shortly occupied by another Late Neolithic culture- the Xinzhai culture². It was first named in the 1980s, to describe a distinctive ceramic assemblage that earlier than Erlitou but later than Longshan (Zhao 2004). These known sites containing Xinzhai elements are mainly distributed in the core region of the Central Plain surrounding the Song mountains in Henan province, with two regional centers, Xinzhai in the Xinmi and Huadizui in Gongyi (Pang and Gao 2008; Liu and Chen 2012). Current archaeological evidence indicates complex societies characterized by walled settlements, bronze ornaments, etc. which are comparable to the societies in the Longshan period were formed during the Xinzhai period (Zhao 2004; ACAC-PK and Zhengzhou 2008; Pang and Gao 2008; Zhao and Zhang 2010).

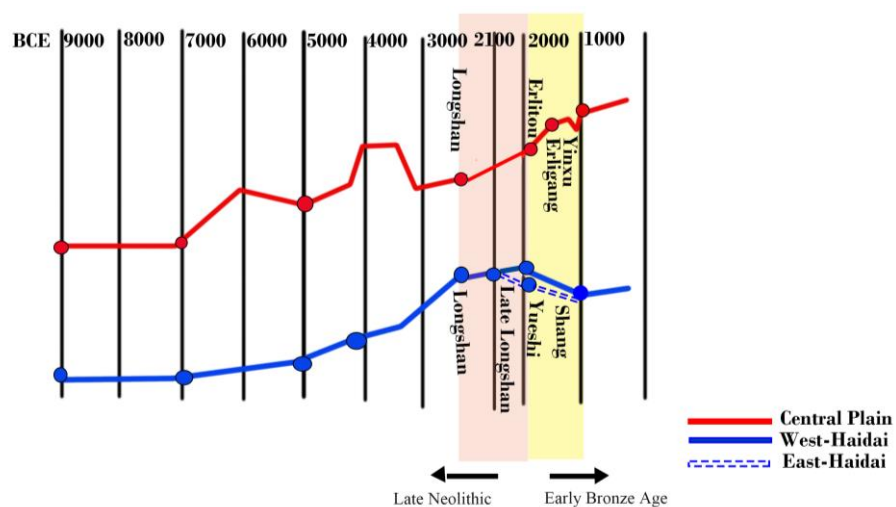


Figure 1. 2. 1 Comparison of the social processes between the Central Plain, West-Haidai and East-Haidai (modified from Han 2019)

² There have been and still are different opinions about the classification of the Xinzhai period and the definition of the Xinzhai culture. Du (2004) suggests combining Erlitou phase I with Xinzhai period as Xinzhai culture, Li (2002) declaims Xinzhai period belongs to the early phase of Erlitou phase I; Gu (2002) thinks the late phase of Xinzhai is one of the sub-cultures of Erlitou; Wei (2018) suggests that the phase II and III in the Xinzhai site all belong to the Xinzhai culture and earlier than Erlitou; However, the mainstream opinion is only phase II in the Xinzhai site is the Xinzhai culture and the Xinzhai period is earlier than Erlitou and later than Longshan (e.g. Zhao 2004; ACAC-PK and Zhengzhou 2008; Zhao and Zhang 2010). This research follows the mainstream, thus, puts the Xinzhai period into the Late Neolithic.

Abrupt social transformations in the Early Bronze Age Erlitou/Yueshi period (1800/1750-1550/1450 cal. BCE)

The prosperity of Longshan culture (and also Xinzhai culture), however, has shifted to a new era around 1800 BCE (Fig. 1.2.2b). In sharp contrast to the cultural continuity from the Longshan period, through Xinzhai, to the Erlitou period and finally stepped into a state-level society in the Central Plain, a cultural collapse or derailment with a population decline and disappear of high-quality black-surface pottery is well documented in the East-Haidai towards the end of the Longshan time and towards the Yueshi period in the West-Haidai (Liu and Chen 2012; Luan 2016; Han 2019b). Settlement number can be used as an good example for these social transformations. Full coverage regional survey projects show there was an increase in the number of sites through Longshan (165) to the Erlitou period (248) in the Central Plain (Zhang 2017a). On the opposite, an abrupt decline in the number of sites from 104 to only 13 marks a social transition from the early Longshan to the late Longshan in the East-Haidai, and in the West-Haidai, although there was an increase of sites from 44 in the early Longshan to 53 in the Late Longshan, a remarkable reduction also occurred during the Yueshi period (Shandongsheng 2005; Underhill et al. 2008; Luan 2016) (Table 1.2.1).

Table 1. 2. 1 Settlement numbers from archaeological survey

	Central Plain	West-Haidai	East- Haidai
Survey areas	Wei-Qin River; Yin-Luo River; Luoyang Basin; Upper and Middle Ying River	Chengziya surrounding, Tonglin surrounding, Xiaoqinghe, Upper Shu River	South-eastern Shandong
Longshan period	165	141	536
Erlitou/Yueshi period	248	25	19

*Information of settlement numbers in Table 1.2.1 comes from Zhang 2017a.

Gradually cultural integration in the subsequent Shang period (1550-1046 cal. BCE)

The next Shang period is a slow process of the eastward of Shang culture from the Central Plain to the Haidai Region (Fig. 1.2.3a,b). In Haidai, local Yueshi cultural components of Zhenzhumen co-existed with Shang elements of Erligang during the early Shang period for a while, but gradually diminished as a result of Erligang political domination (Chen 2007; Fang 2007). At the beginning of the Erligang period, a settlement with typical Erligang assemblage appeared at Daxinzhuang in

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Jinan, northern Shandong. This site represents the first known intrusion of early Shang people into the Haidai Region (Fang 2007, 2013). During the Middle Shang period, Shang settlements in Haidai increased rapidly in number. Elite material assemblages such as bronze and jade unearthed from settlements are in the typical Shang style whereas the indigenous status symbols of the Yueshi culture - painted pottery - disappeared completely. These phenomena suggest that in Haidai Region, the Shang colonization was achieved by replacing the local authorities with Shang elites (Fang 2007, 2013). During the Late-Shang of Yinxu period, the Shang population spread over most of Shandong, and the indigenous Zhenzhumen culture was pushed further east to the Jiaodong Peninsula (Chen 2007; Fang 2007, 2013).

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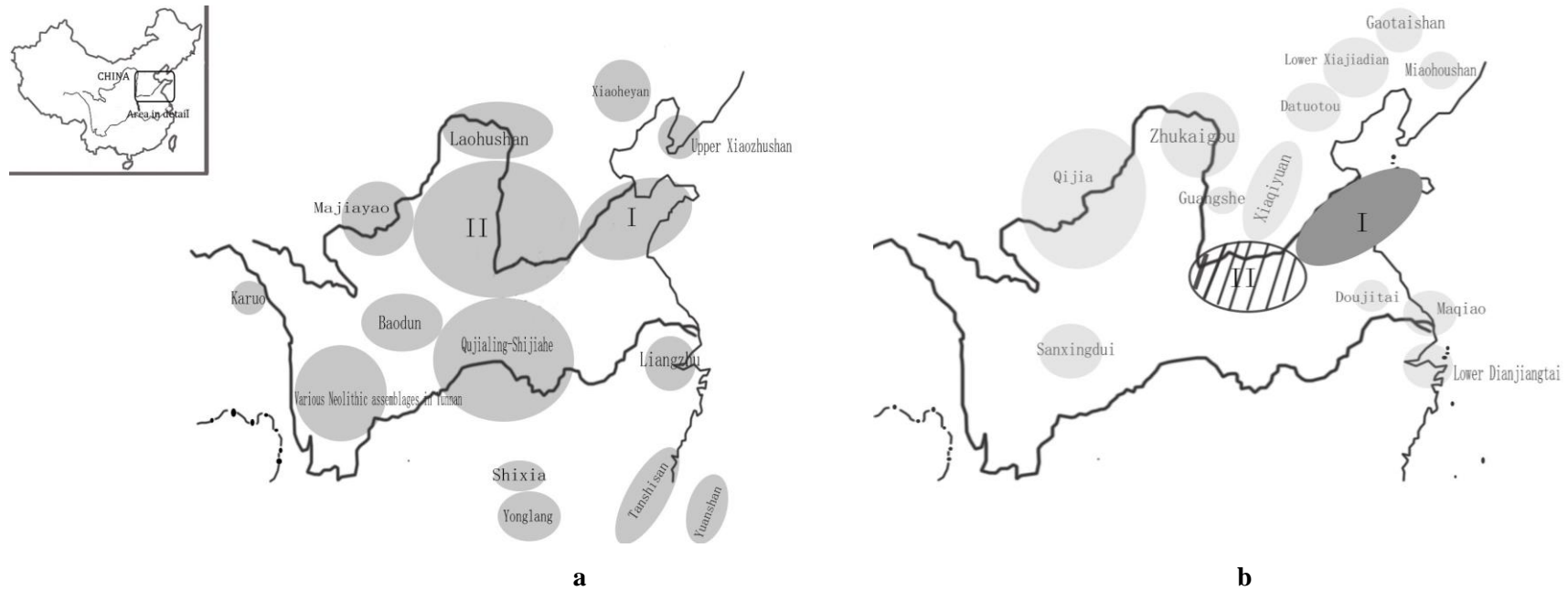


Figure 1. 2. 2 Distribution of contemporary cultures during **a.** the Longshan period (I: Late Dawenkou-Shandong Longshan; II: Henan Longshan); **b.** the Erlitou/Yueshi period (I: Yueshi; II: Erlitou) (modified from Liu and Chen 2012)

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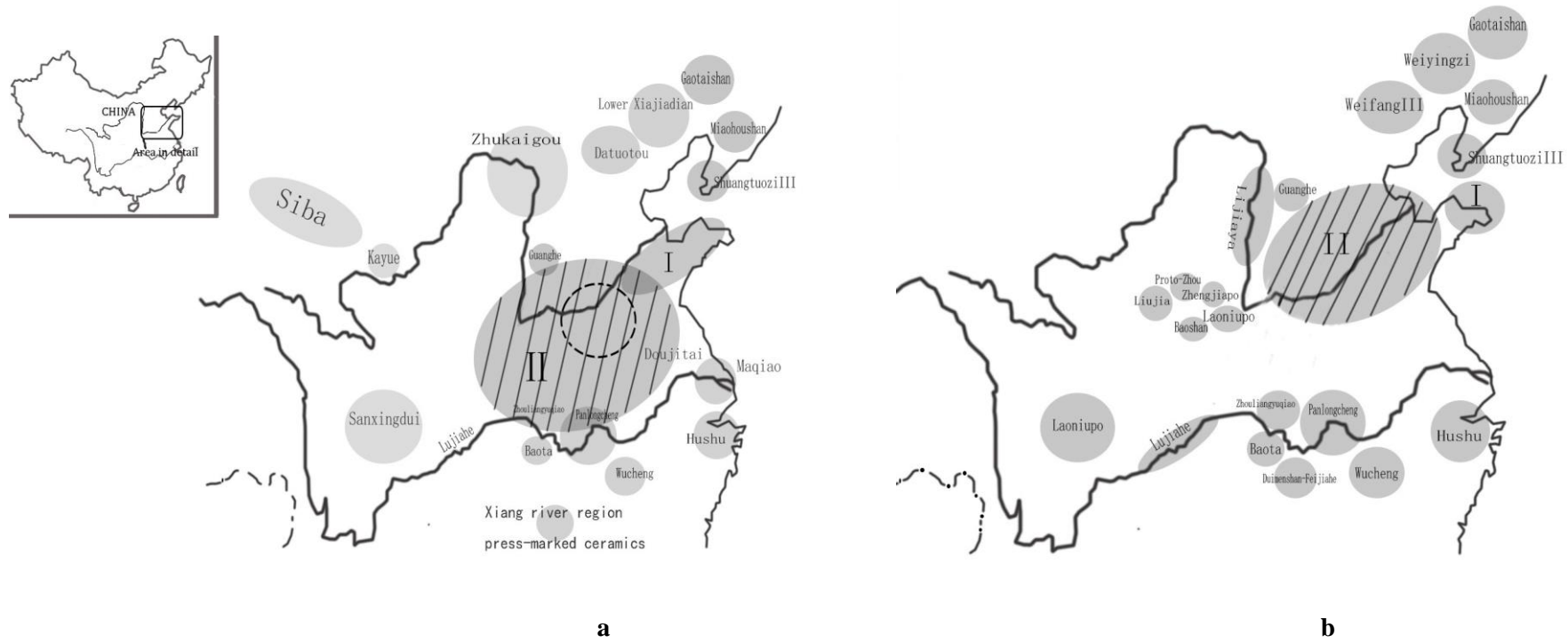


Figure 1. 2. 3 Distribution of contemporary cultures during **a**. Early Shang (I: Yueshi; II: Erligang; dotted line is the core distribution of Erligang culture); **b**. Late Shang (I: Zhenzhumen; II: Shang) (modified from Liu and Chen 2012)

1.3 Paleoclimate reconstructions

Current problems in using paleoclimatic data to interpret archaeological samples and social topics

In recent years, a growing number of studies on paleoclimate reconstruction across various regions of China have been recorded. They offer a fine resolution on shifts in precipitation and temperature and their effect on landscape and vegetation. These results have greatly enriched Chinese archaeologists' knowledge of the Holocene environment and have been used in conjunction with archaeological data to reconstruct the relationship of environment to cultural sequences. However, extra attention has to be pointed out on some issues (Liu 2005; Weisskopf 2010).

First, most of geological chronologies used for paleoclimatic reconstruction are drawn from uncalibrated radiocarbon dates (BP) while archaeological chronologies are derived from calibrated dates (cal. BCE). Because uncalibrated dates underestimate calendar dates by as much as a thousand years, these two sets of data are not directly comparable (Liu 2005; Weisskopf 2010). Moreover, for those uncalibrated BP dates generated by geological studies, the standard deviation is not available for most of the cases, thus, they are also impossible to be further calibrated. Taking these factors into account, uncalibrated dates and calibrated dates have been compared separately in this research. Furthermore, most information on paleoclimate is largely obtained from pollen profiles. Since a time-lag of up to 300 years exists between climate change and vegetation response (Bradley 1999), paleoclimatic information from pollen profiles in fact does not indicate the time when the climate change took place (Liu 2005). Besides, it takes time for societies to respond to environmental change and finally being reflected on archaeological records (Bradley 1999; Liu 2005). Therefore, there is an interval between climate and vegetation change and also another pause between environmental change and social response. This statement, however, does not suggest that the results of current environmental studies and archaeological studies are irrelevant. On the opposite, such data may provide good opportunities to evaluate the resilience of human societies by evaluating the possible correlation between these two sets of data.

Paleoclimate reconstruction in northern China from the Late Neolithic to the Early Bronze Age

In China, the Holocene Climatic Optimum (HCO) or the Mega-thermal is from 6500 to 1000 BCE (Shi et al. 1992). According to Zhu (1972), during 3000-1100 BCE, the average temperature is 2°C higher than nowadays and in winters, this difference can increase to 3-5°C. The research timeframe of 2400-1046 cal. BCE in this research is at the end of HCO, thus, it was generally warm and wet in the climate. In the meanwhile, the global Holocene climate was punctuated by a series of millennial-scale shifts, expressed as abrupt cooling and/or drying events (Bond et al. 1997). Similar events have been documented in China as well but varied considerably in the temporal dimension among different regions (Zhou et al. 1991; Shi et al. 1992; Yao et al. 1992; Kong et al. 1992; Zhang et al. 2000; Jin and Liu 2002; Yi et al. 2003) (Table 1.3.1).

Current paleoclimatic constructions, no matter with uncalibrated dates (Fig. 1.3.1a-c) or calibrated dates (Fig. 1.3.1d-f), a drop in temperature and precipitation from approximately 2800-2300 BCE and 2200-1800 BCE can be seen in the curves spreading many places of China. Besides, huge climate changes have strong impacts on river courses (Wang 1993, 1999), the observation of ancient river courses therefore can provide additional evidence for huge climate changes. A timetable of prehistoric changes in the Yellow River's lower course has been tentatively reconstructed based on the distribution of Neolithic sites along the lower river course as well as ancient texts which record the locations of the Yellow River (Wang 1993, 1999). Two major shifts of the river course: changing to the northern Jiangsu Plains and emptying into the Yellow Sea around 2600 BCE and switching back to the Huabei Plains around 2000 BCE have been recorded. These changes in the river course are consistent with the climate changes recorded in the paleoclimatic construction.

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Table 1. 3. 1 Records of the cool and drought climatic event around 2000 BCE from Paleoclimate reconstruction (most with uncalibrated radiocarbon dates)

Regions	Sample location	Materials	Records of the cool and drought event	References
Western China	Qilan Mountains	Dunde ice core	2000 BCE	Yao et al. 1992
Southern China	Guizhou	Dongge cave stalagmite	2400 BCE	Wang et al. 2005
North-eastern China	Jinchuan	Peat bog	2900-2200 BCE	Hong et al. 2003
Qinghai-Tibet Plateau	Hongyuan	Peat bog	2600-2200 BCE	Xu et al. 2002
Northern China	Beijing	Taishizhuang peat bog and pollen	2600-2300 BCE	Jin and Liu 2002
Western China	Review		2000 BCE	Zhou et al. 1991
Whole China	Review		2000 BCE	Shi et al. 1992
Northern China	Yellow River delta region	Boreholes H9601, H9602	2500-700 cal. BCE	Yi et al. 2003
Northern China	Review		2800, 1400 BCE	Kong et al. 1992
North-western China	Desert-loess transition belt	Pollen, lacustrine $\delta^{18}\text{O}$, soil contents	2300-1740 BCE	Zhang et al. 2000
Tibet	Sumxi Co lake	Lake sediments $\delta^{18}\text{O}$	2300 BCE	Gasse et al. 1991
West pacific	Okinawa Trough and South China Sea 255, 170, 17940-2	<i>Pulleniatina obliquiloculata</i>	2000 BCE	Jian et al. 1996

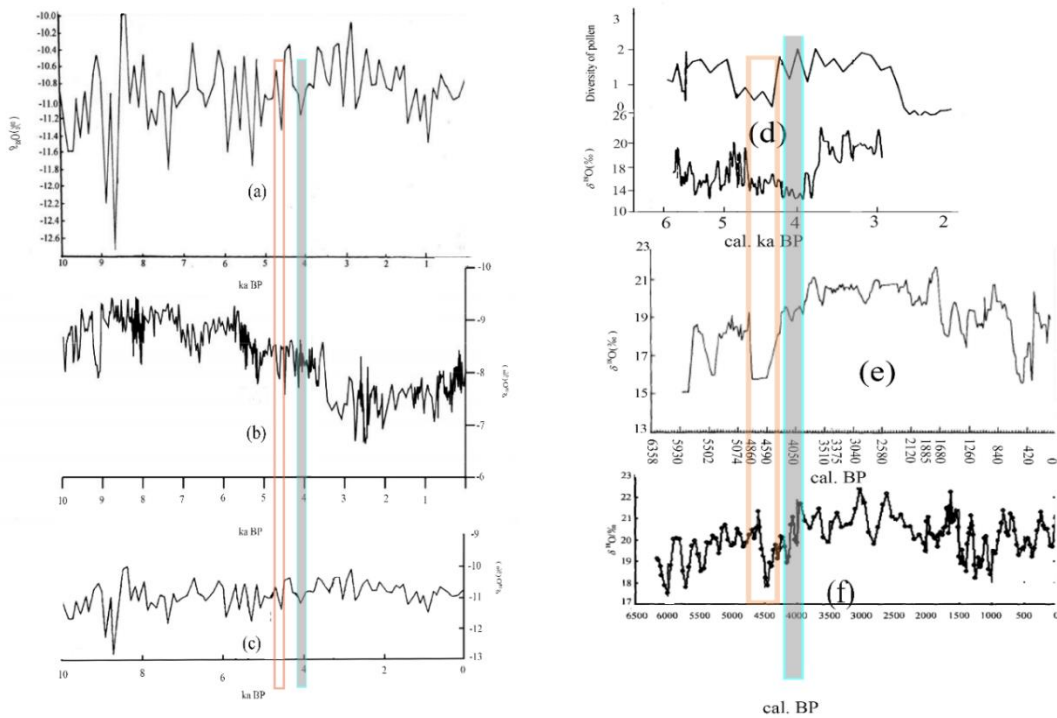


Figure 1. 3. 1 Comparison of the paleoclimatic records in **a.** oxygen isotope record in Dunde ice core; **b.** oxygen isotope record in Dongge cave stalagmite; **c.** oxygen isotope record in Taishizhuang peat bog; **d.** pollen and detailed oxygen isotope record in Taishizhuang peat bog; **e.** oxygen isotope record in Jinchuan peat bog; **f.** oxygen isotope record in Hongyuan peat bog (**a-c:** uncalibrated radiocarbon dates BP, **d-f:** calibrated dates cal. BP)

Futhermore, to tentatively recover the paleoclimatic conditions in the research area in this project, available regional climatic indicators were collected (Table 1.3.2).

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In these paleoclimatic indicators, most of them derived from pollen profiles and the majority of the results are published in uncalibrated dates which makes the comparison with archaeological dates difficult. Also, different time scales in each research also increase the difficulty of restoring the ancient environment. Nevertheless, after comparing these calibrated dates and uncalibrated dates separately and also taking the results from the whole China as mentioned above into account, the paleoclimatic information can roughly correspond to archaeological cultures (Fig. 1.3.2). It shows from the Late Neolithic to the Early Bronze Age, the climate in the Central Plain and Haidai Region were marked by several fluctuations. The Longshan period experienced a climate change from warm, wet to cool, dry around 2200 BCE, this kind of cool and dry climatic condition lasted until 1300 BCE with a short warm and wet phase during the Xinzhai period.

Table 1. 3. 2 Regional climatic indicators of the Haidai Region and the Central Plain from Paleoclimate reconstruction with both calibrated and uncalibrated radiocarbon dates

Haidai Region	Sample location	Materials	Climatic records (calibrated dates cal. BCE; uncalibrated dates BCE)	References
Shandong	Xinxian; Yuchengxian; Huiminxian; Zoucheng	Pollen (H-1, H-2, H-3, J55, S32, ZK1)	3000-2000 BCE warm, wet ~2000 BCE event 2000-1500 BCE cool and dry	Bian 2004
Eastern Shandong	Qingdao	Pollen	2900-2550 cal. BCE warm but end of Holocene Climatic Optimum 2550-1900 cal. BCE cool, dry 1900-1500 cal. BCE warm, dry	Chen and Wang 2012
South-eastern Shandong	Yi-Shu River basin Xuejiayao section	Grain size, magnetic susceptibility, geochemical analysis	2970-2260 BCE warm, wet 2260-1880 BCE cool, dry 1880-1050 BCE unstable cool	Gao et al. 2006
Central Plain	Sample location	Materials	Climatic records	References
Henan	Luoyangsi	Pollen	2925-2580 BCE cool, dry but turns better 2580-2125 BCE warm, wet 2125-1545 BCE cool, dry 1545-1265 BCE cooler, drier 1265-1090 BCE warm, wet ~1090 BCE warm, wet	Sun and Xia 2005
Henan	Mengjin	Mollusks fossils in lacustrine deposits	3660-2900 BCE warm, wet 2900-2300 BCE warmer, wetter 2300-2100 BCE dry 2100-1500 BCE dry	Liang et al. 2003
Henan	Mengjin	Salinity in lacustrine deposits	2610-2020 BCE warm, wet 2020-1755 BCE cool, dry	Cao and Xia 2008
Henan	Xinmi	Pollen, soil carbon and nitrogen isotopes, geochemical analysis	2050-1900 cal. BCE warm, dry 1850-1750 cal. BCE warm, wet ~1750 cal. BCE warm, dry	ACAC-PK and Zhengzhou 2008
Western-Henan	Luanchuan	Dongshiya cave stalagmite	2200-1800 cal. BCE drought	Zhang et al. 2018

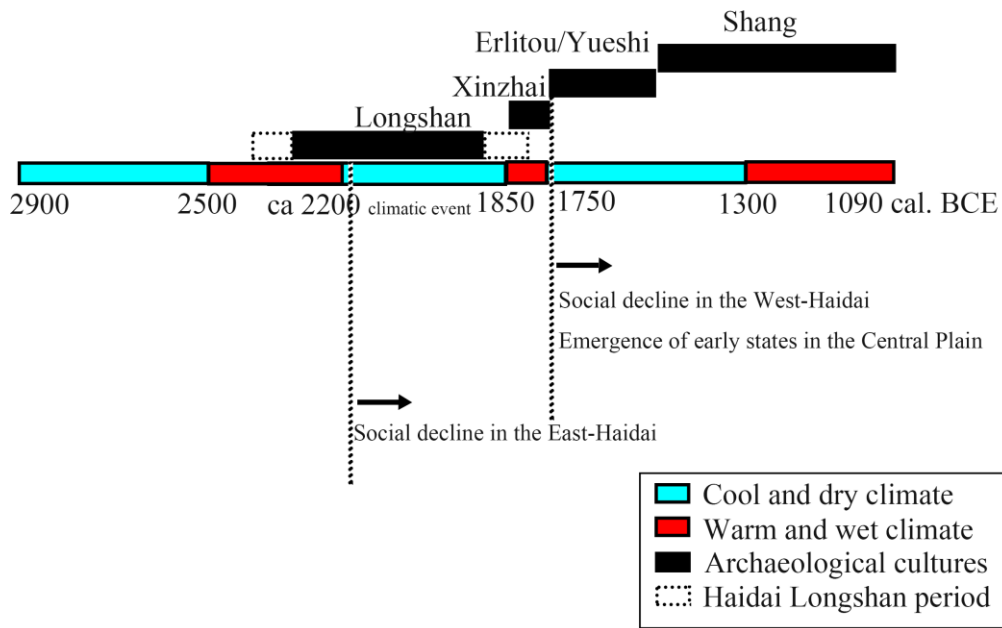


Figure 1. 3. 2 A general correspondence of paleoclimate and archaeological culture (drawn by JP An)

1.4 Current hypotheses on the role of agriculture underlying social changes in the research areas and existing problems

The role of ancient agriculture in social transformation, especially in the occurrence of the first state in the Central Plain, has long been a topic under debate. The most popular hypothesis is compared with other cultures that developed mono-crop farming such as rice farming in the Yangtze River and millet farming in the Lower Yellow River, the multi-cropping farming (*Setaria italica*, *Panicum miliaceum*, *Oryza sativa*, *Triticum aestivum*, *Glycine max*) in the Central Plain is closely related to the exclusive advance of the Erlitou culture (Zhao 2007, 2011; Zhao and Liu 2019). It was beneficial in raising the total value of agricultural output, alleviating natural calamities, increasing the diversity of crops, thus, provided a solidary foundation for the formation of early states (Zhao 2011). Some scholars further propose that due to the central geological location of Central Plain as well as the great diversity in topography with high platforms and lowlands alternately distributed (Wang 2004; Zhang 2007; Zhang et al. 2008; Liu and Feng 2012; Cao 2012), its local micro-environment got far less impact from natural disasters, instead, the environmental condition in this region was probably more or less climatically optimal around 2000 BCE, neither too dry like in the far north of China

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nor too wet like in the far south of China (Liu and Feng 2012). Hence, various crops especially water-requiring species managed to be cultivated. Also, because of these natural advantages, the Central Plain can attract immigrants from the adjacent areas, and the resulting population pressure and associated resources shortage might have acted as a catalyst to force the society to a more organized and advanced level (Liu and Feng 2012). However, this hypothesis could interpret why there was an unexpected high find of rice regardless of the undesirable climatic condition but cannot explain the concentration of rice in central settlements. In the Erlitou period, the regional distribution of rice was restricted to major centres (Lee and Bestel 2007; Zhang et al. 2014; Zhao and Liu 2019). Rice likely played a primarily social role as a prestige crop and status symbol rather than just satisfying basic dietary needs.

Moreover, wheat was only a minor component in the local system during the Erlitou period (Zhou and Garvie-Lok 2015; Chen 2016; Guo and Jin 2019; Deng et al. 2020) and it was until the Shang period, the significant importance of wheat can be noticed (Zhao 2011; Chen 2016; Guo and Jin 2019; Zhong 2020). Therefore, it is highly unlikely to have huge contributions to social change (Deng and Qin 2017). Furthermore, being accepted as a prominent food, wheat took approximately 200 years through Erlitou to Shang in the Central Plain but around 1400 years from Longshan to Western Zhou (1046-771 cal. BCE) in the Haidai Region, although wheat has been imported into the latter region far earlier (An et al. 2016). Many factors including dietary preference, policy guidance of the ruling class, more demand as a staple food for the intensive population, or a more resilient system that can easily accept a new exotic crop into the local system have been proposed as underlying reasons (Chen 2016; Guo and Jin 2019). However, agricultural techniques are overlooked in previous studies. It is not hard to imagine that a new water-requiring species is more easily accepted by areas with the support of sophisticated irrigation systems. Surely, this hypothesis needs to be thoroughly tested. It is therefore necessary to bring agricultural techniques into the discussion.

In the case of the Haidai Region, the cultural collapse of the whole region during the Yueshi period has been mainly noticed. For this, the environmental deterioration caused by the 2.2 ka BC event, the abandonment of rice farming, and the shrinkage of population have long been considered as main causations (Qi et al.

2006; Gao et al. 2007; Peng et al. 2010; Chen et al. 2011). However, in many Longshan sites or sub-regions, millet dry farming rather than rice farming has played an important role (Zhao 2004, 2006; Jin 2013; Ma and Jin 2017). Thus, the collapse of Yueshi culture turns out to be an issue related to rice farming as well as millet farming. In the meantime, the different speeds of social collapse after the climatic event around 2200 BCE between East- and West-Haidai has mainly been a topic among archaeologists (Liu and Chen 2012; Luan 2016; Han 2019a,b) and has never been connected with archaeobotanical results, although sub-regional variations in the farming system have been recognized by archaeobotanists (Zhao 2004, 2006; Jin 2013; Ma and Jin 2017). Thus, the effect of climatic events on different agricultural systems and further on human societies is necessary to be discussed between these two sub-regions.

1.5 Archaeobotanical data and research method

Archaeobotanical investigation has the potential to provide insights into ancient agriculture and related social issues. In a comparative research, using previous archaeobotanical data without distinction can bring bias in the interpretation. Such samples from burial contexts are not ideal materials for the exploration of agricultural activities and occasional finds that were selected and filtered manually by excavators while doing the fieldwork can increase the influence from anthropic factors. Therefore, it is necessary to pre-treat the database before the analysis. Only systematic flotation results from settlement sites were collected in this research (Table 1.5.1). In total, macro-botanical data were collected from 27 sites in the Central Plain, 20 sites in the West-Haidai and 18 sites in the East-Haidai. Moreover, phytolith data from the site of Xinzhai and Dongzhao were collected as well in the comparative study of the Xinzhai period. Besides, archaeobotanical samples including 59 phytolith samples and 220 macro-botanical samples from the Xinzhai site (excavation season 2016, 2018) were collected and provided a case study. Sampling and flotation information of the Xinzhai site can be found in chapter 2 section 2.1, 2.2.

Plant remains in this research are entirely preserved by charring which could be the result of the arid climate in northern China. Archaeobotanical records are not equally rich among regions and the volume of samples and sites per period differs

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greatly. The data in the Central Plain is most well presented. It is because the primary object for Chinese archaeologists in the past century was to construct national history. Xia, Shang, Zhou, as pre-imperial three dynasties *Sandai* (三代), is believed to develop in the Central Plain which consistent with the location of early dynasties from historical recording (Chang 1999; Liu 2005). Therefore, archaeological and archaeobotanical investigations have long been focused on this area. Likewise, ancient sites that are closely associated with Xia, Shang, Zhou cultures were more attractive for archaeologists rather than those ones with indigenous cultures. Hence, sites of pure Zhenzhumen culture in the Haidai Region have been overlooked and currently have no available archaeobotanical data.

Table 1. 5. 1 Archaeobotanical data in this Ph. D. project

Periods	Central Plain (Zhengluo Region)	West-Haidai	East-Haidai
Longshan	1. Wangchenggang; 2. Chengyao; 3. Wadian 2007-2008, 2007, 2009; 4. Guchengzhai; 5. Zhengzhou Shang City; 6. Xijincheng; 7. Dalaidian; 8. Xinzhai 1999	1. Ningjiabu; 2. Huangsangyuan; 3. Pengjiashuang; 4. Dinggong; 5. Fangjia; 6. Tonglin; 7. Shilipubei; 8. Zhuanglixi; 9. Wangjiacun; 10. Haojiatai; 11. Pingliangtai 1, 2*; 12. Beitaishang	1. Wutai; 2. Xuejiashuang; 3. Zhaojiashuang; 4. Liangchengzhen; 5. Liujiashuang (六甲庄); 6. Dongpan; 7. Houyangguanzhuang; 8. Yangpu; 9. Luchengzi; 10. Yuchisi; 11. Yuhuicun; 12. Diaoyutai; 13. Gongzhuang
Xinzhai	*1. <i>Xinzhai</i> 1999, 2014, 2016, 2018; 2. <i>Dongzhao</i> ; 3. Huadizui; 4. Zhengzhou Shang City		
Erlitou/Yueshi	1. Nanwa; 2. Erlitou; 3. Dongzhao; 4. Guchengzhai; 5. Wangchenggang; 6. Huizui; 7. Xipingshangpo; 8. Wadian 2007-2008, 2007, 2009	1. Tonglin; 2. Yinjia; 3. Shilipubei; 4. Pengjiashuang; 5. Maan	1. Miaohou; 2. Zhaogezhuang 2007, 2008; 3. Liujiashuang (六甲庄); 4. Yangpu
Shang	1. Nanwa; 2. Zhongyixueyuan; 3. Wangchenggang; 4. Guchengzhai; 5. Dongzhao; 6. Zhengzhou Shang City; 7. Huanghezongxue	1. Shilipubei; 2. Daxinzhuang 2003, 2015; 3. Liujiashuang (刘家庄); 4. Tonglin	

*Site names in **bold** and *italic*: phytolith samples from these sites were analyzed as well.

Different archaeobotanical databases about the Pingliangtai site are available: Pingliangtai 1. Deng and Qin (2017), Pingliangtai 2. Zhao et al. (2019).

The analysis of archaeobotanical remains in this study was dependent on a variety of methods. First, observation conclusions from ethnographic investigations were used as references for the interpretation of archaeological samples. It includes the different categories of modern rice water regimes and cultivation systems (dry rice: upland rainfed, intermediate rice: groundwater/lowland rainfed, flooded/decree, and wet rice: irrigated paddy, deep-water rice, wild rice) in India (Weisskopf et al. 2014) (in section 2.1), the modern model of rice processing in Thailand, India, and China (Thompson 1992, 1996; Harvey and Fuller 2005; Weisskopf 2010), of millet processing in India (Reddy 1994) and China (Song et al. 2013, 2014), and of free-

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threshing pulses processing in India (Fuller and Weber 2005; Fuller and Harvey 2006) (in section 2.2). Second, results from experimental studies were used as comparative data while explaining archaeological samples. Examples include the phytolith formation under different water regimes of the C₄ plant of sorghum *Sorghum bicolor* in Jordan (Jenkins et al. 2020; Predanich 2020) (in section 2.1) and C₃ plants of emmer wheat *Triticum dicoccum*, bread wheat *Triticum aestivum*, spelt wheat *Triticum spelta*, durum wheat *Triticum durum*, six-row barley *Hordeum vulgare*, and two-row barley *Hordeum distichon* in Near East and rice *Oryza sativa* in India (Madella et al. 2009; Fuller and Weisskopf 2011; Jenkins et al. 2011, 2016; Weisskopf et al. 2014) and the evolution of weed floras on the cultivation plots in southwestern Germany under different cultivation regimes (Bogaard 2002) (in section 2.4).

Besides, to avoid the bias from different sampling strategies, sample volumes and sample processing, a semi-quantitative approach- the Representativeness Index (RI)- was applied to the regional investigation and the diachronic comparative study (Stika and Heiss 2013a,b; Effenberger 2018) (in section 2.1, 2.3, 2.4). While dealing with Chinese archaeobotanical database, this method was modified after Effenberger's system (2018). Since the higher ubiquity one taxon has, the more representative it should be. The ubiquity of every species in each site was considered. Moreover, crop species of both large- and small-sized grains were found in Chinese archaeobotanical database. Because one grain of large size can provide more energy and higher nutrition than one grain of small size, same amounts of large- and small-sized grains should have different representativeness. Except for that, one single plant which carrying small-sized grains normally produces more grains than one cereal plant with large-sized grains in sheer numbers. Thus, the large number of small-sized grains is not necessarily representative of its importance at one site. Hence, the ratio between different cereals based on a thousand grains weight was also counted as one factor in the RI method (more details see section 2.4 materials and methods). In the last, the Correspondence Analysis (CA) was used to reveal the potential relationships of variables (Kneisel 2010). It shows great significance in examining the underlying connection of crop species and settlement hierarchies (in section 2.1), and also the spatial distribution of crop species on a regional scale (in section 2.1, 2.3, 2.4).

1.6 Structure of this dissertation

In the following second chapter, four research papers are bundled:

2.1 *Jingping An*, Marta Dal Corso, Chunqing Zhao, Wiebke Kirleis, Guiyun Jin: Identifying the water regime and its association with crop hierarchies in the Xinzhai period (1850-1750 cal. BCE): a case study on the Xinzhai site. *Archaeological and Anthropological Sciences*, under review.

2.2 *Jingping An*, Wiebke Kirleis, Chunqing Zhao, Guiyun Jin: Understanding crop processing and its social meaning in the Xinzhai period (1850-1750 cal. BCE): a case study on the Xinzhai site, China. *Vegetation History and Archaeology*, forthcoming, DOI : 10.1007/s00334-021-00851-0.

2.3 *Jingping An*, Wiebke Kirleis, Guiyun Jin: Changing of crop species and agricultural practices from the Late Neolithic to the Bronze Age in the Zhengluo region, China. *Archaeological and Anthropological Sciences*. 2019, 11(11), 6273-6286, published, DOI : <https://doi.org/10.1007/s12520-019-00915-3>.

2.4 *Jingping An*, Wiebke Kirleis, Guiyun Jin: Understanding the collapse of the Longshan culture (2400-1800 cal. BCE) and the 2.2 ka BC event in the Haidai Region of China from an agricultural perspective. *Environmental Archaeology*, after peer review and re-submitted (after revision, under review).

In 2.1 and 2.2, a case study on the Xinzhai site in the Central Plain is presented. Hydrological conditions in different crop fields and their connections with food hierarchies are discussed in section 2.1 and an analysis of the crop processing method and its indication in labour distribution and social organization is reviewed in section 2.2. In 2.3, a chronological analysis of archaeobotanical data from the Central Plain is conducted. The possible influence of the practice of irrigation on ancient agriculture and social organization form in the subsequent Erlitou and Shang periods can be, therefore, explored. In the last section 2.4, the different social changes since the Late Longshan period between East- and West-Haidai are discussed from an agricultural perspective. It is a pilot study using ecological information of arable weeds to explore cultivation regimes and agricultural strategies in response to the 2.2 ka BC event. In summary, this research tries to uncover the different roles of agriculture underlying the social changes in the Central Plain, the East-Haidai, and the West-Haidai during a period with frequent

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climatic fluctuations and significant social transformations.

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As mentioned in the introductory section, among several huge social changes in Chinese prehistory, the most outstanding one is the transition of complex chiefdom societies to the state-level societies during the end of the 3rd millennium BCE and the beginning of the 2nd millennium BCE in the Central Plain (e.g. Chang 1999; Liu 2005; Li and Chen 2012; Xu 2012; Zhang 2017). The agriculture in the Central Plain has long been featured by rainfed agriculture based on foxtail millet *Setaria italica* and broomcorn millet *Panicum miliaceum* during most of the Neolithic, until the Erlitou period a new era marked by a multi-cropping system was formed which probably provided a solidary foundation for the formation of early states (Zhao 2007, 2011; Zhao and Liu 2019). In this multi-cropping system, water-requiring species managed to be cultivated regardless of the profound impact on local environment triggered by the dry and cool event around 2200 BCE. Archaeological evidence suggests that the Erlitou culture developed locally from the Longshan culture through an intermediate period - the Xinzhai period (Zhao 1986; Yuan 1996; Zhao 2002). The understanding of agriculture in this intermediate period is, thus, of great interest, particularly because it is closely connected with the emergence of early states in the subsequent Erlitou period. In the following section 2.1, archaeobotanical remains including phytolith and macrobotanical remains from the Xinzhai site were analyzed. This site contained a multicomponent of Longshan, Xinzhai, and Erlitou but was mainly occupied by the Xinzhai culture. During the Xinzhai period, this walled-settlement site was acted as one of the regional centres (Pang and Gao 2008), therefore, offers a proper case study to reveal agriculture in a complex society.

In a complex society, agriculture could contribute to social complexity in many ways (Fuller and Stevens 2009). First, surplus staples, such as grains, can be mobilized to support the elite. To gain agricultural surplus, agricultural intensification through intensive inputs including labour and advanced techniques is a common option, although other strategies like extensive agriculture are also possible (McClatchie 2014). Second, by limiting access to prestige goods, such as certain 'luxurious' crops, elites can gain economic and political advantages (Peregrine 1991). Also, prestige-item production often correlates with greater

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political centralization because more centralized societies tend to use more complex prestige items, many of which require significant labour investment and sophisticated techniques to process them (Peregrine 1991). Intensive and/or extra inputs of labour and time during the preparation of food (Fernández-Armesto 2002) and the cultivation of crops such as running a sophisticated irrigation system could associate food intimately with social-cultural distinction (Smith 2006; Morrison 2016). A good example is in southern India, what all of the elite cuisines share is a primary focus on the products of intensive, irrigated agriculture (Smith 2006; Morrison 2016). Hence, the development of the irrigation system, especially in those arid and semi-arid areas is an important aspect of the evolution of social complexity. Examples include in the Near East, one of the principal requirements for the emergence of early state societies is a complex farming system employing labour-intensive irrigation (Wittfogel 1957; Scarborough 2003; Mithen et al. 2008) and in India, the spread of rice and its associated irrigation works from the Ganges have contributed to the establishment of elite-supported Buddhism and urbanism in central India (Shaw and Sutcliffe 2003; Shaw et al. 2007) and also to the emergence of Tamil city states in southern India after 1000 BCE (Shaw and Sutcliffe 2003; Fuller and Qin 2009; Morrison 2015). Therefore, the practice of irrigation remains a key issue for the social evolution, particularly in arid and semi-arid areas. However, questions concerning this aspect are still open for discussion in the emergence of the Chinese earliest states. In section 2.1, crop water regimes were discussed and connected with crop hierarchies. It reveals how crops have participated in the social complexity through the capital input of irrigation during the Xinzhai period.

2.1 Case study on the Xinzhai site-I

Identifying the water regime and its association with crop hierarchies in the Xinzhai period (1850-1750 cal. BCE): a case study on the Xinzhai site

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This is the author's original manuscript (AOM) of an article that was submitted to *Archaeological and Anthropological Sciences*, currently under review.

Abstract

A vital factor in the rise of urbanization in many cases is the development of a complex farming system employing labour-intensive irrigation. It is, therefore, of great significance to probe crop water regimes in the Xinzhai period (1850-1750 cal. BCE), a key period pursuing the emergence of early urbanization in China. To recover the water management in this period, correspondence analyses based on the phytolith ecological categories and ratio analyses of Sensitive to Fixed morphotypes of 59 phytolith sediment samples from the Xinzhai site were performed. They clearly show that rice and millet were grown in different ecological settings with possibly intensive rice farming under an irrigation system and a rainfed millet farming. Meanwhile, a regional comparative-research suggests that rice was more concentrated in central settlements and the aristocratic residential area in the Xinzhai site. Rather than ecological factors, we argue that this uneven distribution of rice is out of cultural factors: due to the intensive labour inputs, irrigated rice has been chosen from ordinary ingredients into prestige food for the wealthy and powerful while rainfed millet was more for calorific needs probably as a major staple. This research proves archaeobotanical evidence can enable us to evaluate how certain crops became powerfully associated with social-cultural distinction and also how they possibly participated in the social complexity.

Keywords Xinzhai site· Xinzhai period· Phytolith analysis· Crop water regime· Crop hierarchy

Introduction

The development of farmland water management system has long been considered as an important aspect of the evolution of social complexity in several parts of the world. Examples include one of the principal requirements for the emergence of early state societies in the Near East is a complex farming system employing labour-intensive irrigation (Wittfogel 1957; Scarborough 2003; Mithen et al. 2008); the establishment of elite-supported Buddhism and urbanism in central India and the emergence of Tamil city-states in southern India after 1000 BCE are intimately connected with the spread of Ganges' rice and its associated irrigation works (Shaw and Sutcliffe 2003; Shaw et al. 2007; Fuller and Qin 2009; Morrison 2015). Therefore, the understanding of water management systems remains a key issue for understanding social complexity. Moreover, intensive and/or extra inputs of labour and time during the preparation of food (Fernández-Armesto 2002) and the cultivation of crops such as running a sophisticated irrigation system could associate food closely with social-cultural distinction (Smith 2006; Morrison 2016). A good example is in southern India, what all of the elite cuisines share is a primary focus on the products of intensive, irrigated agriculture (Smith 2006; Morrison 2016).

In China, crop water management has long been entangled with social development as well. A well-known case study is in the lower Yangtze River area, rice farming has witnessed an increasing human intervention from a wild rice similar growing setting (4800-4300 BCE) to a flooding and drying drainage system (3950-3700 BCE) to a prolonged deep-water irrigation system (3000-2300 BCE) (Weisskopf 2017), and the final establishment of the intensive irrigated-paddy system around 2000 BCE has triggered local social changes towards a highly hierarchical society and accelerated the dispersal of rice and population out of the Yangtze core (Fuller and Qin 2009). Given the seasonality and variability in precipitation under a monsoon system and the arid or semi-arid conditions over northern China, it would be difficult for the water-demanding crop species to grow without the development of water management techniques. However, such an assumption is difficult to be testified archaeologically since field systems and irrigation ditches are rarely preserved. Currently, archaeologically identified earliest irrigation remains in this region is a two-stage artificial levee dating to 700 BCE (the Late Bronze Age) at

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Sangyangzhuang site (Kidder et al. 2012; Kidder and Liu 2017). In this aspect, phytolith can serve as an alternative method. It has as proven by many experimental investigations such as in the fields of emmer wheat *Triticum dicoccum*, bread wheat *Triticum aestivum*, spelt wheat *Triticum spelta*, durum wheat *Triticum durum*, six-row barley *Hordeum vulgare*, and two-row barley *Hordeum distichon* in Near East (Rosen 1992; Rosen and Weiner 1994; Mithen et al. 2008; Madella et al. 2009; Jenkins et al. 2011, 2016), in the farmlands of sorghum *Sorghum bicolor* in Jordan (Jenkins et al. 2020; Predanich 2020), in the farming fields of finger millet *Eleusine coracana* and pearl millet *Pennisetum typhoides* in North Africa (Lancelotti et al. 2019), and in the fields of rice *Oryza sativa* in India and China (Fuller and Weisskopf 2011; Weisskopf et al. 2014; 2015a,b; Fuller et al. 2016; Weisskopf 2017). Hence, in this research, phytolith samples are used to recover crop water regimes in the settlement.

Furthermore, differentiation between past crop water regimes can afford information on the trajectory to social complexity due to differing water management technologies and labour requirements (Weisskopf 2017). In central China, the Neolithic and Bronze Age are periods of great social-economic development from egalitarian villages in the early Yangshao (ca. 5000-4000 cal. BCE) to the emergence of the first city-state at Erlitou period (1750-1550 cal. BCE) (Weisskopf 2010). The Xinzhai period (1850-1750 cal. BCE), as the former period of Erlitou, is one of the primary foci for pursuing Chinese social development (Liu and Chen 2012). However, the current understanding of archaeobotanical data recovered in the Xinzhai period is limited to the agricultural economy (Zhao CQ 2005; Yao et al. 2007; Zhong et al. 2016; Tang et al. 2018). Questions concerning crop water regimes and their implications in societies are still open. In this paper, for the first time, this topic is profoundly investigated through analyses of phytolith remains from the Xinzhai site. Additionally, the influence of different crop water regimes on food hierarchy and social complexity can be discussed through comparative research of archaeobotanical remains from the Xinzhai period.

The Xinzhai period and the Xinzhai site

The Xinzhai period (1850-1750 cal. BCE) was first named in the 1980s, to describe a distinctive ceramic assemblage that earlier than Erlitou (1750-1550 cal. BCE) but

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later than Longshan (2400-1900 cal. BCE) period (Liu and Chen 2012). These known sites containing Xinzhai elements are mainly distributed in the region surrounding the Song mountains in Henan province (Fig. 2.1.1a,b) (Liu and Chen 2012). This area nowadays belongs to the semi-arid monsoon climate zone with clear transitions between seasons: hot wet summers contrasting with cold dry winters and 45-65% of the total annual rainfall occurs during summer seasons (Zhao J 2005; Weisskopf 2010). Back in the Xinzhai period, this area generally witnessed a warm and humid/semi-humid climate and formed warm-temperate forest-steppe vegetation as suggested by multi-indicators including the analysis of pollen, carbon-oxygen isotope, organic components in soil samples (Xia et al. 2004; ACAC-PK and Zhengzhou 2008). Moreover, current archaeological investigations revealed two medium-sized centers in this period: Xinzhai in Xinmi which offers the new samples in this research, and Huadizui in Gongyi (Pang and Gao 2008; Liu and Chen 2012).

The site of Xinzhai is situated on the eastern floodplain of the Song mountain and the north bank of the Shuangji river (Fig. 2.1.1b). As being considered as the primary center which was occupied by a linear succession of kings (e.g. king *Qi*, *Houyi*, *Hanzhuo*) related to the first legendary Xia dynasty (Gu 2002; Xu 2004; Zhao 2004; Liu and Chen 2012), once it was discovered in the year 1964, continuous excavations have been conducted to the present (Zhao 2009). The settlement reveals three cultural periods: the late Longshan (2050-1900 cal. BCE), the Xinzhai, and the early Erlitou period (later than 1750 cal. BCE) (ACAC-PK and Zhengzhou 2008). It witnessed the full development of being surrounded by two concentric outer ditches and an inner rammed-earth wall with moats during the Xinzhai period (Zhao 2009). The new phytolith samples discussed in this research collected from the excavation season of the year 2018 (Fig. 2.1.1c). It is in the northeast of the Liangjiatai village in the inner city. This excavation together with the excavation in the year 2016 recovered a residential district comprising many rammed-earth house foundations. Exquisite artefact finds (e.g. an elaborate-painted ceramic bird, oracle bones, bronze wares) indicate that this area was highly possibly occupied by elites and/or clergies. Besides, a storage area with numerous large neat-shape storage pits was recorded in the excavation year 2014 (Zhao et al. 2017) and a semi-subterranean architectural structure (~1400 m²) which has been

defined as *Shan 壇* or *Kan 坎* for religious purposes was found during the excavation in the year 2003-2005 (Xinzhai and Zhengzhou 2009) (Fig. 2.1.1c).

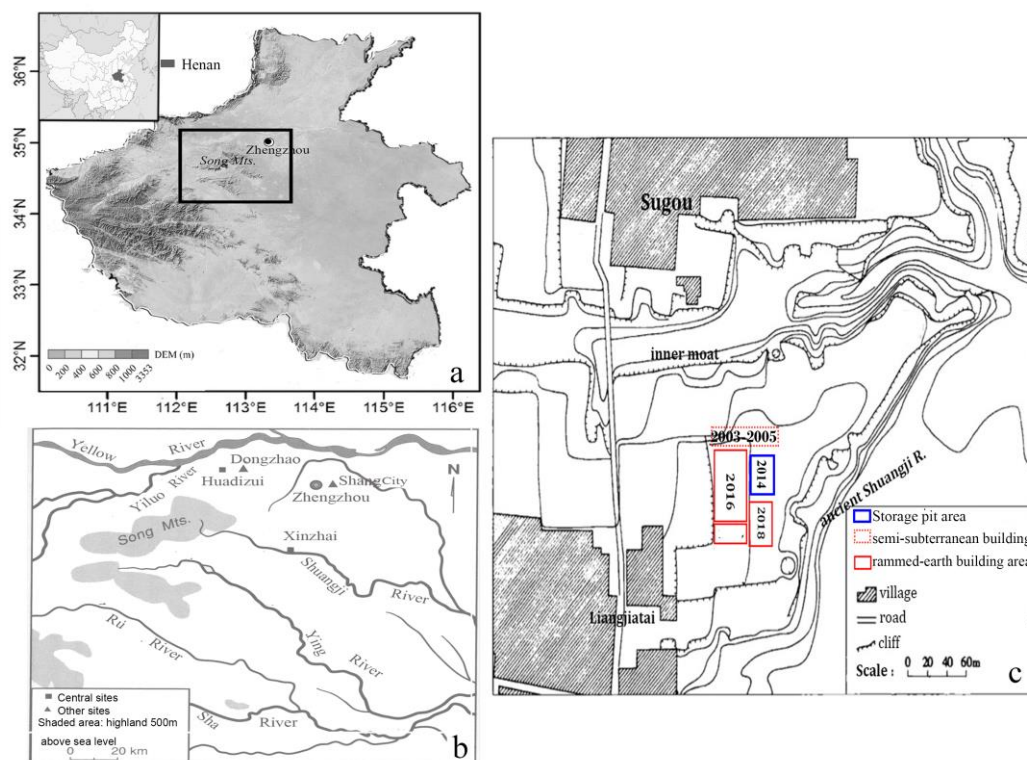


Figure 2. 1. 1 **a.** Main distribution area of Xinzhai period culture; **b.** main sites from the Xinzhai period in this research (modified from Pang and Gao 2008); **c.** excavation map of the Xinzhai site with different excavation seasons (modified from Xinzhai and Zhengzhou 2009)

Materials and methods

To investigate crop water regimes, 59 phytolith samples from nine *Huikeng* (H: 灰坑) - pit features were collected from the Xinzhai site during the excavation season of 2018 (Table 2.1.1; Fig. 2.1.1c; Appendix Figure-I.1, I.2). With massive depositions of potsherds, animal bone fragments, and stone (tool) fragments, these pits are defined as refuse pits. During the collection of samples, relative dates of each sample were offered through stratigraphic and typological information. Additionally, AMS ^{14}C dating was conducted on charred seeds (fruits) from six samples by the Leibniz Laboratory for Radiometric Dating and Stable Isotope Research at Kiel University, Germany (Appendix Table-I.1). After combining the calibrated dates by the OxCal program 4.4, samples are dated between 1878-1697 cal. BCE (1σ) with the highest (40.4%) probability of 1781-1737 cal. BCE

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(Appendix Figure-I.3). Accordingly, all samples are categorized into the Xinzhai period.

Soil samples were collected either based on sub-layers that presenting the formation process of one pit (A in Table 2.1.1) or by every 20 cm in homogeneous units (B in Table 2.1.1) or combining these two methods in those pits with thick-deposited sub-layers (C in Table 2.1.1) in the fields. Afterwards, they were sent to the Ancient Parasite and Starch Analysis Laboratory in the Henan Institute of Cultural Relics and Archaeology for extraction. The procedure includes weighing out 2 g soil, adding 30% hydrogen peroxide (H₂O₂) and 10% hydrochloric acid (HCL) to each sample to remove organic matter and carbonates, and using zinc bromide (ZnBr₂, density 2.37 g/cm³) heavy liquid to extract phytolith. The identification, counting, and photographing were carried out in the laboratory of the Institute of Pre- and Proto-history at Kiel University. Phytoliths were mounted on slides with immersion oil, sealed with nail polish, fixed with cover glasses, and ultimately observed with a Leica DM750 light microscope at 400X magnification. Main references for identification were from Twiss et al. (1969), Wang and Lu (1993), Ball et al. (1996,1999), Lu and Liu (2003), Lu et al. (2009), Zhang et al. (2011, 2018, 2019), and Dal Corso (2018). Wherever concentration was high enough, a sum of at least 300 items including plant phytoliths, pollen grains, and other siliceous remains (e.g. sponge spicules, diatoms) was counted with the counting program CountPol 3.2 (by Dr. Ingo Feeser, Kiel University). Phytolith nomenclature follows the ICPN 2.0 system (ICPT 2019). Every multicellular aggregate was registered as one silica skeleton and named after the predominant cell type (usually elongate long cells) (Madella 2007). In the following discussion, phytolith morphotypes are expressed in abbreviation codes with original codes that can be found in Appendix Table-I.2.

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Table 2. 1. 1 Sample information in this research

Pits*	Detailed information on each pit	Sample volumes [#]	Sampling strategies
H84	281 cm deep, 12 layers, in trench T0207	20 samples	C
H37	117 cm deep, 3 layers, in trench T0204	3 samples	A
H67	190 cm deep, 3 layers, in trench T0407	4 samples	C
H50	213 cm deep, 4 layers, in trench T0201	7 samples	C
H143	280 cm deep, 2 layers, in trench T0408	6 samples	C
H95	157 cm deep, 2 layers, in trench T0204	2 samples	A
H100	125 cm deep, 2 layers, in trench T0408	2 samples	A
H51	280 cm deep, 5 layers, in trench T0306	9 samples	C
H165	130 cm deep, homogeneous unit, in trench T0307	6 samples	B
Total sample volumes		59 samples	/

*H is the abbreviation of *Huikeng* 灰坑 which means pit; # Each sample contains around 250 g soil.

Phytolith can be used to probe the growing ecology of crops, hence provides further information about the type of water system used by ancient inhabitants (Weisskopf et al. 2014). To differentiate water regimes, phytolith morphotypes were grouped into six ecological categories in this research (Table 2.1.2) and further analyzed by correspondence analysis (CA) with program CAPCA 2.1 (Kneisel 2010). The grouping and phytolith morphotypes in each group are based on Weisskopf et al. (2014), Weisskopf (2017), and Kingwell-Banham (2019). Sensitive forms comprise long cells and stomata cells of grass that mainly form silica bodies when there is sufficient water uptake. Fixed forms comprise all short cells of grass and those silica skeletons containing only short cells (SKE_VER_BIL) that all are genetically predisposed to form phytoliths. Dicotyledonous indicators compose a separate category for the indication of dry environments. Morphotypes of bulliform are indicators for a wet or submerged growing environment with an excess supply of water (Sangster and Parry 1969; Bremond et al. 2005). Morphotypes from Cyperaceae family (CON and LOG_ROD), diatoms, and sponge spicules which are more prevalent in moist habitats (Pearsall 1994) are included as one category. In the category of rice, the skeleton of parallelly arranged bilobates (SKE_PRA_BIL) is counted as well. Although rather than being a unique characteristic feature of *Oryza*, this morphotype also exists in *Leersia* and *Zizania* and usually being quoted as an indicator of Oryzoideae subfamily (Pearsall et al. 1995), considering no weeds from *Leersia* and *Zizania* are found in macrobotanical remains (Appendix Table-I.3) and it is also commonly found together with other diagnostic morphotypes of rice (BUL_FL_A_FL_A, DOU), it is therefore used as a indicator of rice. Meanwhile, the ratio of sensitive types compared to fixed types (*S:F* ratio) was calculated as an additional index to identify the

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difference in hydration of each sample (Madella et al. 2009; Weisskopf et al. 2014) (Table 2.1.2; Appendix Table-I.4).

Table 2. 1. 2 Categories of phytolith morphotypes used for CA analysis and for S:F ratio

Categories	Rice	Sensitive	Fixed	Bulliform flabellate	Dicotyledon	Others
Indication	Wet	Wet	Dry	Wet	Dry	Wet
Phytolith morphotypes*	BUL_FLA_FLA DOU SKE_PRA_BIL	ELO_ECH ELO_PSI ELO_SIN ELO_CRE ELO_BOA STO	BIL POL RON TOW_HOR SAD CRO SKE_VER_BIL	BUL_FLA BUL_FLA_SHI BLO SKE_BLO	SPH_ECH SPH_PSI POY FAV_AGG MUL_JIG	DIA SPO_SPI CON LOG_ROD

*Images of main morphotypes see Appendix Figure - I.4, I.5, I.6.

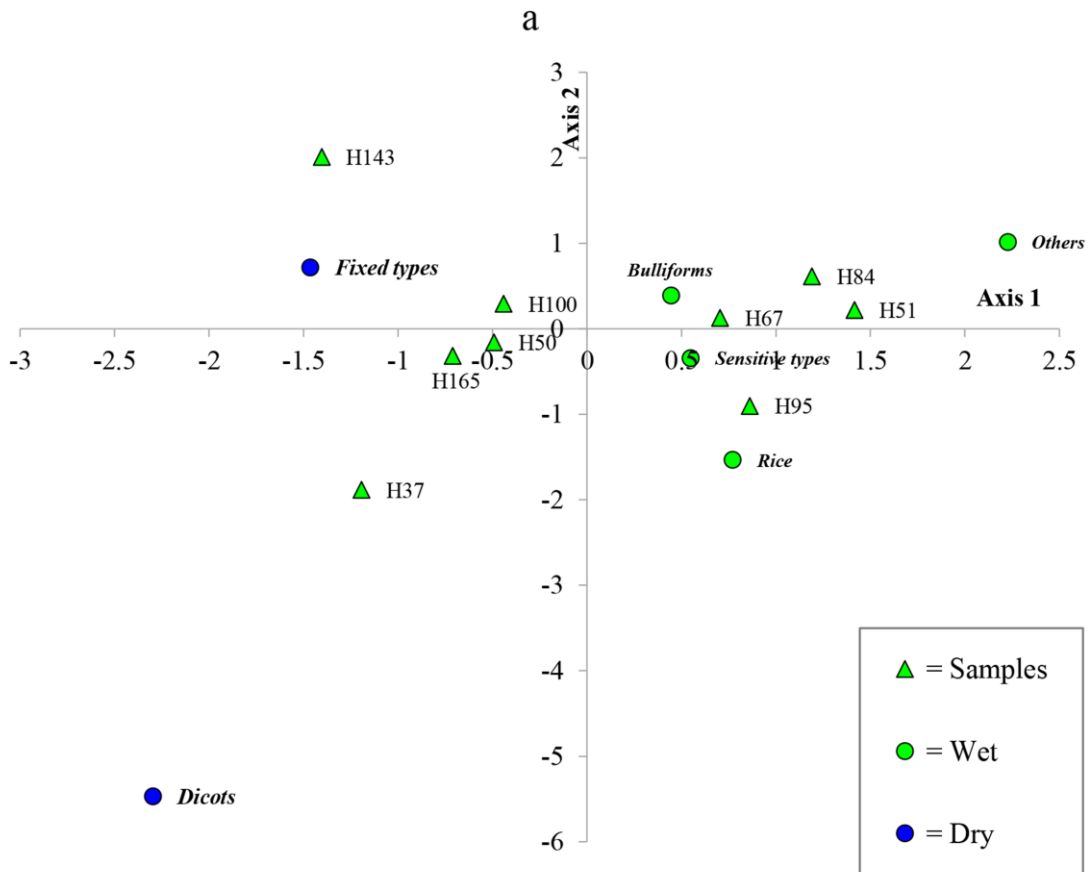
Results

The phytolith recovered from the Xinzhai site yields abundant crop finds with morphotypes from four species: foxtail millet *Setaria italica*, broomcorn millet *Panicum miliaceum*, rice *Oryza sativa* and bread wheat *Triticum aestivum* (Appendix Table-I.2). Among them, foxtail millet and broomcorn millet are drought-tolerant species with a broad ecological amplitude while the growth of rice and wheat is indispensably involved with water. Besides, the recovery of arable weeds from millet fields (e.g. *Setaria viridis*, *Digitaria sanguinalis*), rice fields (e.g. *Echinochloa crus-galli*, *Schoenoplectus juncooides*), and rice spikelet bases in macro-botanical remains (Zhong et al. 2016; An et al. forthcoming) (Appendix Table-I.3) as well as the abundant finds of phytolith morphotypes from leaves and stems of rice plants (Yao et al. 2007; this research) suggest a high possibility of local cultivation of rice and millet which makes the assessment on their cultivation ecology feasible. In contrast, the phytolith remains of wheat are not rich enough to conduct a similar analysis. Considering only the phytolith morphotype from inflorescence is recorded, wheat might have been traded into the site instead of being locally cultivated. As a result, the following discussion mainly focuses on the water regimes in rice fields and millet fields.

The CA plot of phytolith ecological categories based on individual samples shows a clear separation between samples (Fig. 2.1.2a): those dry condition indicators, fixed phytoliths, present more in the sample of H143, H37, H100, H50, and H165 on the negative end of Axis 1 while the wet condition displayed by sensitive phytoliths, bulliforms, and other moist indicators cluster around the sample of H51,

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H67, H84, and H95 on the positive end of Axis 1. In addition, a similar pattern is revealed by the *S:F* ratio (Fig. 2.1.2b). Samples of H51, H67, H84, and H95 include high proportions of sensitive phytolith types and their *S:F* ratios are between 2-2.2. This result is much higher than samples H143, H37, H100, H50, and H165 of which their *S:F* ratios are below 1.5. The results from the CA analysis and the *S:F* ratio, therefore, show high consistency.



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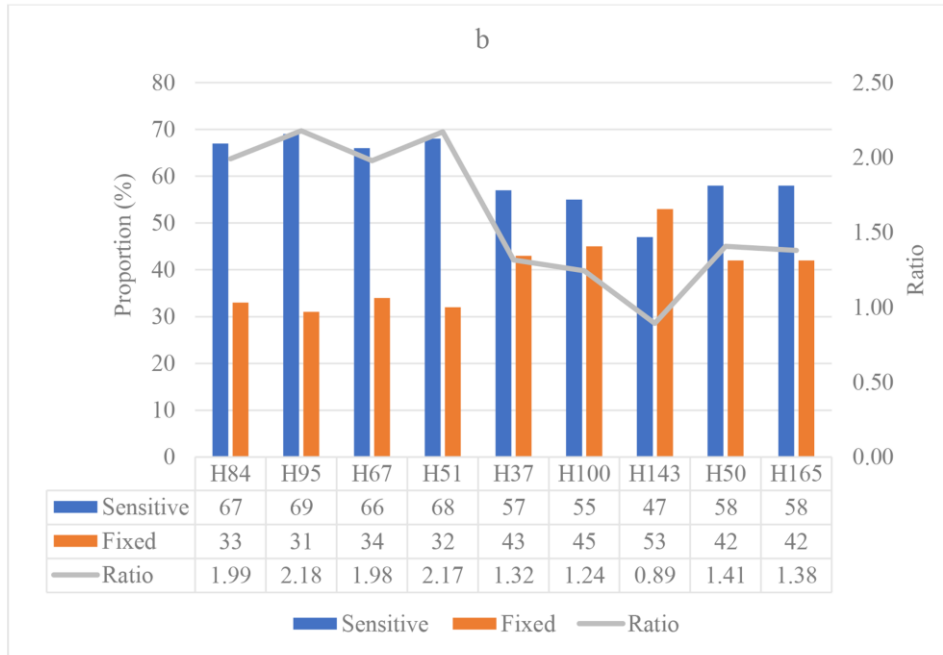


Figure 2. 1. 2 **a**. The CA plot of phytolith ecological categories and samples on 1. and 2. principal axes; **b**. Percentages of sensitive and fixed phytolith morphotypes and S:F ratios in each sample

Discussion

Crop water regimes

With different water supplies during the growing season of plants under different water regimes, phytolith assemblages may comprise different morphotypes that in return can be used to reflect water regimes (Weisskopf et al. 2014; 2015a,b; Weisskopf 2017). As testified by Weisskopf (2017), there is a clear difference in phytolith assemblages between rainfed millet farming and wet rice farming in the archaeological sites of Xipo, Baligang, and Huizui. Based on the analysis of dominant phytolith morphotypes in each sample, in this research, we declare that the clear separation of samples (both in the results of CA analysis and S:F ratios) in the Xinzhai site highly possibly reflects different moisture conditions during the growth of millet and rice and further displays different water regimes of rice farming and millet farming in the settlement.

To evaluate the water conditions of different crop fields, millet dominant samples have to be first distinguished from those rice dominant samples. Modern sample investigation depicts that the relative proportion of phytoliths extracted from crop seeds can be used to evaluate the yield of crops (Zhang et al. 2010; Luo et al. 2018).

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The same weight of rice, foxtail millet, and broomcorn millet seeds lead to the phytolith count with a ratio of 1:1.28:1.23 (Zhang et al. 2010). That means the equal weight of grains, two species of millet produce almost equivalent amounts of phytolith, but if evaluating rice by the count of husk phytolith, the yield could be underestimated. Therefore, while evaluating crops in each sample, phytolith morphotypes derived from crop seeds were used in the comparison and the ratio of 1:1.28:1.23 was also considered. It shows, in Xinzhai samples, if taking over 50% as dominant species, the dominant cereal in sample H84, H67, H95, and H51 is rice while samples of H143, H50, H37, H165, and H100 are represented by millet (Fig. 2.1.3). Therefore, the CA plot of samples and phytolith ecological groups now can be interpreted as on the negative end of Axis 1, millet dominant samples are connected with dry condition indicators whereas on the positive end of Axis 1, rice dominant samples are clustering around wet condition indicators (Fig. 2.1.4). Combing with the *S:F* ratios, rice dominant samples have higher ratios than millet dominant samples, since a higher *S:F* ratio implies a more adequate water supply in the arable system (Weisskopf et al. 2015b), thus, rice dominant samples display a much wetter condition with sufficient water resources than millet dominant samples.

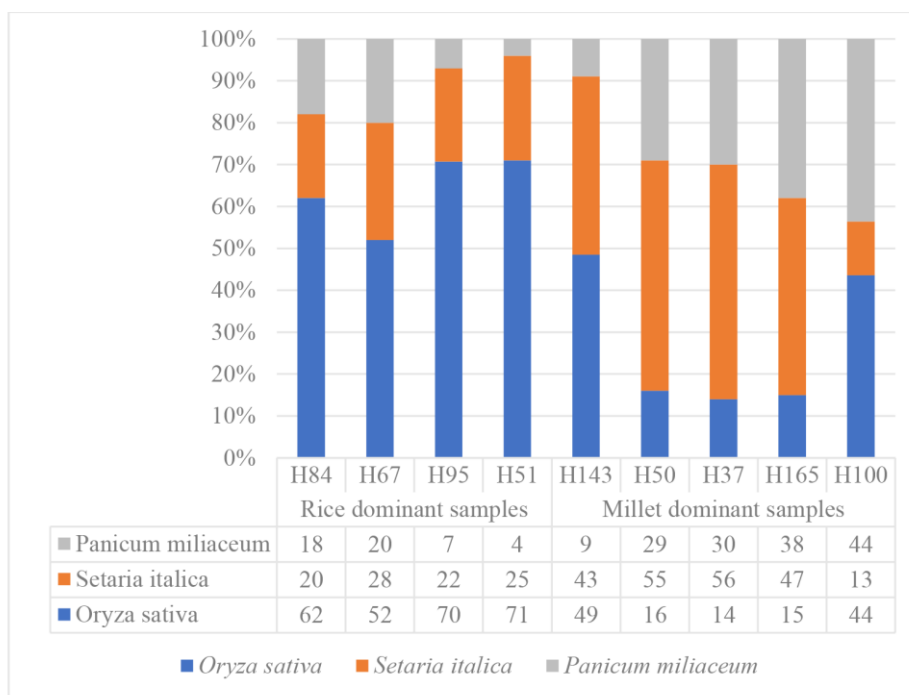


Figure 2. 1. 3 Proportions of cereals in each sample based on the cereal husk morphotypes

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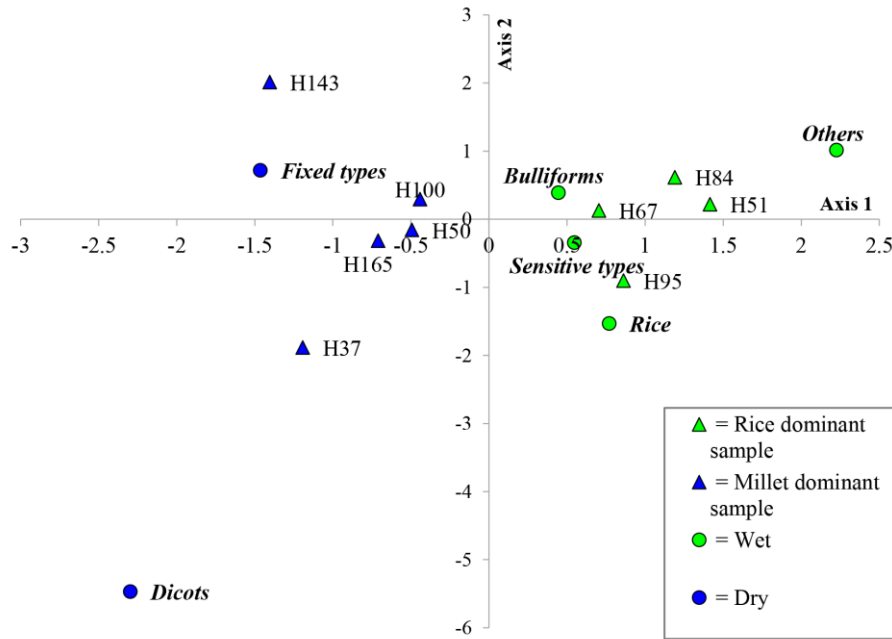


Figure 2. 1. 4 The CA plot on phytolith ecological groups and samples with their dominant crops on 1. and 2. principal axes

Moreover, comparative studies on modern rice stands suggest that the $S:F$ ratio can track degrees of wetness in different rice fields which can be carefully used as references to interpret archaeological samples (Weisskopf et al. 2014; 2015a,b; Weisskopf 2017; Wang et al. 2018, 2019; Luo et al. 2020). With differing micro-niches or eco-types, modern rice fields from the Western Ghats and Orissa in India have been divided into dry rice (upland rainfed), intermediate/semi-wet rice (groundwater/lowland rainfed, flooded/decrue), and wet rice (irrigated rice, deep-water wild rice) by Weisskopf and her colleges (2014). The $S:F$ ratio increases from dry (0.7) to intermediate (1.1/1.3) to wet (1.7/2.3) (Weisskopf et al. 2014). This ratio is further summarized by Fuller et al. (2016) with <1 as definitely dry, between 0.9-1.2 as semi-wet, and >1.25 as wet. In a latest publication, the standard from Kingwell-Banham is cited: $S:F$ ratio <1.5 indicates dry ecology while >1.5 is indicative of wet ecology (Dal Martello et al. 2021). Xinzhai rice dominant samples contain many wet indicators with high $S:F$ ratios between 2-2.2 (Fig. 2.1.2b). It suggests a wet condition, wetter than the analogue of Indian dry and semi-wet rice, but similar to the setting of wet rice where rice has grown in standing water throughout most of the growing season (Fig. 2.1.5). This value is comparable to the wild rice setting in the Hemudu Tianluoshan site (2.5/2.8), Yangshao and pre-Yangshao Baligang site (1.7/2.2/3.9), and the irrigated system in Liangzhu

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Maoshan site (1.3/2.3) of which are all wet rice categories (Weisskopf et al. 2015 a,b) (Appendix Table-I.5; Fig. 2.1.5). Besides, the difference between wet- and dry-rice can be highlighted by the different weed assemblages as well. For example, *Echinochloa crus-galli*, *Schoenoplectus juncooides*, *Cyperus* sp. are commonly found with wet rice while *Cyperus rotundus*, *Chloris barbata*, *Brachiaria reptans*³ are weeds of dry rice (Thompson 1996; Fuller and Qin 2009; Weisskopf 2010; Weisskopf et al. 2014). In this aspect, arable weeds from macro-botanical remains can offer direct evidence (Table 2.1.3). That the wet rice weeds are more frequently found (644/701) but typical dry rice weeds are hardly recorded (57/701) in the site indicates a cultivation regime under a wetland/irrigated condition. Therefore, rice farming in Xinzhai can be evidently attributed to a wet rice farming system. However, since only the *S:F* ratio above 3 can be definitely linked with systematic irrigation while these values between 1.5-3 can only be referred as wet rice but unnecessarily irrigated (this standard from Kingwell-Banham in Dal Martello et al. 2021). As a consequence, with the consideration of only the *S:F* ratio, both growing settings of wild rice and irrigated rice could be possible in the Xinzhai settlement.

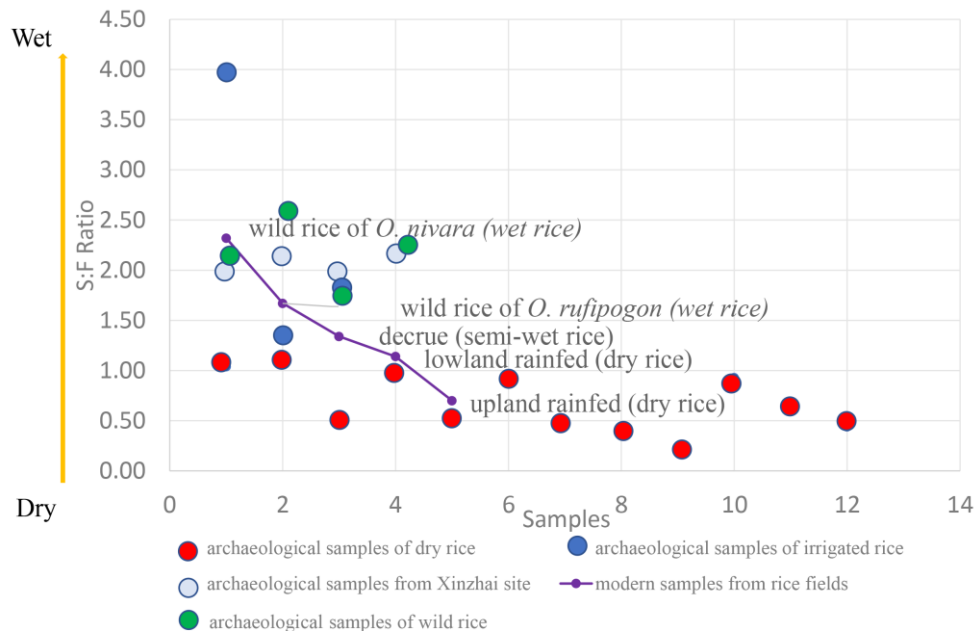


Figure 2. 1. 5 The comparison of *S:F* ratios among Xinzhai samples, modern rice field samples, and other archaeological samples (ratio values based on Appendix Table-I.5)

³ The scientific name of *Brachiaria reptans* is updated to *Urochloa reptans* according to the Plant Plus of China (see www.iPlant.cn) that hosted by the State Key Laboratory of Systematic and Evolutionary Botany Institute of Botany, the Chinese Academy of Sciences (LSEB, IB, CAS).

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Table 2. 1. 3 Rice farming-related arable weeds in the Xinzhai site (counts)

Weed species	Wet/dry [#]	Ecology [*]	Year 2014	Year 2016	Year 2018	Total
<i>Echinochloa crus-galli</i>	Wet rice	Lowland irrigated	1	135	141	277
<i>Cyperus serotinus</i>	Wet rice	/	39	39		78
<i>Schoenoplectus juncooides</i>	Wet rice	Lowland irrigated/ tidal	4	109	75	188
<i>Carex diandra</i>	Wet rice	/	3			3
<i>Pycnus sanguinolentus</i>	Wet rice	Lowland irrigated/tidal/rainfed	2	55	41	98
<i>Eleusine indica</i>	Dry rice	Upland		2		2
<i>Physalis angulate</i>	Dry rice	Upland		1		1
<i>Portulaca oleracea</i>	Dry rice	Upland		2		2
<i>Cyperus iria</i>	Dry rice	All type of rice fields		33	19	52
Total	Wet rice		49	338	257	644
	Dry rice		0	38	19	57

*Ecological information see Soerjani et al. 1987; # Wet rice and dry rice information see Fuller and Qin 2009.

However, with multiple evidences, a scenario of irrigated wet rice farming can be further suggested in the Xinzhai site. First, it can be certain that Xinzhai rice is not a wild type. One convincing evidence is after the morphological observation of 50 rice spikelet bases in macro-botanical remains, no one shows wild rice features (An et al. forthcoming). Another available indicator for an intensive irrigated farming is it is almost unique in the process of flooding fields and transplanting seedlings to fertilize and reduce weeds for raising crops, therefore, irrigated rice farming inevitably involves much fewer arable weeds (Weisskopf et al. 2014; Kingwell-Banham 2019). The low find of sedges (128/20,019) in phytolith assemblages and the much lower number of rice field weeds (698) in contrast to millet field weeds (5,223) in charred remains clearly point to a cultivation practice to combat weeds which could be achieved through deep irrigation or transplanting (Appendix Table- I.2, I.3). It has been proposed that during 4000-2000 BCE, the spread of rice out of the Yangtze River towards the Central Plain appears to have occurred only after rice was fully domesticated and labour-intensive paddy-field cultivation was finally established (Fuller and Qin 2009; Qin 2012). It is, thus, no surprise that fully domesticated rice together with the irrigation technique has been spread into the Central Plain rather than rice *per se*. As proven by the investigation of the landscape evolution and rice planting in this region, after the Late Longshan period (2100-1900 cal. BCE), at least until the Erlitou period (~1750 cal. BCE), rice was successfully planted on drought loess plateau valley areas regardless of natural constraints (Li and Zhang 2020). This might reflect a consequence of the practice of irrigation. Moreover, according to the observation of modern irrigated rice fields

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on lowlands as well as on higher elevations where the terrain is hilly in Indonesia, both types of fields demand accessibility to water resources and also considerable efforts either to create levees, bunds, dikes to control water depth in lowland flat plots or create irrigation features to move water from various water reservoirs to terraces (Soerjani et al. 1987). In terms of the Xinzhai site, geomorphic evidence shows that the ancient Shuangji river channel is found running through the settlement during the Xinzhai period which could provide sufficient water resources (Xia et al. 2004; ACAC-PK and Zhengzhou 2008). Besides, as a regional center, the settlement had substantial amounts of workforce which can be proven by the construction of large public-structures, such as the rammed-earth city wall and the semi-subterranean architecture. Hence, on the condition of an ample supply of water and an available amount of labour, the Xinzhai settlement could fulfil all the requirements for the practice of an irrigated rice farming. To conclude, multiple evidences point to the fact that an irrigated wet rice farming was highly possibly performed in the Xinzhai site.

Furthermore, it has been testified that this observed correlation of $S:F$ ratio with plant water availability identified in C_3 (rice, wheat) plants also hold true for C_4 species of sorghum, finger millet, and pearl millet (Lancelotti et al. 2019; Jenkins et al. 2020; Predanich 2020). Therefore, the water regime of Chinese millet fields can be carefully discussed as well (Weisskopf 2017). In Xinzhai, millet dominant samples are much drier ($0.9 < S:F < 1.5$) in comparison to rice dominant samples but still have a large proportion of sensitive morphotypes (over 50%) suggesting a relative wet condition. Rather than implicating of artificial water supply, we argue it might be a reflection of the palaeoecological environment around the settlement. As indicated by multi-climatic proxies, during the occupation of the Xinzhai period, the settlement witnessed a wet and warm climatic condition (ACAC-PK and Zhengzhou 2008). Thus, the occurrence of relatively large proportions of sensitive forms might be a consequence of relatively adequate precipitation. Compared with the rainfed millet farming in the Yangshao Huizui site (1.6) (Weisskopf 2017), Xinzhai samples have slightly lower $S:F$ ratios. It is mainly because the Yangshao period was under the Holocene Climatic Optimum- the warmest and wettest climate -in the whole Neolithic Age (Feng et al. 2006; Rosen 2008). In conclusion, rice and millet, according to $S:F$ ratios, appear to have been cultivated under

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different ecological settings. Rice was grown under an irrigation system with massive water supplies during its growing season while millet was cultivated as rainfed species and might have received its maximum water supply during the summertime under the summer monsoon system.

Food hierarchy in the Xinzhai period

In China, especially northern China, rice as a prestige food being favored by elites has long been recognized in the Bronze Age (~1750 cal. BCE) through historical literature (Song 2008; Zeng 2016), archaeological context analysis (Lee and Bestel 2007; Chen 2007), and stable isotope analysis (Qi et al. 2006; Zhang et al. 2012). In this research, a similar preference for rice can be found with central settlements and high societies during the Neolithic Xinzhai period. To investigate the distribution of rice and millet on a regional scale, all the available archaeobotanical data including macro-botanical remains and phytolith remains from the Xinzhai period are collected (Table 2.1.4; Appendix Table-I.6). Phytolith is only recorded in the Xinzhai and Dongzhao site. The result from the year 2007 of the Xinzhai site (Yao et al. 2007) is no longer considered in the analysis due to its unclear sampling background and undetailed identification of phytolith. Meanwhile, macro-botanical remains are derived from four sites (Appendix Table-I.6) but the result from the excavation season 1999, 2000 of the Xinzhai site (ACAC-PK and Zhengzhou 2008) is excluded. It is because the sieves used for flotation were so large in mesh (5×5 and 1×1 cm) that small-grain millets were most possibly lost and eventually causes the over-presence of rice. Moreover, while weighting importance of crops among sites, to mitigate the bias brought by differing sample volumes in each site and also to better apply CA method to investigate the variation of crop species among sites, the semi-quantitative Representativeness Index (RI) following An et al. (2019) is applied in the comparison.

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Table 2. 1. 4 Compilation of archaeobotanical data from the Xinzhai period

Materials	Site names	Description of samples	Sampling locations	References
Macro-botanical remains	Xinzhai (Year 1999, 2000)	11 samples from pits; 3 samples from sub-layers of exploratory trench T11	residential area	ACAC-PK and Zhengzhou 2008
	Xinzhai (Year 2014)	108 samples from pits; 1 sample from a kiln	storage area	Zhong et al. 2016
	Xinzhai (Year 2016, 2018)	220 samples from 168 pits	residential area	An et al. forthcoming
	Zhengzhou Shang City	4 samples from a profile		Jia et al. 2018
	Huadizui	25 samples from pits		Tang et al. 2018
	Dongzhao	34 samples from pits and 3 samples from moats		Yang et al. 2017
Phytolith	Xinzhai Year 2007	1 sample from sub-layer ⑨ of the exploratory trench	inner-city, unclear	Yao et al. 2007
	Xinzhai Year 2018	59 sediment samples from 9 pits	residential area	This study
	Dongzhao	36 sediment samples from 28 relic units		Luo et al. 2018

In the results, a relative higher occupation of rice in central settlements is very well-marked in the comparison of both phytoliths and charred remains (Fig. 2.1.6a,b). By comparing the phytolith morphotypes from inflorescences, rice takes a much higher percentage in the regional center Xinzhai site than the Dongzhao site (Fig. 2.1.6a). The CA plot of sites and cereals based on RI values of charred remains indicates that the regional center of Xinzhai and Huadizui cluster around rice on the negative end of Axis 1 while the other sites of Dongzhao and Zhengzhou Shang City are close to foxtail millet and broomcorn millet on the positive end of Axis 1 (Fig. 2.1.6b). It is noteworthy that, as an outlier, the samples from the storage area of the Xinzhai site seem to disagree with the other samples from that site: rice is apparently more concentrated in the residential area rather than the storage area. Archaeological evidence suggests that the Xinzhai site formed a hierarchical society that comprises elites, clergies, ordinary residents, and servants (slaves) (Fu 2016). This residential area was highly likely occupied by elites and/or clergies due to its centralized location in the inner city and also the abundant finds of exquisite artefacts. Thus, rice turns out to be overwhelmingly presented in central settlements as well as the residential area of elites and/or clergies in one settlement.

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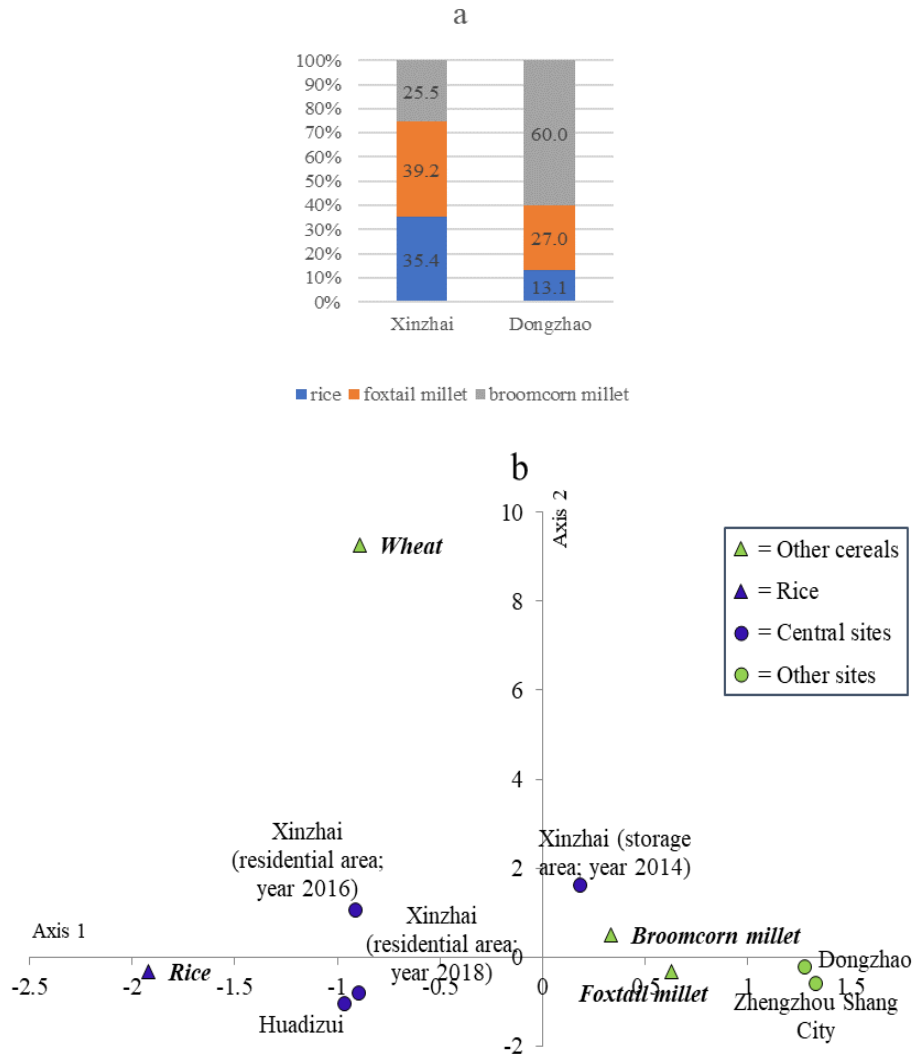


Figure 2. 1. 6 Comparison of *a.* phytolith and *b.* macro-botanical remains among different sites of the Xinzhai period

In previous studies, ecological factors were mostly accepted as the main reasons for the ‘privilege’ of rice in the arid and semi-arid northern China during the Bronze Age: rice-unfavourable cooling, dry environment caused the limited cultivation of rice and further added extra symbolic values to this scarce resource (Lee and Bestel 2007; Chen 2007). In this study of the Xinzhai period, however, paleoclimatic reconstruction recovered a possible rice-favourable wet and warm environment (ACAC-PK and Zhengzhou 2008). Therefore, massive cultivation of rice is theoretically feasible just like the unprecedented cultivation of rice under suitable climatic conditions during the Longshan period in northern China (e.g. Central Plain and Haidai Region) (Jin and Luan 2006; Zhong 2020). Under this precondition, limited access to rice in the Xinzhai period actually should have been

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driven by social factors rather than ecological factors. In a hierarchical society, one way that elites mark their social status is through access to luxury food and exotics (Goody 1982; Gumerman 1997; Mintz and Du Bois 2002; Palmer and Vander Veen 2002). Residue remains analysis on human dental calculus from the Dongzhao site shows starch granules of millet was found in 100% of samples but only 25% of samples had rice remains (Sun et al. 2018). It clearly shows only a few individuals may be a certain group could have reached rice. Meanwhile, starch granules from millet and other plants (e.g. *Coix lacryma-jobi* and *Vigna angularis*) were commonly found on potteries (Sun et al. 2018) and stone knives (Tang 2018), but rice was missing. It is a strong indicator that rice was treated differently from other crops: it was harvested by specialized tools and cooked/stored in isolated containers which might due to its privileged social-role. Another more convincing evidence is the tentative link of social identity and group differentiation with dietary patterns by stable isotope analysis (Somerville et al. 2013; Knipper et al. 2015). Current stable isotope analyses on human skeletons and domestic animals (pig, sheep, goat, cattle) from the Xinzhai site show that humans and local animals both had high intakes of C₄ food and might have shared a similar millet-based diet (Wu et al. 2007; Zhang and Zhao 2015; Dai et al. 2016a,b). Considering current human samples are all from small burials that representing low social status, thus, C₃ food including rice had contributed minor or even absent in this certain group. Taking the spatial distribution of rice in the Xinzhai site into account, it is practical to assume that rice was more likely to be controlled or occupied by elites and/or clergies while millet was stored on a large scale as a common food or security food for ordinary residents and local animals.

But, why rice has been chosen as an prestige food being favored by central settlements and elites? To answer this question, the different hierarchies of crop species can be assessed together with the social implication of different crop water regimes. The control over water is and has long been intimately associated with social and political power (Morrison 2016). Limiting certain irrigated crop species to the wealthy and powerful is one of the expressions. One example is in southern India, rice along with a variety of other irrigated crops, dairy products and spices came to form the basis of aristocratic cuisines during the Middle period (1300-1600 CE) (Morrison 2016). In this research, we argue that the irrigation technique that

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facilitated rice cultivation through intensive labour inputs has increased the social value of rice which eventually led to the limitation of rice to the wealthy and powerful high societies but under a labour-saving rainfed system, millet was acted as a common food or security food. Besides, to practice an irrigation system, a large investment of labour is demanded throughout the production cycle of rice, from the preparation of fields to the planting of seeds or transplantation of young plants (Greenland 1997; Chang 2000). This labour requirement must usually be balanced with labour demands for other agricultural activities so that the implementation of an irrigated-rice component has a significant impact on all other aspects of the agricultural cycle (Morrison 1995). In fact, this impact has already been verified by the deployment of workforce before and after the storage in the Xinzhai site. That all summer crops were stored in semi-processed forms pinpoints less labour was available for the processing of crops (An et al. forthcoming). Bearing these factors in mind, an irrigated rice farming can (or even only can) be largely operated in settlements that were densely populated and also had proper social systems to organize massive labour to accomplish cooperative projects which usually are these central settlements. As a great rewarding, this labour- and time- consuming irrigation system helps to manage rice-weed vegetation to produce the optimum yield of rice (Soerjani et al. 1987), therefore, can guarantee considerable production in central settlements. In conclusion, social factors of the differential time and labour investments in different water regimes are highly likely to lead to the food hierarchies in the Xinzhai period.

At last, based on above conclusions, it is possible to discuss how crops participated in social complexity. As suggested by many archaeologists (Earle 1987; Gilman 1987; Hirth 1992; Liu 2005): in a complex society, the political-economic system includes 'wealth finance' and 'staple finance'. In the former, valuable material was produced by elites, exchanged for staples and redistributed as symbols of rank on a regional level. It was used to cement alliances between the leaders of different groups, and to attract and establish personal clientage relationships with headmen of smaller groups. In the latter, it is surplus staples, such as grains, that were mobilized to support elites. In Xinzhai period, rice might have participated in the political-economic network as part of the 'wealth finance'. By more or less exclusively producing rice and controlling rice in the exchange network, powerful

settlements could reinforce their important social and/or economic roles on a regional scale and individuals could also maintain their high social status in hierarchical societies. This uneven accessibility to agricultural resources among social groups further accelerated status and wealth differential which was an vital element for the social complexity. As declared by Van der Veen (2003), in simple societies the emphasis was on the quantity of food while in strongly hierarchical societies more emphasis was paid on exotics and differentiated cuisines (low and high cuisines). Hence, with an emphasis on luxury rice to elites, a highly hierarchical society was likely formed during the Xinzhai period.

Conclusions

In this research, a labour-intensive irrigated rice farming and a rainfed millet dry farming are testified in the Xinzhai site through the correspondence analysis of phytolith ecological groups, the ratio analysis of sensitive to fixed morphotypes, and the complementary evidence of arable weeds from macro-botanical remains. With this conclusion, it is possible to interpret the priority of rice in the aristocratic residential area in the Xinzhai site and also in central settlements of the Xinzhai period. The results suggest that instead of ecological factors, this pattern is more likely to be caused by social factors. With different labour requirements or schedules between irrigated and dry-farmed lands, cultural values attached to different water regimes were also varied. Since rice is highly likely to be regarded as a food for the wealthy and powerful, therefore, it is highly possible that the irrigation system with intensive labour and time inputs qualified rice as an elite food while rainfed crops such as millet were possibly acted as an ordinary food or security food.

The conduction of the irrigated rice farming system has a profound impact on the agricultural system and the whole society. By occupying massive labour in irrigation and off-season tasks such as building dams, maintaining canals, and cleaning and desilting reservoirs, the irrigated rice farming in conjunction with other production activities forced the society to deploy labour in small household units instead of communal communities in crop processing to mitigate labour pressure during the harvesting season, and also restricted rice to the wealthy and powerful high societies as a luxury food to enhance the social status of certain

groups. Thus, through this study, it proves that intensive irrigated rice farming in cooperation with other social factors has accelerated the social complexity during the Xinzhai period.

Acknowledgements

The new research samples come from a collaborative excavation of the Xinzhai team of the Institute of Archaeology in the Chinese Academy of Social Sciences, the Archaeological Institute in Zhengzhou, and the Institute of History at Anhui University. Sampling was assisted by the 2016-undergraduate students from the Institute of History at Anhui University. Weihong Wu, Huadong Zhu (Anhui University), Honghong Wei (Archaeological Institute of Zhengzhou), and Guangxiang Geng (Xinyang Museum) offered archaeological information during and after the fieldwork. Wanli Lan and Yaping Li (Henan Institute of Cultural Relics and Archaeology) kindly offered lab facilities and assistance for preliminary lab works in China. The Young Academy of the Cluster of Excellence ROOTS (EXC 2150) at Kiel University provided facility supports for the subsequent lab work. We gratefully acknowledge the financial support from the China National Natural Science Foundation (41771230) and the China Scholarship Council for a Ph.D. degree (Fund No.201706220058).

Appendix I

Table I.1-I.6 and Figure I.1-I.6

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2.2 Case study on the Xinzhai site- II

In non-mechanized ancient societies, agriculture and its related activities are important areas that create the need for assistance between human groups (e.g. households) and provide a recurrent situation in which labour organized and social relationships developed (Fuller et al. 2014). Among all the agricultural activities, except for the inputs required during crop growth such as sowing, weeding, manuring, and irrigation, the processing of crops from harvesting to final consumption usually demands the most massive labour and time inputs. Accordingly, it creates the most need for assistance between social groups. This factor determines that in ancient settlements, especially those conducted other huge public constructions, proper social systems were required to arrange time efficiently and also to organized labour legitimately to accomplish agricultural production. As suggested in the last section 2.1, labour-intensive irrigated rice farming was highly likely to be practiced in the Xinzhai site. It demands a large investment of labour throughout its production cycle, from the preparation of fields to the planting of seeds or to the transplantation of seedlings (Greenland 1997; Chang 2000) and also a long-term investment of labour in the creation and maintenance of paddy fields and irrigation facilities (Fuller and Qin 2009). These labour requirements must usually be balanced with other agricultural activities so that the implementation of an irrigated rice component has a significant impact on all other aspects of the agricultural system (Morrison 1995). Likewise, in the Xinzhai settlement, it is highly possible that the labour input in the irrigation system has a profound influence on the distribution of labour in other agricultural activities such as in crop processing.

This assumption can be testified through the analysis of archaeobotanical remains. With focusing on when crops were stored during the processing sequence, archaeobotanical assemblages can contribute to the understanding of how labour was organised and scheduled at various sites and on a broader level in past societies (Stevens 1996, 2003; Fuller 2002; Fuller and Stevens 2009; Fuller et al. 2014). The basic principle behind this idea is that the most important source for seeds and chaff in ancient sites were from routine, daily crop processing activities for food preparation, in which crops and contaminants such as weed seeds were taken from storage and processed for consumption with household labour (Stevens 2003;

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Fuller et al. 2014). Thus, crop storage forms can be used to reflect the size of the seasonal workforce used during the harvest period before storage versus that needed for daily food preparation in the households. Moreover, comparative study of archaeobotanical remains from seasonal activities with those from everyday processing can provide important insights into the wider social systems of an archaeological culture. Whether a community organized its agricultural activities through some centralized pool of labour or with different types of human groups such as households is a fundamental part of how a society works. Thus, the pattern of labour mobilization can be indicative of the social organization type (Fuller et al. 2014). In this section, the crop processing method in the Xinzhai settlement was discussed in detail and the labour distribution reflected in crop processing further offered information on how societies were organized and how the practice of irrigation might have impacted the coordination of labour resources.

So far, similar studies are limited in China (Fuller and Zhang 2007; Song 2011; Weisskopf et al. 2015; Song et al. 2019). Almost all of them are about the Central Plain (Fig. 2.2.1). Moreover, existing researches cover the Yangshao period (5000-2500 cal. BCE), Longshan period (2300-1900 cal. BCE), and Erlitou-Shang period (1750-1046 cal. BCE) with the absence of the Xinzhai period (1850-1750 cal. BCE) (Table 2.2.1). From this point of view, this research perfectly fills in the time gap and makes the full sequence complete. According to the conclusions from previous studies, societies have witnessed a transformation in the distribution of labour concerning crop processing and also social organization. In the Yangshao period, with all of the settlements deployed centralized labour or large-scaled communal activities, there was no differentiation in the social organization within the community among sites. However, some of the sites began to focus on small-scaled households while the others kept on the centralized communal societies in the Longshan period. This kind of differentiation highly possibly persisted in the Erlitou-Shang period. In this section, related information about the Xinzhai period showed a high consistency in social development through time.

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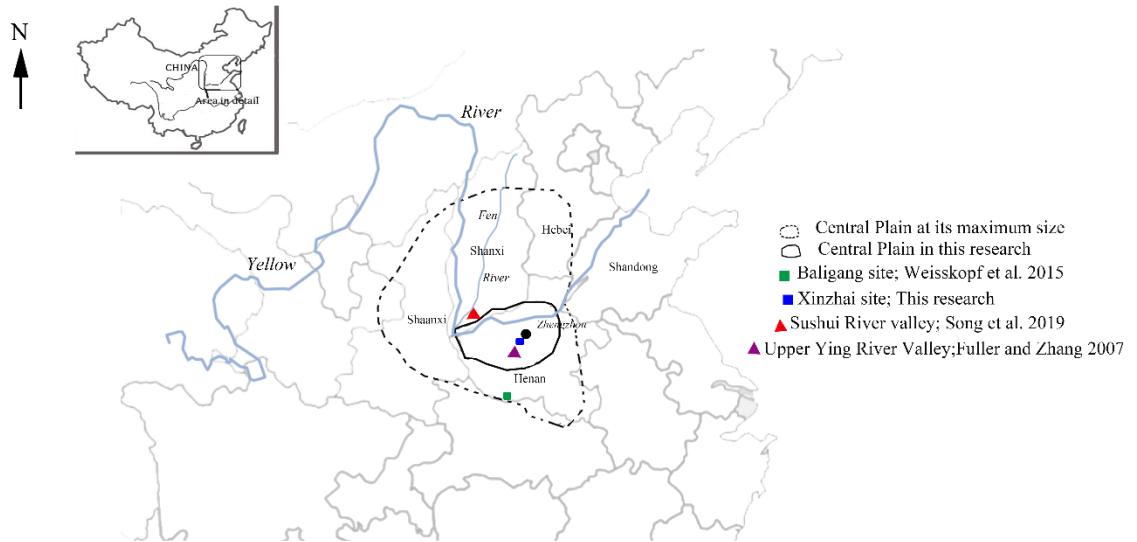


Figure 2. 2. 1 Location information in different research papers about crop processing within this project

Table 2. 2. 1 Chronological information in different research papers about crop processing within this project

Archaeological culture	Yangshao/Maodigou II	Longshan	Xinzhai	Erlitou-Shang
cal. BCE	5000-2500	2300-1900	1850-1750	1750-1046
Labour organization in the crop processing	On a communal basis	A shift to households on many but not all sites	?	Communal and small households
	Uniformity	Diversity		Diversity
References	Fuller and Zhang 2007; Song 2011; Weisskopf et al. 2015; Song et al. 2019	Fuller and Zhang 2007; Song 2011; Weisskopf et al. 2015; Song et al. 2019	An, et al. this research	Fuller and Zhang 2007; Song 2011; Weisskopf et al. 2015; Song et al. 2019

Understanding crop processing and its social meaning in the Xinzhai period (1850-1750 cal. BCE): a case study on the Xinzhai site, China

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This is the final, citable version of an article that is in press by *Vegetation History and Archaeobotany*. Article DOI : 10.1007/s00334-021-00851-0.

Abstract

Although the Xinzhai period (1850-1750 cal. BCE) has been widely regarded as a critical time for the development of urbanization in China, little is known about the labour and social organization of the time. In this paper, archaeobotanical assemblages have been used to explore evidence of crop processing and they have provided further insights into the organization of labour and society at the Xinzhai site on the Central Plain of China. This is the first case study linking agricultural activities and social organization in the Xinzhai period. By discussing macro-botanical and phytolith results together, we conclude that the hulled cereals *Setaria italica* (foxtail millet), *Panicum miliaceum* (common or broomcorn millet) and *Oryza sativa* (rice), and the free-threshing pulse *Glycine max* (soybean) were all partly processed before storage to reduce labour demand in the harvest period. Since these summer-sown crops are all harvested in autumn, the practice of partial processing might imply that less labour was needed before storage. Thus, the labour for crop processing appears to have been organized on the basis of small production units such as households. This pattern is different from the communal bulk processing of crops before storage by the contemporary inhabitants of Dongzhao. Different patterns of social organization in various settlements in the Xinzhai period can thus be suggested. This conclusion contributes to a comprehensive understanding of the social development of communities living on the Central Plain and indicates that a steady increase in social complexity was very likely in the period before urbanization.

Keywords Xinzhai period· Macro-botanical remains· Phytoliths· Crop processing· Labour mobilization· Social organization

Introduction

In studying past societies, one fundamental issue that needs to be addressed is how labour was organized within them (Fuller et al. 2014). As suggested and testified by many researchers, archaeobotanical assemblages can contribute to the understanding of how labour was organised and scheduled at various sites and on a broader level in past societies, by studying at what stage in the processing sequence crops were stored (for example, Hillman 1981, 1984; Jones GEM 1984; Jones MK 1984, 1985; Stevens 1996, 2003; Fuller 2002; Fuller and Stevens 2009; Bates 2011, 2016; Fuller et al. 2014; Bates et al. 2017). The basic principle behind this idea is that the most important sources of seeds and chaff preserved in ancient sites were from routine daily crop processing activities for food preparation, in which crops and contaminants such as weed seeds were taken from storage and processed for consumption with household labour (Stevens 2003; Fuller et al. 2014). Crop storage methods can therefore be used to reflect the size of the seasonal workforce used during the harvest period before storage versus that needed for daily food preparation in the households. Furthermore, comparative study of archaeobotanical remains from seasonal activities with those from everyday processing can provide important insights into the wider social system of an ancient culture. Whether a community organized its agricultural activities through some centralized pool of labour or with different types of human groups such as households is a fundamental part of how a society works. Thus, the labour mobilization pattern can be indicative of the social organization type (Fuller et al. 2014).

Being widely recognized as the place where the first urban centres emerged during the Erlitou culture (1750-1550 cal. BCE) in China, archaeobotanical investigations on the Central Plain (Zhongyuan) are of particular interest, especially for the process of social complexity and its organization of societies (Liu and Chen 2012). Rather than an abrupt change, urbanization was a protracted process of social evolution. The emergence of the first urban centre from 1750 cal. BCE can therefore be traced back to the continuous social development in the preceding Xinzhai period (1850-1750 cal. BCE). Because of this, knowing the type of social organization in the Xinzhai period is vital in the understanding of early urbanization in China. However, we know surprisingly little about this. Although archaeobotanical data have shown great value in the exploration of labour and

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social organization, current archaeobotanical investigations on a small number of individual sites related to the Xinzhai period have been almost exclusively focused on crop finds (Yao et al. 2007; ACAC-PK and Zhengzhou 2008; Zhong et al. 2016; Yang et al. 2017; Tang et al. 2018) and questions concerning crop processing with its related social aspects were not considered. The idea of linking crop processing with social organization has only occurred recently in China, particularly aided by the ethnographic investigation of *Setaria italica* (foxtail millet) processing published in Chinese by Song et al. (2014).

Macro-botanical remains and phytoliths, with their differing preservation potentials, have successfully provided complementary insights into crop processing methods in small village-type settlements and also into urban-rural subsistence relationships in India (Bates 2016; Bates et al. 2017). However, research in China at present has either only focused on macro-botanical remains or phytoliths. Macro-botanical studies have investigated, for example, the social organization transformation in the river valleys of the upper Ying (Fuller and Zhang 2007) and Sushui (Song 2011; Song et al. 2019), with discussions on the processing of *Setaria italica* (foxtail millet) and *Panicum miliaceum* (common millet). Phytolith studies, on the other hand, have explored social organization at the Baligang, Shunshanji and Hanjing sites through the analysis of *Oryza sativa* (rice) processing (Weisskopf et al. 2015; Luo et al. 2021). Also, even though pulse processing methods have been recorded by ethnographical investigations in India (Fuller and Harvey 2006), *Glycine max* (soybean) processing in archaeological samples in China has never been discussed so far. In the present study, processing methods of *Setaria*, *Panicum*, *Oryza* and *Glycine* were studied through a combination of two lines of botanical proxy evidence from the Xinzhai site, macro-botanical remains and phytoliths. Moreover, although there has been a sophisticated study showing the great potential of arable weeds in indicating crop processing methods (for example, Reddy 1994, 1997), they have been overlooked in current Chinese studies. Therefore, arable weeds were included in this research as well. This project is not only a pioneer study for exploring crop processing through the integration of two types of archaeobotanical remains in China but also the first systematic research into labour and social organization in the Xinzhai period.

The Xinzhai site and its setting

The Xinzhai site is located 22.5 km from the city of Xinmi in Henan province. It is situated on the floodplain east of the Song mountains and north of the Shuangji river (Fig. 2.2.2a). After its first discovery in the 1960s, it has been continuously excavated from 1979 (Second team et al. 1981) to the present. Occupation at this site includes three phases, the Neolithic late Longshan period (2050-1900 cal. BCE), the Neolithic Xinzhai period (1850-1750 cal. BCE) and the Bronze Age Erlitou phase 1 (later than 1750 cal. BCE) (ACAC-PK and Zhengzhou 2008). Settlement at the site was fully developed during the Xinzhai period, when it was surrounded by two concentric outer ditches and an inner rammed earth wall with moats. Exquisite artefacts of jade, copper, elaborate pottery vessels and particularly a large (ca. 1,400 m²) semi-subterranean building illustrate the advanced social and political status of the site (Zhao et al. 2009). It has been proposed as the capital of the Xia ruler Qi (齐) (Xu 2004; Zhao 2004) or of Houyi (后羿) and Hanzhuo (寒浞), who came from the Dongfang (东方) and took power in the Xia dynasty (Gu 2002). These interpretations assume that the Xinzhai site was the primary centre occupied by a continuous succession of leaders related to the first legendary Xia dynasty in China (Liu and Chen 2012). Currently, among all the sites that contain Xinzhai assemblages, Xinzhai in this research and Huadizui in Gongyi were two regional centres on the Central Plain, while Xinzhai was the largest (Liu 2005).

The samples analysed in this research were from the 2016 and 2018 excavation seasons, for which collaborative excavations were conducted by the Xinzhai team of the Institute of Archaeology in the Chinese Academy of Social Sciences, the Institute of Archaeology in Zhengzhou and the Institute of Archaeology at Anhui University (only in 2018). The excavations consisted of 53 trenches, each measuring 5 × 5 m, northeast of the modern village Liangjiatai (Fig. 2.2.2b). They were located on the highest area in the inner city at 143.8 m a.s.l. (Xinzhai and Zhengzhou 2009). During the excavation, rammed earth building foundations, pits and burials were exposed, mainly dating to the Xinzhai period, but a few to the Neolithic Longshan and Bronze Age Erlitou periods.

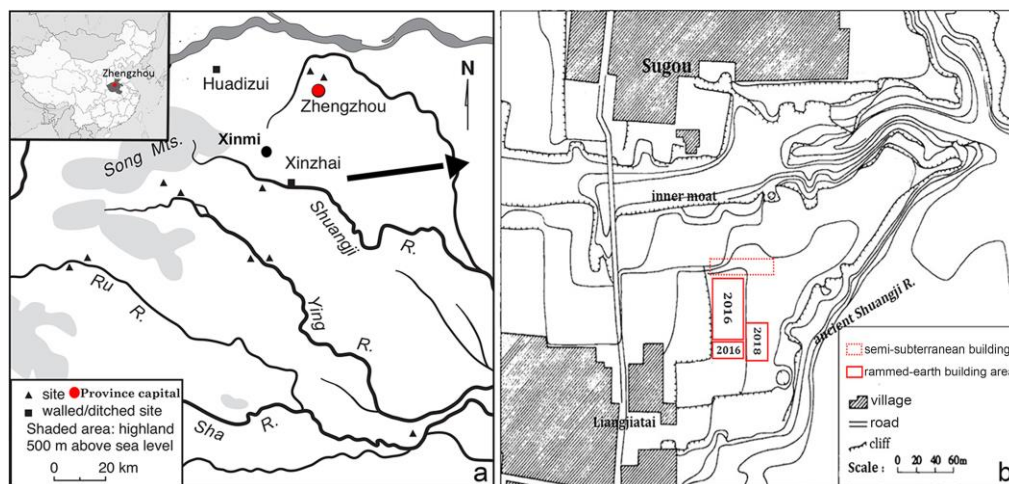


Figure 2. 2. **a.** distribution of major Xinzhai period sites, Central Plain, China (modified from Pang and Gao 2008, Fig. 1); **b.** excavation areas (modified from Xinzhai and Zhengzhou 2009, Fig. 1)

Materials and laboratory processing

In investigating crop processing methods from archaeological contexts, the combination of macro-botanical remains and phytoliths can provide better evidence than either alone (Bates 2016; Bates et al. 2017). In this research, 220 flotation macrofossil samples and 59 phytolith samples were collected from waste pit features (Appendix Table-II.1). Archaeobotanical remains of material in situ are rather rare, because most archaeological contexts do not normally contain primary botanical refuse that was burnt within the context from which the remains were recovered, but are mostly made up of tertiary refuse in which the plant remains came from many different activities and charring events, or at least made of secondary refuse in which the plant remains from one discrete burning event were moved to another context (Hubbard and Clapham 1992; Fuller et al. 2014; Filatova 2020). However, by understanding the formation processes of deposits containing charred plant remains, it is possible to connect the resulting plant assemblages with past human activities. The analysis of charred plant remains from many different types of sites and from various periods shows that most samples are very similar in their composition (van der Veen 2007). This similarity argues for the case that the majority of plant remains can be related to a closely related set of activities. More than that, charred assemblages clearly represent a very limited range of the total floristic diversity, as almost all taxa are connected with cultivated crops, including cereals, cereal chaff and associated weeds, with only the exception of wild edible

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plants. According to van der Veen (2007), charred plant remains that are found in archaeological samples mainly come from five routes of entry: 1. intentional and casual use of fuel; 2. contact with fire during crop processing or preparation of food; 3. accidental burning of stored food and fodder; 4. cleaning out of grain storage pits using fire and 5. destruction of diseased or infested crops with fire. The first two of these represent routine daily activities and the last two are rare events. Since charred plant components resulting from everyday activities are more likely to be represented in archaeobotanical material than occasional rare events (Fuller et al. 2014), most charred plant remains therefore are the waste from daily activities of burning fuel, processing crops and preparing food. So with the exclusion of firewood and gathered wild plant remains, the charred plant remains from the waste pits in Xinzhai can be used to indicate crop processing and food preparation. All the samples collected from the Xinzhai site are from the Xinzhai period between 1880 and 1745 cal. BCE, according to the stratigraphy, typology of finds and also the AMS ^{14}C dating results from charred seeds and fruit remains from eight samples (Appendix Figure-II.1).

Macro-botanical remains were obtained by using a bucket flotation system. An average of 10 L of sediment per sample was aimed for, although in some cases such as when the context was smaller, it was impossible. The lighter floating materials and heavier sinking materials were retained by 0.2 mm and 1 mm mesh sieves, respectively. After drying, the samples were sent to laboratories for analysis. The sorting work was carried out at the ancient parasite and starch analysis laboratory (APSA) in the Henan Institute of Cultural Relics and Archaeology, China. Light fraction samples were first sieved with meshes of 1, 0.5 and 0.2 mm and the fractions <0.2 mm were excluded since no charred seeds or fruits were found in these tiny remains. The identification, counting and photographing of the charred remains were done in the laboratory of the Institute of Pre-and Proto-history at Kiel University (IPPH), Germany. Identification was done by comparison with modern reference material and followed the identification methodology of Kroll (1983), Liu et al. (2008) and Fuller (2017).

Phytolith samples were collected either by sampling sub-layers in a pit or by sampling sections every 20 cm in homogeneous units from a profile, or by the combination of two methods in the pits with thick sub-layers (Appendix Table-II.1).

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The extraction of phytoliths was carried out at APSA in Henan. Sub-samples of 2 g soil were weighed and then treated with 30 % hydrogen peroxide (H₂O₂) and 10 % hydrochloric acid (HCl) to remove organic matter and carbonates. Phytoliths were extracted by zinc bromide (ZnBr₂, density 2.37 g/cm³) heavy liquid flotation and mounted on slides in immersion oil, using cover slips sealed with nail polish. They were observed, identified and counted with a Leica DM750 light microscope at 400× magnification at IPPH in Kiel. The main references used for identification were Twiss et al. (1969), Wang and Lu (1993), Ball et al. (1996, 1999), Lu and Liu (2003), Lu et al. (2009), Zhang et al. (2011, 2018, 2019) and Dal Corso (2018). In each sample, a sum of at least 300 items was counted. They included identifiable morphotypes, undefined morphotypes (such as indeterminate, fragmented, highly corroded silica bodies), other siliceous remains such as sponge spicules and diatoms, and pollen grains. Phytolith nomenclature followed ICPN 2.0 (ICPT 2019) and silica skeletons were named after the predominant cell types (usually elongate long cells) (Madella 2007).

Research methods

When interpreting botanical remains from archaeological contexts, ethnographic observations of crop processing methods in modern non-mechanized agricultural societies can be tentatively applied as references (Harvey and Fuller 2005; Song et al. 2019). Ethnographical investigations which were cited for the Xinzhai samples are first mentioned in the discussion of each crop (Appendix Figure-II.2). Because the differentiation of crop processing steps is based on the recognition of different types of plant remains from various processing stages (Harvey and Fuller 2005), the macro-botanical finds are arranged into several groups, with only arable weeds, crops and chaff included, as they are connected with crop processing (Appendix Table-II.2). For *Glycine max* (soybean), which requires sieving during its processing, the beans are classified by their size. The length of modern soybean is in general >5 mm, but in the early stage of domestication, it varied and many of the seeds were <5 mm (Zhao and Yang 2017). Accordingly, soybean finds in Xinzhai were divided into “large soybean” (with a length >5 mm) and “small soybean” (<5 mm) (Fig. 2.2.3). For *Setaria italica* (foxtail millet), *Panicum miliaceum* (common millet) and *Oryza sativa* (rice), which need to be winnowed to remove the chaff after threshing, the ratio of immature and unhulled crop grains against mature and

hulled crop grains and the ratio of arable weeds against crop grains were used. The separation of millet and rice grains into immature and mature ones followed the identification methods of Song et al. (2013, 2014) and Fuller and Qin (2008). In both millet species, the smaller, flatter, semi-filled or unfilled grains usually with wrinkled endosperms were considered to be immature ones and the circular, fat and large ones were mature. Likewise, in rice, unfilled or lightly filled, small, thin grains, sometimes with sharp papery edges were recorded as immature (Fig. 2.2.3).

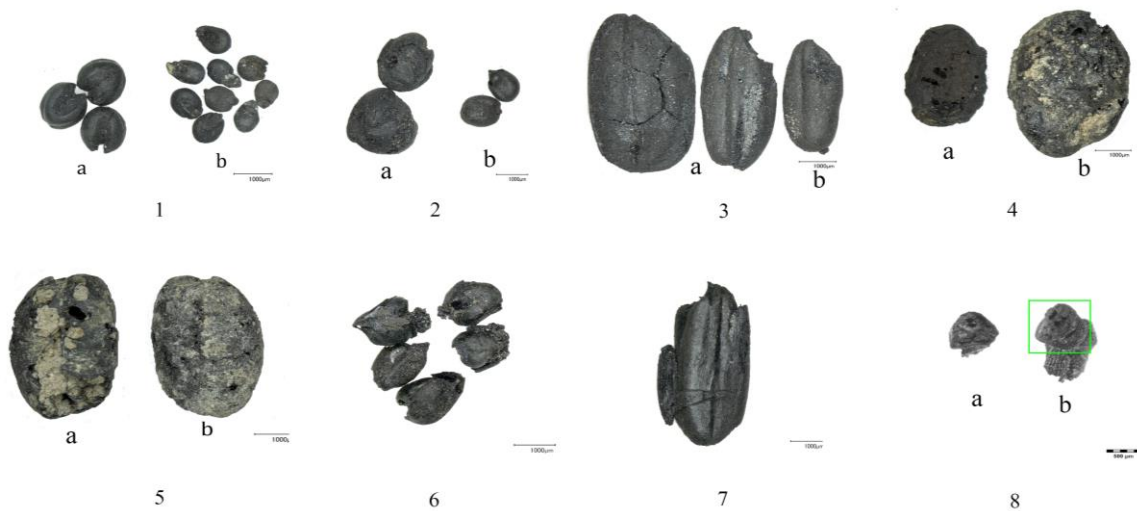


Figure 2. 2. 3 Main crop macro-remains, **1a.** mature *Setaria italica* grain; **1b.** immature; **2a.** mature *Panicum miliaceum* grain; **2b.** immature; **3a.** mature *Oryza sativa* grain; **3b.** immature; **4a.** small *Glycine max* bean; **4b.** large; **5a.** top (dorsal surface) of *Triticum aestivum* grain; **5b.** bottom (ventral surface); **6.** *Panicum* grain with husk; **7.** *Oryza* grain with husk (partly); **8a.** mature *Oryza* spikelet base; **8b.** immature (protruding scar shown in the green square); scale bars 1 mm

However, except for the different stages in processing, the proportions of immature grains, hulled grains and arable weeds impact by several factors. Drought years, poor soils and early harvesting time under adverse weather all have the potential to lead to a high percentage of immature crop grains (Song et al. 2019). The percentage of hulled grains might be overestimated, because cereal grains and especially those small-sized ones have extremely fragile lemmas and paleas that are readily removed by charring (Reddy 1994; Bates et al. 2017), so grains without attached husk remains are not necessarily fully cleaned products (Fuller and Zhang 2007). Similarly, many factors such as harvesting by gathering panicles, intensive

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weeding during crop growth and transplanting of seedlings in paddy fields all can effectively avoid gathering weeds and eventually affect the presence of arable weed remains in the assemblages (Weisskopf 2010). In this research, additional indicators were used to minimize these potential biases caused by single lines of evidence. First, arable weeds with different physical characteristics such as those with and without seed heads, big and small, light and heavy, vary in plant assemblages from various stages of processing (Jones GEM 1984). Thus, they were analysed according to their weights, sizes and abilities to retain their seed heads. Second, phytolith data were used to complement the interpretation from macrobotanical remains. The composition of phytolith morphotypes derived from different parts of plants varies in the remains from different crop processing steps (Harvey and Fuller 2005), so the morphotypes are arranged into different groups based on the plant parts where they occur (Table 2.2.2). The processing stage of each crop is indicated by the comparison of samples based on the variation of three phytolith groups, those from crop husks, from arable weed husks, and from crop and weed leaves and stems. Phytolith morphotypes included in each group are based on Weisskopf (2010), Weisskopf et al. (2015) and Bates et al. (2017). The morphotype of silica skeleton with columellate long cells (except for ω - and η -types) is included in the processing of both rice and millet, as it was difficult to identify to species or genus level.

Table 2. 2. 2 Phytolith morphotypes representing *Setaria*, *Panicum*, *Oryza* and weeds

	Morphotypes [#]	Attribution	Groups
Millet and related weeds	SKE_COL_ ω , SKE_COL_PAP	Husk: foxtail millet	Millet husk
	SKE_COL_ η	Husk: common millet	
	SKE_COL	Husk: weedy grass	Weed husk
	SKE_VER_BIL,SKE _ELO_PSI, SKE_ELO_SIN, SKE_ELO_CRE	Leaf/Stem: weedy grass	Millet and weed leaf/stem
Rice and related weeds	DOU	Husk: rice	Rice husk
	CON	Husk: weedy grass (Cyperaceae)	Weed husk
	SKE_COL	Husk: weedy grass	
	SKE_PAR_BIL	Leaf/Stem: rice	Rice and weed leaf/stem
	BUL_FL_A_FL_A	Leaf: rice	
	LON_ROD	Leaf/Stem: weedy grass (Cyperaceae)	
	BUL_FL_A, BLO, SKE_BLO	Leaf: weedy grass (wild Poaceae)	

[#]Phytolith codes see Appendix Table-II.3.

Results

The macro-botanical remains and phytoliths recovered from this site indicate the same cereal taxa, but *Glycine max* (soybean) is not represented in the phytolith assemblage (Appendix Table-II.2, II.3). *Oryza sativa* (rice) was domesticated according to the morphological features of the spikelet bases (Fuller et al. 2007, 2009; Fuller and Qin 2008). In 50 of these, except for three spikelet bases which had immature features with protruding scars, all the rest showed domesticated features (Fig. 2.2.3). The solitary find of a *Triticum aestivum* (wheat) grain in the macro-botanical remains proved to be an intrusion from the preceding Longshan period (2050-1900 cal. BCE) after AMS dating (2033-1886 cal. BCE). However, wheat is still listed as a possible crop, because another charred wheat grain was recorded in a previous report from this site (Zhong et al. 2016) and more importantly, phytoliths from wheat inflorescences were found by Yao et al. (2007) and also in this study. Moreover, following Zhao and Yang (2017), cultivated soybean only included examples where the seed coats after burning burst into pieces with the explosion of the cotyledons, forming empty holes on the surface (Fig. 2.2.3). In contrast, those with intact and tightly attached seed coats were distinguished from cultivated ones and counted as wild soybeans (Appendix Figure-II.3). Therefore, the crops at Xinzhai comprise four cereal species, *Setaria italica* (foxtail millet), *Panicum miliaceum* (common millet), *Oryza sativa* (rice), *Triticum aestivum* (wheat) and one pulse *Glycine max* (soybean). The raw data on which the following discussion is based can be found in Appendix Table-II.2 for macro-botanical remains and Table-II.3 for phytoliths. Images of the main finds are given in Appendix Figure-II.3 - II.9.

Discussion

In this research, foxtail and common millets together with rice are native hulled cereals which need extra processing for de-husking, but for soybean, it is essentially the same as for free-threshing wheat. The remains of wheat are too few to do processing analysis properly. Considering that only a small amount of phytoliths from wheat inflorescences is recorded, wheat might have been processed elsewhere or even brought to the site by trade. For other crops, their processing sequences were broadly divided into early and late stages to better display the

results. Early processing stages refer to the initial steps before storage, which were done after harvesting and usually took place in the field or on specially prepared threshing floors. Late processing stages include those completed after storage and when the crop was about to be consumed. Such later stages were repeated regularly throughout the year, usually within settlements and were mainly done within a household (Fuller et al. 2014).

The processing of Setaria italica (foxtail millet) and Panicum miliaceum (common millet)

A significant study of millet processing is the ethnographic investigation of crop processing in India and its application to archaeological samples (Reddy 1994, 1997, 2003). Many researchers have adapted this model and included phytoliths as well (Harvey and Fuller 2005; Harvey 2006; Weisskopf 2010; Bates 2011, 2016; Bates et al. 2017). In China, there are local ethnographic works on millets and their wild ancestors (for example, Lu 1998, 2002; Liu 2010; Liu et al. 2017), but the most widely cited one is the investigation of foxtail and common millets in Shandong province by Song and her colleagues (Song 2007, 2011; Song et al. 2013, 2014). Their discussion on the ratios of crop grains to weeds, immature and unhulled to mature and hulled crop grains has been widely applied to the interpretation of archaeological samples (Fuller and Zhang 2007; Zhang H et al. 2010; Deng and Gao 2012; Song et al. 2019). In this research, the exploration of millet processing is mainly based on the models from Reddy (1994) and Song et al. (2013, 2014), and the general model is in Appendix Figure-II.2a.

As the first step in crop processing, the harvesting method has a critical effect on plant composition in the following stages. It is therefore important to understand harvesting before pursuing further explanation of processing methods (Reddy 2003). To study the harvesting method, the growth height of weeds can be used (Hillman 1981). If the crop was harvested by uprooting or cutting low on the straw, this might be represented in weed remains with more low growing or prostrate taxa. In contrast, if the crop was reaped high on the straw or only the panicles were harvested, more weed remains from tall plants and fewer low growing ones would be present in the processing remains (Reynolds 1985). However, the growing height of climbing plants such as *Galium tricornutum* with a twining habit that is easily gets tangled up with other plants is difficult to estimate. After dividing by the

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maximum height of plants (Li 1998), 55.7 % (2,520) of the millet field weeds belong to the low category, 23.6 % (1,066) to the medium category, 20.7 % (936) to the tall category and only 0.1 % (3) to the uncertain category of climbing plants (Appendix Table-II.2). This overwhelmingly high proportion of low and medium growing weeds is indicative of cutting low on the straw. Besides, these two millet species grown in China, *Setaria* and *Panicum*, fall into Reddy's type B small hulled millets (Reddy 1994). In her ethnographic observation, these ones, such as *Panicum miliare*, are usually harvested at the base of the plant due to its slender stalks, rather than only harvesting the panicles which is usual for the thick stemmed type A millets such as *Sorghum bicolor*. Residue analyses on harvesting tools can offer relevant evidence as well (Liu et al. 2018). As both sites of Xinzhai and Huadizui acted as regional centres during the Xinzhai period (Liu and Chen 2012), the subsistence system at Xinzhai might be comparable to that of Huadizui. The finds of millet starch granules and Panicoideae leaf and stem phytoliths on the harvesting tools of stone sickles and knives give direct evidence for cutting millet plants at their bases at Huadizui (Tang 2018) and this was likely to have been done at Xinzhai as well.

After harvesting and before consumption, the stems and leaves as well as a wide variety of weeds have to be methodically removed through various processing steps. The plant assemblages in the archaeobotanical remains from each step change as various elements are removed, resulting in a changing ratio of crop grains to weeds to chaff (Stevens 1996, 2003). In the following discussion, the ratios of millet grains to arable weeds against the ratios of immature and unhulled millet grains to mature and hulled ones are applied to individual samples (Fuller and Zhang 2007; Song et al. 2019) and the results are plotted in Fig. 2.2.4a. During the calculation, the samples which have no arable weed finds were given the maximum value of 100 for the ratio of millet grains to arable weeds. In general, immature and unhulled millet grains decline compared to mature and hulled grains in material from later stages of the processing sequence. Thus, the lower right side of the diagram contains samples that represent de-husking remains from only the late processing stages and the upper left side includes samples that represent primitive winnowing remains from the early processing stages. In primitive winnowing remains, most samples have the ratio of immature and unhulled grains to mature

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and hulled grains of <1 (Fig. 2.2.4a, blue dots on the upper left). Immature millet grains are quite common in macro-botanical remains (Fuller and Zhang 2007; Zhang et al. 2010; Song et al. 2013), as millet seeds normally ripen unevenly (Trifonov et al. 2017) and in the past Chinese farmers started harvesting as soon as half of the grains were ripe to avoid a loss of grains (Song et al. 2013). Immature grains therefore have long been a concern to Chinese farmers during millet processing and they mostly have to be removed during the primitive winnowing stage so that the mature to immature ratio in the by-product is much less than 1 but many times greater than 1 in the product (Song et al. 2013). Hence, most of the Xinzhai samples are likely to be the products of primitive winnowing as they are predominated by mature grains.

Weed seeds are also a strong indicator for the identification of crop processing methods (for example, Hillman 1981, 1984; Jones GEM 1984; van der Veen 1990, 1992; Reddy 1994, 2003; Graham and Smith 2013). Comparison between the large amount of millet grains (39,571) and the small quantity of millet weed seeds (7,603) in the Xinzhai material suggests later processing stages. Moreover, in the processing of millet, features of weed seeds including the presence of seed heads (measured as headed or free), seed weight (measured as light or heavy) and seed size (measured as small or big) are of equal importance (Reddy 1994). Based on these factors, weed seeds have been divided into eight categories: small free light (SFL), small free heavy (SFH), small headed light (SHL), small headed heavy (SHH), big free light (BFL), big free heavy (BFH), big headed light (BHL) and big headed heavy (BHH) (Reddy 1994). The weeds from the Xinzhai millet fields fall into four of these categories: SFH (4,459), BFH (8), SFL (52) and SHH (6) (Fig. 2.2.4b). Among them, heavy weed seeds (SFH, BFH, SHH) are most common at 99.6 % of the total. As they can easily remain until the late processing stages and some of them even have to be removed by hand sorting in the last step (Reddy 1994), their importance at Xinzhai indicates later stages of millet processing. A similar conclusion can be drawn by clustering the phytolith groups on the tri-plot (Fig. 2.2.4c). Most samples contain large amounts of husks from millet and related weeds, but relatively fewer from leaves and stems. The fundamental principle in crop processing is to remove the larger non-crop components such as leaves and stems in the early stages of processing, then to separate the smaller parts such as

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husks in the later processing stages. The abundance of husk phytoliths over ones from leaves and stems suggests late processing stages. Therefore, millet appears, according to both botanical macro- and micro-remains, most likely to have been stored in spikelet form after which only the later processing stages would have been needed.

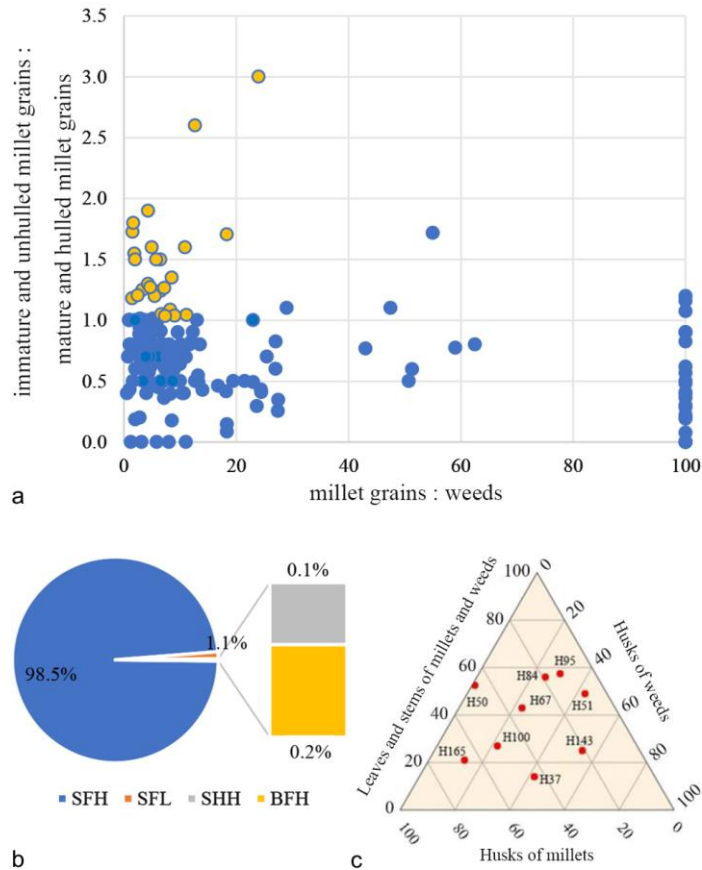


Figure 2.2.4 **a.** scatter plot showing ratio of *Setaria* and *Panicum* grains to weeds against ratio of immature and unhulled *Setaria* and *Panicum* grains to mature hulled *Setaria* and *Panicum* grains (upper left, yellow dots are the by-products of primitive winnowing with ratio >1 and blue dots are the products of primitive winnowing with ratio <1; **b.** proportions of millet field weeds in different categories; SFH, small free heavy; SFL, small free light; SHH, small headed heavy; BFL, big free light (Reddy 1994); **c.** a tri-plot of individual samples showing the relative proportions of phytolith morphotypes relating to millet processing

However, some by-products from early millet processing stages seem to appear as well. Not many, but still some samples in the primitive winnowing remains have a ratio of immature and unhulled to mature and hulled crop grains >1 (shown as yellow dots in Fig. 2.2.4a). They can be defined as primitive winnowing by-

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products. Also, during primitive winnowing, the closer weed seeds are in size to crop grains, the harder they are to separate, so they tend to remain together (Reddy 1994). After measuring 40 *Setaria* grains (immature and mature), 40 *Panicum* grains (immature and mature) and 50 weed seeds of millet (15 species), many weed seeds were found to be smaller than 1.5×1.5 mm and similar in size to immature grains of foxtail and common millets (Fig. 2.2.5, Appendix Table-II.4). Their presence indicates that these weed seeds accompanied immature millet grains in the primitive winnowing by-products. Due to the economic value of crop processing residues such as straw, they can enter archaeobotanical records in various ways. The most common ones are from animal fodder and organic fuels which include dried plants and animal dung (Fuller et al. 2014). Organic fuels are very difficult to distinguish from crop processing residues, although several breakthrough studies have been done recently (Lancelotti and Madella 2012; Spengler 2019). However, using animal dung and herbaceous plants as fuel can be tentatively excluded in this research, because they are more commonly used in arid and especially unwooded areas and also among herding economies (Lancelotti and Madella 2012; Spengler 2019). So far, there is little evidence that such fuels were important for the agricultural societies of east China, where there were rich wood resources and also climatic constraints on drying dung and crop chaff from seasonally intensive rains. Therefore, it is feasible to argue that the presence of millet by-products in the Xinzhai settlement might be due to intentional collection for animal fodder instead of using them as fuel. As observed by Reddy (1994), if millet is intended to be used as human food alone, harvesting just the panicles is better, as only the grains are wanted. However, if millet is used as both human food and animal fodder, harvesting the entire plant by cutting it off at the base is preferred, which fits the case in Xinzhai. Besides, the analysis of animal remains suggests that domestic animals including pigs, sheep and cattle were dominant rather than wild animals in Xinzhai (Yuan et al. 2007; ACAC-PK and Zhengzhou 2008). Among these, cattle and pigs consumed substantial amounts of millet by-products throughout the whole year, as indicated by strong C₄ signals from stable isotope analysis (Wu et al. 2007; Zhang and Zhao 2015; Dai et al. 2016a, b), and sheep were grazed in the natural environment (C₃) but consumed millet by-products (C₄) in late summer when millet by-products were available (Dai et al. 2016a, b) with more than 70 % of them being

fed to maturity for their wool (Dai et al. 2014). Thus, millet by-products or at least part of the by-products from primitive winnowing were most probably brought back to the settlement for animal feed and were then deposited in the settlement either as fodder or as dung.

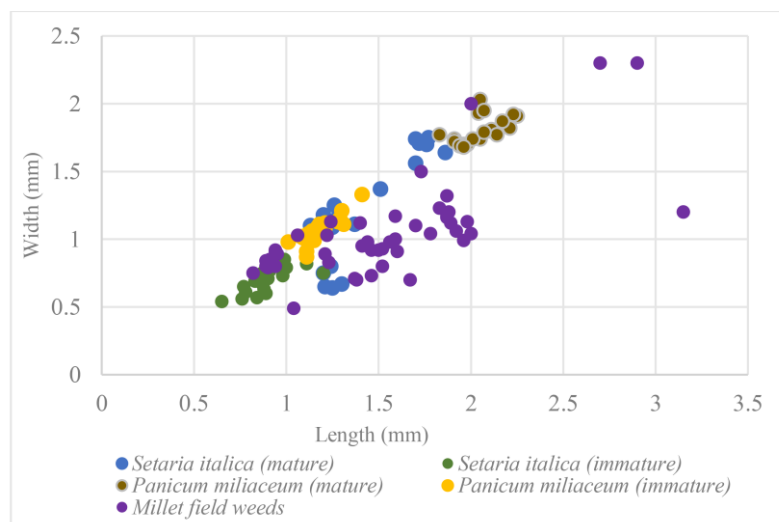


Figure 2. 2. 5 Dimensions of Panicum and Setaria grains and associated weeds

The processing of Oryza sativa (rice)

The ethnographic observation on rice processing carried out by Thompson (1992, 1996) in Thailand is widely cited in archaeological studies. Phytoliths have been incorporated into this model as well (Harvey and Fuller 2005; Harvey 2006; Weisskopf 2010; Bates 2011, 2016; Bates et al. 2017). As mentioned above, ancient rice processing was mainly discussed from phytolith analysis in China, such as the case study of the sites of Baligang (Weisskopf et al. 2015), Shunshanji and Hanjing (Luo et al. 2021). In the study of the Xinzhai samples, the processing models from Thompson (1992, 1996), Harvey and Fuller (2005) and Weisskopf (2010) were applied, which can be found in Appendix Figure-II.2b.

The harvesting method of rice is not indicated as clearly as for millet by the growth height analysis of the weed remains. In ethnographic investigations three traditional harvesting methods, by sickles, by uprooting, and by finger knives have been recorded in modern Thailand and India (Thompson 1992, 1996; Harvey and Fuller 2005). The use of finger knives is restricted to rice farmers from certain regions, mainly in China and southeast Asia (Harvey 2006). By holding a finger knife, which comprises a sharp-edged blade, usually made of mussel shell, stone, or wood, the panicles of rice are cut off from the rest of the plant (Miles 1979; Murphy 2017).

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Therefore, when harvesting with finger knives, only panicles and occasional tall weeds are collected, but the other two methods produce a similar weed composition with many low growing weeds incorporated. For our material with 48.5% (317) of high height weeds, it seems that harvesting panicles with finger knives is possible. However, there is also a relatively high proportion (in total 51.4 %) of low (36.5 %, 238) and medium height (14.9 %, 97) weeds. Thus, rice was more possibly harvested by sickles or uprooting, since these methods collect both high and low growing weeds, while by using finger knives, tall weeds are almost exclusively incorporated.

To further investigate rice processing, ratios of hulled and mature rice grains to rice chaff and immature rice grains against ratios of rice grains to weeds were calculated (Bates et al. 2017). For this, samples containing pure rice grains without chaff and immature grains, the ratio of hulled and mature rice grains to rice chaff and immature rice grains was given the maximum value of 100. Similarly, for the ratio of rice grains to arable weeds, samples with no arable weeds but only rice grains were given the ratio 100. In Xinzhai, rice chaff was found in the form of spikelet bases and also husk fragments adhering to rice grains. Most samples indicate early processing stages with high proportions of weeds, immature rice grains and chaff (Fig. 2.2.6a, lower left). Rice, like millet, was also winnowed to remove weeds, so the presence of seed heads, the weight and the size are also decisive factors in the understanding of the processing stage. Compared to millet which is dominated by heavy weed seeds, rice has a relatively broader range of weeds, of which 63.7 % (415) are small free heavy (SFH) seeds and 36.2% (236) are small free light (SFL) seeds (Appendix Table-II.2). This fits the pattern that both early and late processing stages were done as routine daily activities. Besides, the greater the difference in size between prime grains and weed seeds, the more efficient is primitive winnowing (Reddy 1994). Size comparison of 70 mature rice grains, 40 immature rice grains and 45 rice field weed seeds (5 species) shows that these weed seeds are much smaller than the rice grains, both immature and mature (Fig. 2.2.6b, Appendix Table-II.4). Since there is no overlap in size between them, primitive winnowing should be very efficient in removing these weed seeds that are smaller than rice grains. Consequently, the presence of small weed seeds together with rice grains in the waste pits might indicate that the material from storage

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contexts had not been winnowed and therefore small weed seeds can be found in the settlement as by-products of the daily practice of primitive winnowing. Moreover, compared to these samples from waste pits, samples from storage pits could offer more direct evidence of ways of crop storage. Unfortunately, botanical finds from the storage area of the Xinzhai site only provide the basic information of absolute counts and ubiquities of the main crops and weeds (Zhong et al. 2016). The only useful information about crop processing is that >50 spikelet bases were found among 381 rice grains. This suggests that rice was not stored as hulled grains, which has no conflicts with current conclusions.

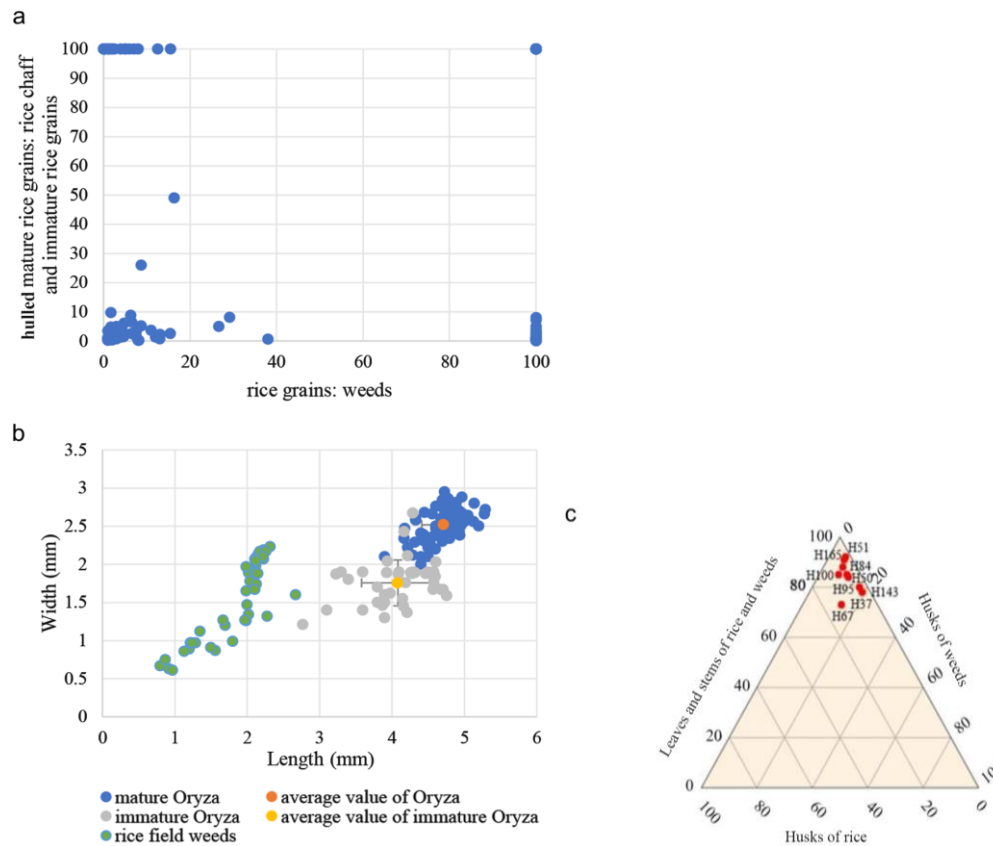


Figure 2.2.6 **a.** scatter plot showing ratios of *Oryza* grains to weeds against ratio of hulled and mature *Oryza* grains to rice chaff and immature *Oryza* grains; **b.** dimensions *Oryza* grains and associated weeds; **c.** a tri-plot of individual samples with the relative proportions of phytolith morphotypes relating to rice processing

By filling in a possible taphonomic gap in the macro-botanical evidence, phytoliths provide useful additional evidence of rice processing (Fig. 2.2.6c). Phytolith morphotypes from leaves and stems of rice and associated weeds were present in large amounts in all samples. As the primary objects to be removed in the processing, leaves and stems occur in dominant quantities mainly or only in the

material from early stages of processing. Additionally, in contrast to millet, by-products of rice processing are unlikely to have been used as animal fodder, since dietary investigations indicate that almost all domestic animals have C₄ signals. Although one sheep in the sample had consumed large amounts of C₃ food, this rather shows a similar diet to wild animals with the consumption of C₃ based vegetation in natural habitats (Dai et al. 2016a,b). Moreover, rice by-products have an unpleasant taste to ruminants (cattle, sheep and goats), a slow rate of digestion and low nutritional content. The amount that can be consumed is insufficient to sustain a reasonable level of meat or milk production (Malik et al. 2015). Thus, even as part of the roughage given to ruminants, rice by-products are not preferred, as in modern India (van Soest 2006). For this reason, the probability that rice leaves and stems were used as animal fodder is quite low and their deposition in the settlement is better interpreted as waste from daily processing for human food.

*The processing of *Glycine max* (soybean)*

While most studies have concentrated on cereals, a processing model for pulses is comparatively rare. Fuller and Harvey (2006) suggested that there are two ways of processing pulses, free threshing and pod threshing. Soybean encountered in Chinese archaeological samples requires no additional pounding and winnowing to remove the beans from the pods, so its processing follows the description of free threshing pulses (Appendix Figure-II.2c; Fuller and Weber 2005; Fuller and Harvey 2006).

For harvesting free threshing pulses, uprooting and cutting off the plants near the base are common methods, while harvesting the pods is more popular in primitive cultivars with uneven ripening (Fuller and Harvey 2006). The time when soybean started to be selected and completed its domestication process is still poorly understood in China (Crawford et al. 2005). According to the size comparison and the oil content comparison by X-ray tomography (Lee et al. 2011; Wu et al. 2013; Zong et al. 2017), during the Xinzhai period, human selection of soybean had started, but the morphological features of domestication were not yet established. In the early phase of domestication, soybeans were much smaller and also more variable in size (Zhao and Yang 2017). We measured 100 Xinzhai soybeans and their average size is much smaller ($4.15 \pm 1.03 \times 2.62 \pm 0.62$ mm) than that of 100 modern soybeans ($7.42 \pm 0.56 \times 6.13 \pm 0.37$ mm) (Zhao and Yang 2017). They also

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have a wide size range with 58 % beans within the first standard deviation (SD) and 39 % within the second SD (Fig. 2.2.7, Appendix Table-II.5). Thus, these Xinzhai soybeans very probably represent an early phase of domestication, and therefore all three harvesting methods were possibly practised.

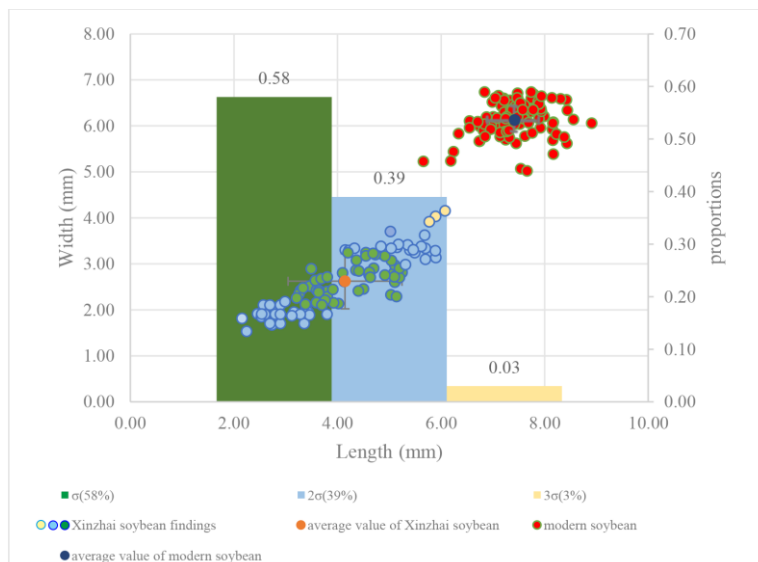


Figure 2. 2. 7 Scatter plot of *Glycine max* based on the measurement data

The first two methods harvest all pods indiscriminately, while by gathering pods individually there is more opportunity to leave unharvested the undesirable small pods that contain small beans. Moreover, soybeans of differing sizes could be separated by sieving, and smaller ones have more chance of being removed in this way (Fuller and Harvey 2006). In sum, 174 out of 512 soybeans were small ones. This mixture of 34 % small beans in the soybean finds indicates a high possibility that they were harvested by uprooting or cutting near the base of the plant and also that they were stored before the coarse sieving. Besides, no soybean threshing remains were found in the plant assemblage, however, instead of being used as evidence for full processing, the absence of soybean residues is better interpreted as a result of taphonomic bias. Soybean threshing remains are rarely preserved in macro-botanical remains. The preparation and consumption of soybean do not necessarily involve contact with fire, so the beans are easily decomposed in the soil rather than preserved as charred remains. Even when soybeans are in contact with fire, they almost invariably burn to ash due to their high oil content. So far, only the survey report of upper Ying river valley (Neolithic Yangshao, Bronze Age Shang) and the excavation report of the Wangjinglou site (Bronze Age, Erlitou) mention

soybean pod fragment finds in China (Fuller and Zhang 2007; Zhao and Yang 2017).

Labour mobilization and social organization

In non-mechanized ancient societies, agriculture and its related activities created a need for cooperation among human groups such as households. The need for labour was a recurrent situation for which its organisation and social relationships developed (Fuller et al. 2014). For harvesting, a substantial amount of labour is required during a short time in cases such as untimely rainfall (Fuller et al. 2014). Early processing stages of hulled crops such as threshing and primitive winnowing often need to be repeated several times to fully release and remove non-crop components, and these steps require intensive labour and time inputs (Reddy 1994). Later processing stages like de-husking and hand sorting are time-consuming, but these can be done during the slack times for farming (Fuller et al. 2014). Therefore, labour availability is the main factor in determining how many processing steps are carried out in bulk shortly after the harvest and how many are done nearer the consumption time (Bates et al. 2017). In other words, it determines if an intensive labour investment is needed before or after storage. With less labour available to complete the large amount of work at harvest time, fewer processing steps can be done before storage.

For the Xinzhai site, the analysis of archaeobotanical remains reveals that none of the crops were fully processed before storage. Foxtail and common millets were stored as spikelets, rice as entire plants and soybean was stored before coarse sieving. Compared with storing crops in the form of hulled grains, these partial types of processing at the Xinzhai settlement indicate that there might have been too little labour to carry out more processing steps shortly after harvest, and so more of them were done later, after storage (Fig. 2.2.8). For this, we tentatively argue that the farming season could be one of the causes. According to Stevens (2003) and Fuller et al. (2014), the seasonality of farming leads to a corresponding requirement for labour, and its availability at harvest time determines the way in which crops were stored. In China, historical documents record rich information about ancient farming seasons (Table 2.2.3; Han 2012; Zhang 2016). Different lunar (Yinli 阴历) and lunisolar calendar systems (Nongli 农历) and different

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starting months of the new year (Suishou 岁首) of Yin (寅) month and Wu (午) month according to the Zodiac system (Tiangan dizhi 天干地支) were used during the Xia (1750-1550 cal. BCE) and Shang (1550-1046 cal. BCE) periods (Wang 1994; Chang 1998; Han 2012; Zhang 2016). Therefore, for reconstructing the farming season based on ancient documents, we need to match the different calendar systems with the Gregorian one used today. Taking the harvest of wheat as an example, oracle inscriptions and historical literature indicate that newly harvested wheat became available for the inhabitants (Shimai 食麦) (Wan 1980; Guo 1983; Miu and Miu 2008) and ancestors (Changmai 尝麦) (Chen 2002; Huang et al. 2007) in May in the Xia calendar, equivalent to January in the Shang calendar and June in the Gregorian calendar (Zhang 2016). After studying all the available historical information, we know that foxtail and common millets, rice and soybean were all native summer-sown summer crops, while wheat was the only autumn-sown winter crop (Table 2.2.3).

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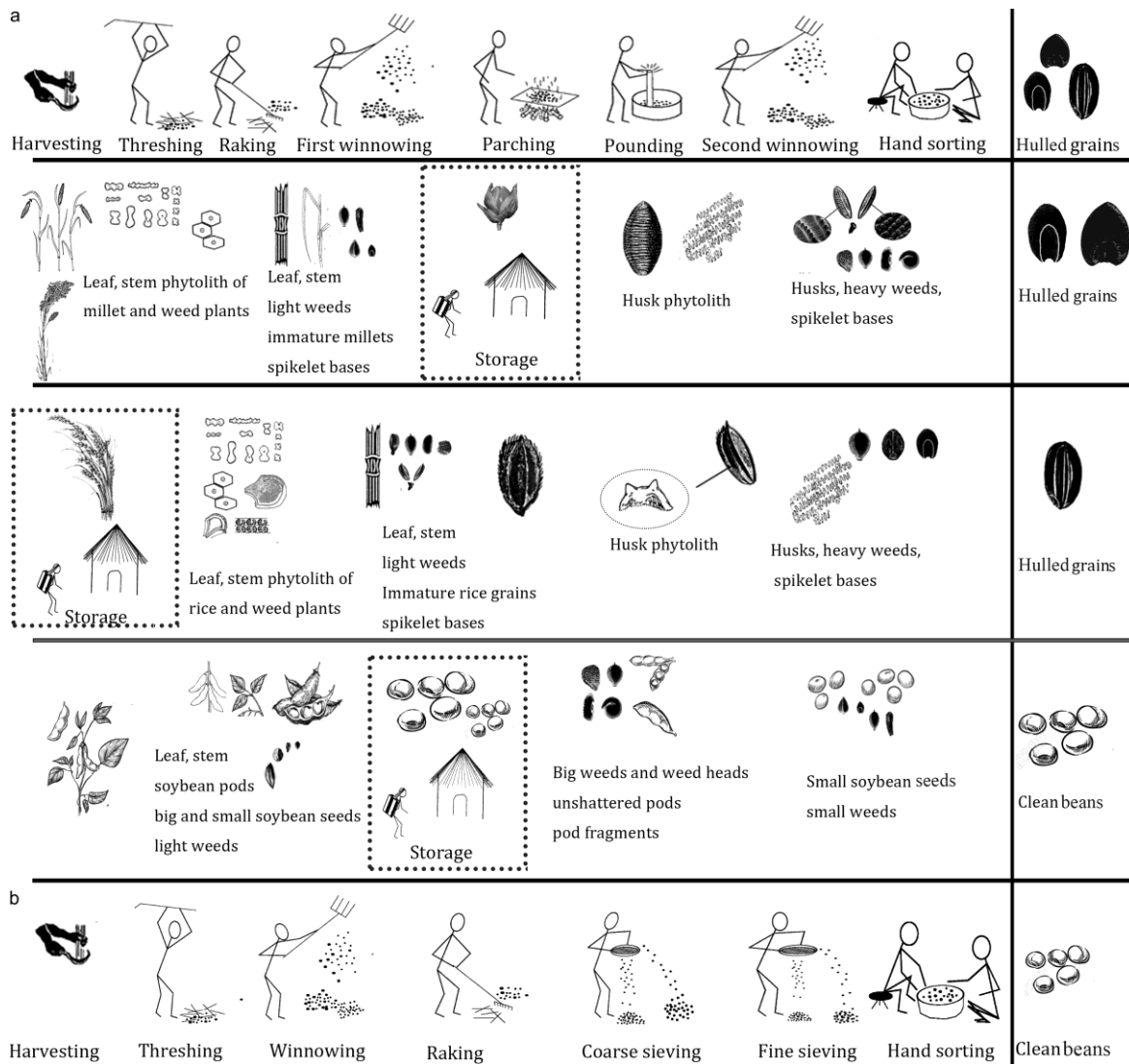


Figure 2. 2. 8 Different types of storage and requirements for the late stages of processing the main crops at the Xinzhai site. **a.** processing stages of hulled crops *Setaria italica*, *Panicum miliaceum* and *Oryza sativa*; **b.** processing stages of free threshing *Glycine max*; after Hastorf 2016, Fig. 4.3; Harvey and Fuller 2005, Figs. 3, 5)

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Table 2. 2. 3 Sowing and harvesting times of different crops based on historical records, shown as months in modern calendar

Crop	Sowing season	Harvesting season	Historical documents	References
<i>Setaria italica</i> (foxtail millet)	May (Xia calendar); January (Yan calendar)	August and September (Xia calendar); April and May (Yan calendar)	<i>Oracle inscription</i> 甲骨文	Guo and Hu 1978-1982
<i>Panicum miliaceum</i> (common millet)	May (Xia); January, occasionally February (Yan)	August (Xia); April (Yan)	<i>Xi Xiaozheng</i> 夏小正; <i>Shuowenjiezi</i> 说文解字; <i>Oracle inscription</i> 甲骨文	Xia 1981; Duan 1988; Guo and Hu 1978-1982
<i>Triticum</i> sp. (wheat)	August and September (Xia); April and May (Yan)	May (Xia); January (Yan)	<i>Xi Xiaozheng</i> 夏小正; <i>Fanshengzhishu</i> 汜胜之书; <i>Dongluwangshi Nongshu</i> 东鲁王氏农书; <i>Liji</i> 礼记·月令; <i>Guanzi-Qingzhongyi</i> 管子·轻重乙; <i>Oracle inscription</i> 甲骨文	Wan 1980; Xia 1981; Miu and Miu 2008; Guo and Hu 1978-1982; Han 2012
<i>Glycine max</i> (soybean)	June (Xia); February (Yan)	September (Xia); May (Yan)	<i>Fanshengzhishu</i> 汜胜之书; <i>Qiminyaosu</i> 齐民要术	Wan 1980; Miu and Miu 2009
<i>Oryza sativa</i> (rice)	January (Yan)	May (Xia); September or October (Yan)	<i>Shijing</i> 诗经·幽风·七月; <i>Oracle inscription</i> 甲骨文	Liu and Li 2011; Guo and Hu 1978-1982

Based on the sowing and harvesting times of the various crops, autumn, from September to November, was the busiest period for the Xinzhai farmers with the harvest season for summer crops (Table 2.2.4). As wheat was sown and harvested at different times compared with summer crops, its growing and harvesting had very little or no labour conflicts with other crops. On the contrary, rather than being an extra burden, wheat growing was probably beneficial as it would have spread the need for labour to a previously slack farming time. More importantly, wheat was only a minor component in the Xinzhai farming system. Therefore, the processing of wheat is not further considered here in the discussion of labour distribution. Nevertheless, the relatively concentrated harvest time of summer crops very probably led to a labour shortage for some processing stages before storage. What is also worth considering is the construction or frequent maintenance of public building works such as the rammed earth city walls, the semi-subterranean architecture and also the irrigation system for rice farming, all of which inevitably occupied much labour. Hence, partial crop processing might have been necessary because of a labour shortage at harvest time.

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Table 2. 2. 4 Farming seasons at the Xinzhai site, according to the ancient Xia and Shang calendars and the modern one

Calendar system	Periods	Spring			Summer			Autumn			Winter		
Lunar calendar (<i>Yinli</i>)	Xia dynasty	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lunisolar calendar (<i>Nongli</i>)	Shang dynasty	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Gregorian calendar (<i>Gongli</i>)	modern	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
Sowing of crops*						S,P,O	G		T				
Harvesting of crops						T			P,S	S,O,G	O		

*S, *Setaria italica* (foxtail millet); P, *Panicum miliaceum* (common millet); O, *Oryza sativa* (rice); T, *Triticum aestivum* (wheat); G, *Glycine max* (soybean).

Further light can be shed on the wider social systems of the past by considering crop processing in terms of routine everyday activities as compared with seasonal ones (Fuller et al. 2014). Indeed, one might expect the whole community to have mobilized its labour in cooperation to do seasonal work, as part of its social organization. Archaeobotanical studies from the upper Ying valley (Fuller and Zhang 2007), Sushui river (Song 2011; Song et al. 2019) and Baligang site (Weisskopf et al. 2015) have suggested that during the Yangshao period (5000-2500 cal. BCE), crop processing was carried out in bulk on a communal basis, while a change to processing by individual households was noted on many, but not all, sites in the Late Neolithic Longshan culture (2300-1900 cal. BCE), and this trend was also observed in the Bronze Age Erlitou-Shang period (1750-1046 cal. BCE). These results show that there was variation in social organization in which some settlements kept the communal organization, but others changed to working as small nucleated household units since the Longshan period.

The results of this research into the Xinzhai period by analysing the phytolith datasets from Xinzhai (this research) and Dongzhao (Luo et al. 2018) show remarkable consistency over time with previous studies. According to Zhang JP et al. (2010) and Luo et al. (2021), rice grain (DOU-type; 357,953±35,968/g) produces almost the same amount of phytoliths as rice leaves and stems (BUL_FLA_FLA-type; 372,646±249,387/g). In Dongzhao, 170 DOU-type phytoliths and 54 BUL_FLA_FLA-type and SKE_PRA_BIO-type were recorded. Therefore, the morphotype from husks (76 %) is dominant in Dongzhao, while in Xinzhai there are more from leaves (61%). Following Fuller and Stevens (2009), we argue that this difference reflects different crop processing methods and also

different social organizations at each site. Rice was stored together with its leaves and stems and further processed on an individual basis probably by small households as routine activities in Xinzhai. In contrast to this, rice was stored as hulled grains after most of the processing steps had been completed, probably on a communal basis in Dongzhao. This conclusion fills the time gap between the Late Neolithic and Early Bronze Age in previous studies. It shows a similar situation to the Longshan period and implies that the differentiation of social organization among settlements might have been continued in the Xinzhai period. This assumption also fits the conclusion from the archaeological settlement pattern analysis, which shows that the social arrangement of the Xinzhai period may have been rather similar to that of the Longshan period (Liu and Chen 2012). Furthermore, a complex and hierarchical society developed together with increasing status and wealth differentials in the Central Plain during the Longshan period (Underhill 1991; Liu 1996, 2005; Liu and Chen 2012). A similar wealth differential can be expected in the Xinzhai period since the agricultural resources were more or less controlled by individual households rather than by the whole communal society, at least at the Xinzhai site. Therefore, the first urban centre that appeared in the subsequent Erlitou period was derived from a complex and hierarchical society, and the development of social complexity in the Central Plain was continuous and without interruption. This kind of gradual social change might be one of the reasons for the outstanding progress of societies in the Central Plain in the early Bronze Age, compared with elsewhere in China.

Conclusions

This research by the analysis of macro-botanical remains and phytoliths from the Xinzhai site, as a pioneer study of its kind, shows the potential of combining two botanical lines of proxy evidence in the study of ancient crop processing methods and also explores the patterns of labour mobilization and social organization in the Xinzhai period for the first time.

The results reveal that the Xinzhai inhabitants harvested rice using sickles or by uprooting it, stored the entire plants and processed the crop in the settlement as daily activities. Millets were harvested by cutting the plants at the base, threshed in open areas and stored as spikelets. The understanding of soybean processing is

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restricted by the absence of processing residues, but as there is a wide range of bean sizes with many small soybeans, they are thought to have been harvested by uprooting the plants or cutting them off near their bases and then stored before coarse sieving. In conclusion, not only hulled crops such as rice and millets, which require a great amount of processing to extract the grains, were stored in a semi-processed form, but also the free threshing soybean. However, in the contemporary Dongzhao site, rice was stored as unhulled grains which then only needed de-husking before consumption. Therefore, the organization of labour and society varied between settlements in the Xinzhai period. So that less labour was needed during the harvest period but more after storage for the routine daily processing, agricultural activities were mostly done by nucleated household units at Xinzhai. In contrast, large amounts of labour were required for processing crops before storage and so agricultural labour was communally organised at Dongzhao. This kind of diversification in labour and social organizations between different settlements has been observed in sites of the Longshan period, and as indicated by this research, very possibly continued into the subsequent Xinzhai period. The development of social complexity towards urbanization in the Central Plain of China from the Neolithic to the Early Bronze Age has therefore been a continuous process.

Last but not least, to complete the current conclusions, more sampling of archaeobotanical remains from primary deposition contexts is required in the future to get more information on the parts of sites where particular crop processing steps were done and therefore to recover the spatial pattern of processing activities. Likewise, comparative samples from outside the inner city of the Xinzhai site, at least outside the core area of elites, are also needed to distinguish the possible differences in labour distribution between the elite living area and that of ordinary inhabitants, to eliminate potential bias caused by social hierarchies.

Acknowledgements

The authors want to thank all the 2016 undergraduate students from the Institute of Archaeology at Anhui University for the collection of samples, Weihong Wu, Huadong Zhu (Anhui University), Honghong Wei (Archaeological Institute of Zhengzhou) and Guangxiang Geng (Xinyang Museum) for detailed archaeological information during and after the fieldwork, Wanli Lan and Yaping Li (Henan Institute of Cultural Relics and Archaeology) for laboratory facilities and preliminary laboratory work assistance in China, the Young Academy of the Cluster of Excellence ROOTS (EXC 2150) at Kiel University for facility support of the subsequent laboratory work, Ingo Feeser (Kiel University) for technical support with the phytolith counting program Countpol 3.2, and Marta Dal Corso (Kiel University) for introducing J. An to phytolith identification and interpretation. We also gratefully acknowledge the financial support from the China National Natural Science Foundation (41771230) granted to G. Jin and the China Scholarship Council for doctoral research (Fund No. 201706220058) granted to J. An. Finally, the editors and reviewers are sincerely appreciated for their precious advice and suggestions to improve this manuscript.

Appendix II

Table II.1- II.5 and Figure II.1- II.9

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2.3 Regional study on the Central Plain

After combining all available archaeobotanical data from previous studies and the results of the Xinzhai period drawn in sections 2.1 and 2.2, a chronological change from the Late Neolithic Longshan period to the Early Bronze Age Shang period (2300-1046 cal. BCE) in agriculture and its related social organization in the Central Plain, therefore, can be discussed in the following section.

In previous studies, the concentration of rice in major settlements has been detected in the Erlitou period (Lee and Bestel 2007; Zhang et al. 2014; Zhao and Liu 2019), according to the analysis in this research, this pattern can be traced back to the preceding Xinzhai period. As a new result, the stable production of rice through the Longshan to the Erlitou period has been recorded in this research. The existing conclusion of wheat began to show an exclusively high frequency and a high amount since the early Shang period (Zhao 2011; Zhong 2020) has been further confirmed by this systematic analysis. More importantly, combined with the conclusions from the Xinzhai period, this research has tentatively used the irrigation technique to explain these changes in the agricultural pattern. Considering the Erlitou period was under a cool and dry climatic condition, the stable production of rice could be attributed to the application of the irrigation system. The same as the concentration of rice in major settlements during the Xinzhai period. Due to the extra inputs of labour and time during the irrigation, rice might have been chosen as a prestige food and participated in the exchange network of elites in the Erlitou period. Furthermore, similar as wet rice, intensive water supply is demanded in the cultivation of wheat and it is of particular importance in northern China. As an exotic winter crop, the vegetation period of wheat witnessed huge conflicts with the local climate. The climatic condition under the East Asian monsoon system fits more of summer crops which rely on summer monsoonal rainfall but is unfriendly to winter crops. Thus, the large-scale cultivation of wheat is inevitably connected with the development of irrigation system. In brief, section 2.3 proves that the practice of the irrigation system has a prolonged impact on the agricultural pattern in the Central Plain.

Meanwhile, the crop processing model analysis of the Xinzhai period, presented in the last section 2.2, shows the organization of labour and society varies among

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different settlements. This kind of diversification among settlements with some of them focused on nucleated household units and some kept communal communities has been observed since the Longshan period and highly possibly continued in the Xinzhai period. By summarizing all available data concerning crop processing such as the spikelet bases of rice in this chronological research, this conclusion has been further confirmed. Therefore, the conclusions from this research demonstrate that the earliest states that appeared in the Erlitou period could be a continuous development of these complex and hierarchical societies from the Xinzhai period and the process of social complexity in the Central Plain was continuous without any interruption. This kind of gradual development of society might be one of the reasons for the outstanding of Central Plain rather than the other places in the early Bronze Age in China.

Changing of Crop Species and Agricultural Practices from the Late Neolithic to the Bronze Age in the Zhengluo Region (Central Plain), China

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This is the final, citable version of an article that was originally published on *Archaeology and Anthropological Science* 2019, 11(11): 6273-6286.

Abstract

An assemblage of charred plant remains from 17 sites in the Zhengluo Region has been collected and analyzed with a semi-quantitative method-RI and also with a multivariate statistical method- CA for this article. It provides a useful perspective for the understanding of the changing in the crop spectrum and crop husbandry practices from ca. 2500 to 1046 BCE in this region. In the Longshan period, rice was subdominant while more dry-resistant broomcorn millet was planted during the Xinzhai and Erlitou periods, however, the importance of rice rose again in the Erlitou period, especially stood out in some central settlements and wheat witnessed a remarkable increase in the Shang period. Combined with the ecological information from arable weeds, it might conclude that agricultural techniques played a much more important role in farming since the Bronze Age. It is possible that in the Bronze Age, an elaborate irrigation system, fertilizer practice, and spikelet-form storage method guaranteed the stable production and the preservation of crops, especially rice in some of the central settlements.

Keywords Zhengluo Region· Late Neolithic to Bronze Age· Crop species· Agricultural practices

Introduction

The emergence of urbanization in ancient China is an important research topic and agriculture is considered to provide an essential foundation for the development and maintenance of the earliest urban center in China (Chen, 2007; Zhao, 2011). The Zhengluo (Yiluo-Zhengzhou) region in the Central Plain witnessed the most marked socio-political transformation, including the emergence of the first urban center at the site of Erlitou during the first half of the 2nd millennium BCE and also the core hinterland of the Shang dynasty (Zhao, 2001). In the process of understanding ancient agriculture, archaeobotanical remains are the most direct and persuasive evidence (Zhao, 2011). However, until recently, most archaeobotanical investigations in the Zhengluo Region are concerning the basic subsistence crops in individual settlement sites or small valley regions. There are only a few explanations on farming and agricultural practices on the whole Zhengluo Region scale. In this paper, archaeobotanical data from previous works is compiled which provides a sound database to apply a new semi-quantitative approach to describe the changing patterns of agriculture in a diachronic perspective for the Zhengluo Region.

The Zhengluo Region locates in the central and western Henan province, between 33° 33' - 35° 16' N, 110° 40' - 113° 20' E. It reaches the southern bank of the Yellow River to the North and the Ru river to the South. It is contiguous to the Xiao mountains to the west and Jiaozuo, Zhengzhou, Xuchang and Pingdingshan line to the east (Bi et al., 2008). This area is surrounded by Xiaoshan, Xiong'er, Funiu, Waifang, and Yunmeng mountains on three sides running W-E, 500-2000m in altitude. Despite these natural barriers, this region is effectively connected by its rivers to regions in all directions, including Luo river, Yi river, Sha river, Beiru river, Ying river, Shuangzi river, Jiaru river, and so on (Zhao, 2001; Xu, 2016) (Fig. 2.3.1). It has a temperate, sub-humid monsoon climate (Ren, 1985). Topographically this area is characterized by a high plateau of loess (wind-blown silt), most of which was deposited during cold dry climatic episodes that occurred in the Pleistocene period (Liu, 1996).

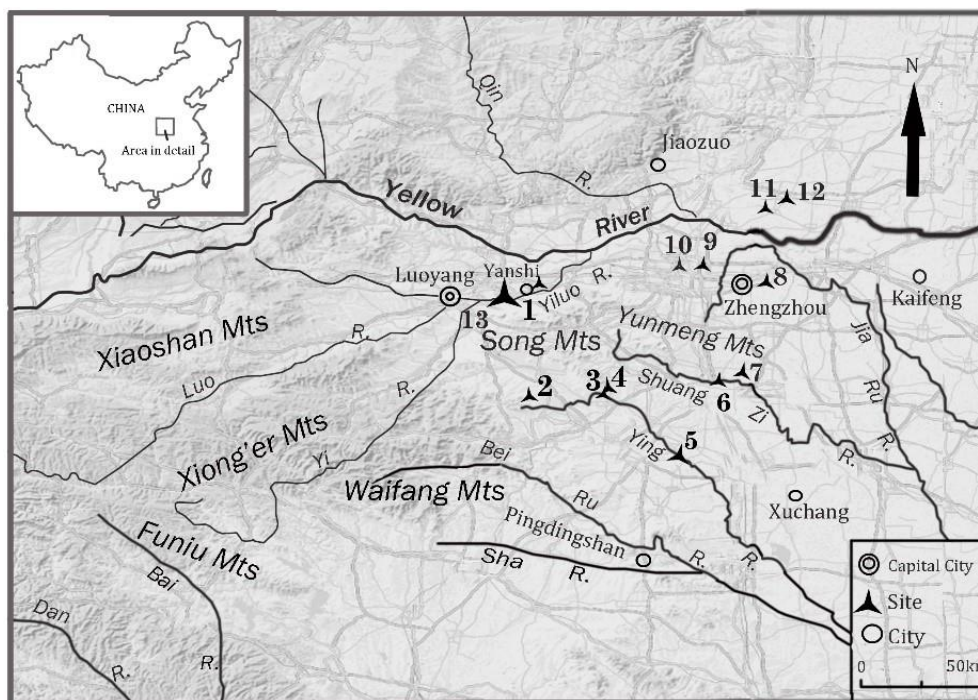


Figure 2. 3. 1 The location and the sites in this research

Site names: 1 Erlitou, 2 Nanwa, 3 Chengyao, 4 Wangchenggang, 5 Wadian, 6 Xinzhai, 7 Guchengzhai, 8 Zhengzhou zhouwei, 9 Dongzhao, 10 Huadizui, 11 Xijincheng, 12 Dalaidian, 13 Huizui Plus: Zhengzhouzhouwei includes four excavation locations, namely Hengligongyu, Huanghezhongxue, Zhongyixueyuan, Zhengzhou Shang City

This project focuses on the time span from Longshan (ca. 2500-1800 BCE), Xinzhai (1850-1750 BCE), Erlitou (ca. 1800-1550 BCE) to Shang (1550-1046 BCE) (Han, 2015; ACAC-PK and Zhengzhou, 2008). This local chronology can be put into two broad archaeological divisions: the Late Neolithic (Longshan, Xinzhai) and the Bronze Age (Erlitou, Shang).

Materials and Methods

In total, systematic flotation reports are available from seventeen sites, also with five sub-regional surveys (Table 2.3.1). All the data is found in the available archaeobotanical and archaeological literature. Due to the limited information on archaeological context (e.g. pits, ditches, storage pits) about samples in some sites, the data is only on the ‘site’ level.

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Table 2. 3. 1 Archaeobotanical data in this analysis

	No.	Periods in reports	Site Name	References
The Late Neolithic	1	Longshan	Chengyao	Zhong, 2016
	2	Longshan	Wangchenggang	Zhao et al., 2007
	3	Longshan	Wadian	Liu et al., 2010; Liu et al., 2018
	4	Longshan	Xinzhai 1999	ACAC-PK and Zhengzhou, 2008
	5	Longshan	Guchengzhai	Chen et al., 2012
	6	Longshan	Zhengzhou Shang City	Jia, 2011; Jia et al., 2018
	7	Longshan	Xijincheng	Chen, 2010
	8	Longshan	Dalaidian	Wu, 2016
	9	Xinzhai,	Xinzhai 1999	ACAC-PK and Zhengzhou, 2008
	10	Xinzhai	Xinzhai 2014	Zhong, 2016
	11	Xinzhai	Dongzhao	Yang et al., 2017
	12	Xinzhai	Huadizui	Zhong, 2016
	The Bronze Age	13	Xinzhai	Zhengzhou Shang City
14		Erlitou	Huizui	Lee et al., 2017
15		Erlitou	Erlitou	Zhongguo, 2014
16		Erlitou	Nanwa	Wu et al., 2014
17		Erlitou	Wangchenggang	Zhao et al., 2007
18		Erlitou	Wadian	Liu et al., 2010; Liu et al., 2018
19		Erlitou	Guchengzhai	Chen et al., 2012
20		Erlitou	Dongzhao	Yang et al., 2017
21		Shang	Erlitou	Zhongguo, 2014
22		Shang	Nanwa	Wu et al., 2014
23		Shang	Wangchenggang	Zhao et al., 2007
24		Shang	Guchengzhai	Chen et al., 2012
25		Shang	Dongzhao	Yang et al., 2017
26		Shang	Zhongyixueyuan	Jia, 2011; Jia et al., 2018
27		Shang	Hengligongyu	Jia, 2011; Jia et al., 2018
28		Shang	Hanghezongxue	Jia, 2011; Jia et al., 2018
29		Shang	Zhengzhou Shang City	Jia, 2011; Jia et al., 2018

In this research, the Representativeness Index (RI) and the Correspondence Analysis (CA) are used for the analysis of crop species and the calculation of arable weeds is based on the absolute numbers. While conducting a supra-regional comparison of different sites, it is difficult to ensure the comparability of the data. Differences in sampling strategies, sample numbers, and sample processing make a distinction in weighting importance among sites. One effective method to analyse the different qualities of materials and make the incomparable data comparable is the RI (Stika and Heiss, 2013a,b). This semi-quantitative approach, on the one hand, provides a measurement for the importance of individual crop species, on the other hand, depicts the representativeness of the data (Effenberger, 2018). As initiators, Stika and Heiss (2013a) used RI for the scale of the whole Europe. Effenberger (2018) afterward downscaled to a smaller area of Northern Germany and adopted the score scaling through refining it.

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In this research, Effenberger's modified system is applied, because it fits the regional data from the Zhengluo Region. Meanwhile, the ubiquity of every species in each site is also considered, since the higher ubiquity one taxon has, the more representative it should be. For Chinese database, the different sizes of cereal grains should also be considered, mainly because both large and small size grains are found in archaeobotanical remains. Since one wheat grain can provide more energy and higher nutrition than one millet grain, the same amount of wheat grains should have different representativeness with millets. Except for that, the large number of small size grain is not necessarily representative of its importance at one site because one millet plant can produce thousands of grains, which is in sheer numbers more than one cereal plant with large-sized-grain can provide. Considering that, the ratio between different cereals has been calculated based on a thousand grains weight (Table 2.3.2).

Table 2. 3. 2 Scoring system of RI with modification

Factor	Ratios between different cereals*	
X1	Foxtail millet	
X2.4	Broomcorn millet	
X8	Rice	
X19	Wheat	
Scores	<1000 Seeds and Fruits	>1000 Seeds and Fruits
1	<10	<10
2	10-49	10-49
3	50-99	50-99
4	>100	100-499
5	-	>500
6	-	25-49%
7	-	>50%
Factors	Requirements per site	
X2	>20 samples or >1000 volume of samples	
X4	>40 samples or >5000 volume of samples	
X5	>100 samples	
X2	No requirement of above applies, but samples contain >10,000 finds	
Scores	Ubiquity	
X1	U<25%	
X2	25%≤U<50%	
X4	50%≤U<75%	
X5	U≥75%	

*Ratios between different cereals=the weight of one thousand wheat (broomcorn millet, rice) grains/ the weight of one thousand foxtail millet grains

To ensure comparability, the following standards were used for unification:

- All the mature and immature (small *Setaria italica*) foxtail millets are included in the '*Setaria italica*' category, the same with broomcorn millet (*Panicum miliaceum*).

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- Determinations of taxa as ‘uncertainty’ are excluded to avoid over-representation of a certain taxon, such as barley, which is only recorded in one site and all of the finds are in fragments with uncertain identification (Liu et al., 2018).
- Following Kreuz et al (2005), cultivated species occurring as solitary finds are not interpreted as intentionally grown crops, they are treated as weeds that were introduced in seed corn. Therefore, taxa with single finds are excluded, like buckwheat (Liu et al., 2018).
- Rice grains are separated from rice spikelet/bases. They are counted respectively.
- For most sites the ubiquity can be found in the reports, either in table form or in bar chart form, for those whose ubiquities are missing, ubiquity below 25% is assumed to minimize the representativeness.

Except for that, CA is used to investigate the diachronic variation of the crop species among sites. Relationships are identified between cereals and sites in different periods. According to previous studies (e.g. Colledge, 2001), small samples should be excluded. For this database, the whole site RI value less than 10 is excluded. The program used to carry out CA is CAPCA 2.1 (Kneisel, 2010).

Results and discussion

In total, there are four cereal species (foxtail millet *Setaria italica*, broomcorn millet *Panicum miliaceum*, rice *Oryza sativa*, wheat *Triticum aestivum*), and two cultivated oilseeds (soybean *Glycine max*, cannabis *Cannabis sativa*) found in this region, meanwhile, wild soybean *Glycine soja* and purple perilla *Perilla frutescens* are also included in oilseeds for a better comparison of oil plants cultivation. Due to the different preservation abilities between cereals and oil plants, they are calculated separately in two categories.

Crop species

Twenty-nine archaeobotanical data in this region contribute to the evaluation of cereal finds. Sites from the Xinzhai (RI=670) and Shang (RI=762) periods are weakly documented. The Longshan period shows moderate representativeness (RI=1306). The Erlitou period is extremely well represented, mainly due to the

well-investigated settlements with huge quantities of plant finds (RI=1646) (Table 2.3.3).

Table 2. 3. 3 RI values of cereals in the Zhengluo Region

	Periods	Foxtail millet	Broomcorn millet	Rice	Wheat	Total
The Late Neolithic	Longshan (n=8)	664	242	324	76	1306
	Xinzhai (n=5)	319	205	136	10	670
The Bronze Age	Erlitou (n=7)	779	453	348	66	1646
	Shang (n=9)	317	155	110	180	762

RI analysis shows that a certain continuity of the Late Neolithic agricultural system up to the Shang period, as foxtail millet remains the main cereal across the whole period. But certain changes are also noticeable, like rice is subdominant in the Longshan period while broomcorn millet is better presented since the Xinzhai period and wheat increases remarkably in the Shang period (Fig. 2.3.2).

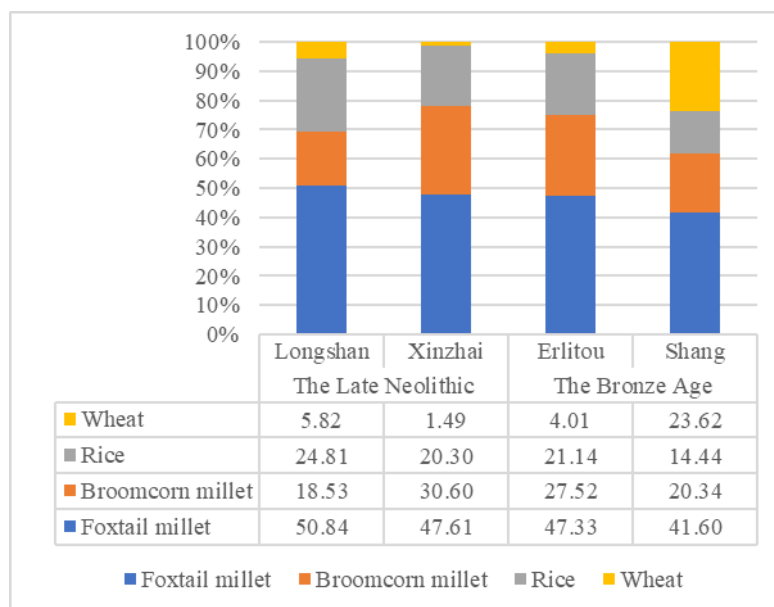


Figure 2. 3. 2 Bar chart of cereals in different periods (percentages are based upon the RI values per period and standardized at 100%)

Meanwhile, to assess the influence of external variables such as different sites and chronological periods on crop species, CA was carried out on cereal RI values (Fig. 2.3.3). In Fig. 2.3.3, with different cereals, millets are close to the origin (0,0 coordinate) while wheat and rice have a long distance from the origin. That means millets are more ‘normal’ or ‘usual’ compositions in all samples while wheat and rice are not. With samples from different periods, there is a clear separation of two particular site groups along Axis 2. Most of the Shang sites cluster around the positive end (circle II), but the majority of the other periods’ sites toward the

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negative end of Axis 2 (circle III). This indicates that there should be some changes in crop species since the Shang period. Moreover, in circle III, the separation between Longshan, Xinzhai and Erlitou samples is weak, but still a certain trend can be observed with the Late Neolithic sites on the bottom and the Bronze Age sites on the top. This indicates that although those sites share similar crop species, there is still a gradual change inside it (Fig. 2.3.3).

Rice is treated as ‘luxury food’ in the Bronze Age in previous researches (e.g. Chen, 2007; Lee and Bestel, 2017). Fig. 2.3.3 also indicates that rice only shows visible importance in certain Bronze Age sites, namely Erlitou and Zhengzhou Shang City sites (circle I). The site of Erlitou is believed to be the ruins of the capital of Xia, the first dynastic state in China (e.g., Zhao, 1987; Gao et al., 1998; Chang, 1999; Xia Shang Zhou, 2000). Zhengzhou Shang City site is generally regarded as either capital *Ao* (Henansheng, 2001) or capital *Bo* (Zou, 1998) in the Shang dynasty. Based on this, it seems like rice has a close relationship with high-level settlements in the Bronze Age. However, CA results indicate that this trend possibly can be traced back to the earlier period, the Xinzhai period. Evidently high representativeness of rice can be observed in Xinzhai (1999) and Huadizui sites, which are two medium-sized regional centers in this period (Pang et al., 2008). But the situation in the Xinzhai site is quite unclear. In the excavation year 1999, the plant assemblage was dominated by rice, however, due to the big size of sieves (5×5cm and 1×1cm, ACAC-PK and Zhengzhou, 2008), millets were highly possible lost during the flotation processing. Moreover, archaeobotanical results from the excavation in 2014, when a sieve with 80 meshes (0.2 mm) was used, yielded numerous finds of millet, indicating the high importance of this species (Zhong et al., 2016). However, in the excavation year 2016-2018, rice may again show higher importance than millet (by author, in process). The archaeobotanical results in Xinzhai site from different excavation seasons are quite different, although all the samples are mainly from pits. Further, there are limited archaeobotanical works about the Xinzhai period, only four archaeobotanical datasets from three sites are analyzed. More archaeobotanical data should be involved in further interpretation.

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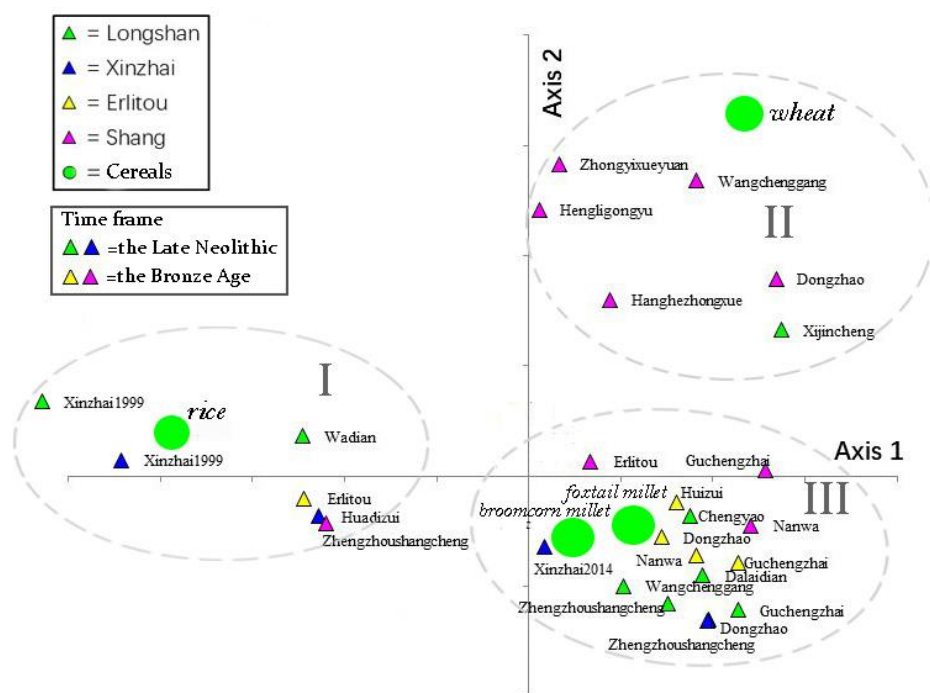


Figure 2. 3. 3 Correspondence Analysis plot of cereals and sites (Based on RI Values of different cereals)

As with the cereals, the RI value of oil plants in the Erlitou period is well presented (RI=383), followed by Longshan (RI=362), Xinzhai (RI=119) and Shang (RI=84) periods (Table 2.3.4). According to historical documents and anthropological researches, oil plants can be roughly divided into two categories: domesticated and wild oil plants (Table 2.3.4). Domesticated plants are dominant and their representativeness increases rapidly towards Shang. Cannabis as a new domesticated oil plant is first present in the Yinxu site, Shang period, but only briefly mentioned in the archaeological report, quantitative analysis is not possible (cited in Chen, 2007). Besides, the representativeness of wild oil plants decreases through time with wild soybean dropping out in the Bronze Age.

Table 2. 3. 4 RI values and percentages of oil plants in the Zhengluo Region

Categories	Species	Longshan	Xinzhai	Erlitou	Shang	Total
		The Late Neolithic		The Bronze Age		
Domesticated oil plants	<i>Glycine max</i>	225(62.15%)	84(70.59%)	379(98.96%)	84(100%)	772
	<i>Cannabis sativa</i>				√	
Wild oil plants*	<i>Glycine soja</i>	28(7.73%)	15(12.61%)			176
	<i>Perilla frutescens</i>	109(30.12%)	20(16.80)	4(1.04%)		
Total		362	119	383	84	948

* The nomenclature of wild oil plants follows the *Chinese weed flora* (Li, 1998).

Crop choices

Intensive study of early Chinese agriculture made it clear that North China along the Yellow River is the center of the origin of dry-land agriculture, with *Panicum miliaceum* more significant before the Middle Neolithic (7000-5000 cal. BP) and *Setaria italica* being dominant afterward (Qin, 2010; Zhao, 2011). The dry, cold climate and arid soils in North China made it difficult for the cultivation of rice but ideal for millets. This might also be the interpretation of the dominance of millets from the Late Neolithic to the Bronze Age in this region (see Fig. 2.3.2). Meanwhile, a certain change can also be observed inside millets with the increase of *Panicum miliaceum* in Xinzhai and Erlitou periods (Table 2.3.5).

Panicum miliaceum matures earlier with a shorter life cycle (60 plus days) than *Setaria italica* (90 plus days) (Pursglove, 1972; Liu et al., 2009). It is more drought-resistant and could grow well in poor soils (Weisskopf, 2010). Because of this, *Panicum miliaceum* is often mentioned as a pioneer species to settle new millet planting areas (e.g. *Qimin Yaoshu* Vol.2 *Shuji*, see Shi et al., 2015) or as an insurance crop in case of drought. However, in this research, attributing the high percentage of *Panicum miliaceum* in Xinzhai and Erlitou periods to the drought seems unlikely. Because compared to the abrupt climate event with cooling and dry fluctuation happening around 2200/2000 BCE in the Late Longshan phase (2050-2000 BCE), the climatic condition at least in the Xinzhai period was warmer and more humid as suggested by pollen analysis (Xia et al., 2003; ACAC-PK and Zhengzhou, 2008: 521-522; Zhang et al., 2011; Liu, 2012; The Institute of Archaeology, Chinese Academy of Social Sciences, 2014). It is also unlikely to be the result of the expansion of millet planting areas since the importance of foxtail millet is decreasing all the time. All in all, for some reasons remaining to be investigated, the ancient inhabitants in Xinzhai and Erlitou periods showed more interest in the cultivation of *Panicum miliaceum*. Same as the sudden growth of wheat in this region during the later period- Shang, it worth pointing out that the preference of *Panicum miliaceum* in the Xinzhai and Erlitou periods is partly determined by ecological factors, but social choice also has a major impact on it (Miller, 1997; Chen, 2016). Thus, social factors like migration, social instability, cultural transmission, labour mobility and so on should also be considered in further research.

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Table 2. 3. 5 Ratio indicator for crop choices

	Periods	Foxtail: Broomcorn	Millets: Rice & wheat
The Late Neolithic	Longshan	2.7:1	2.3:1
	Xinzhai	1.6:1	3.6:1
The Bronze Age	Erlitou	1.7:1	2.9:1
	Shang	2.0:1	1.6:1

*Calculation in Table 2.3.5 is based on the RI values of cereals.

Since the cultivation of rice and wheat requires more sophisticated drainage systems than millets and since rice and wheat also seems to have been less common overall than millets in the local economy, local variations in the ratio of millets to rice/wheat may reflect local community decisions about crop priorities and variations in the sophistication of local agricultural techniques (Zhang et al., 2010). The ‘luxury food’ assumption about rice makes it possible that rice was exchanged or traded to central settlements, but the presence of both cuneiform-bulliform and parallel-dumbbell phytoliths with scooped end derived from the leaves of rice in sediment samples indicates that rice was also likely cultivated locally (Yao et al., 2007; Gui et al., 2007), since exchanged and traded rice are more likely in clean or semi-clean grain form without leaves and straws. In Table 2.3.5, the ratios between millets and wheat/rice indicate that more local economy-millets farm was established in the Xinzhai period but from Erlitou to Shang, irrigation-required wheat and rice gradually became more important. To detect the variations on settlement hierarchies in the Bronze Age, the ratios of the millets versus rice and wheat were calculated in each site. In Table 2.3.6, it clearly shows that the Erlitou site and Zhengzhou Shang City have a much higher percentage of wheat and rice than contemporary sites. This may indicate more sophistication of irrigation techniques in central settlements.

Table 2. 3. 6 Millets versus rice & wheat among sites in the Bronze Age

Periods	Site Names	Millets: Rice & wheat
Erlitou	Erlitou	1.5:1
	Nanwa	11.2:1
	Guchengzhai	20.5:1
	Dongzhao	7.4:1
	Zhengzhouzhouwei	2:1
Shang	Erlitou	3:1
	Guchengzhai	6.8:1
	Wangchenggang	1.1:1
	Zhengzhou Shang City	0.9:1
	Dongzhao	2.1:1
	Nanwa	11.8:1

*Calculation in Table 2.3.6 is based on the RI values of cereals in each site.

Harvesting time

Useful information related to the farming season can be detected from ancient literature. In China, the earliest confirmed historical documents can be traced back to Oracles in the Shang period. As ancient philologists and historians declared, there were different calendar systems in Xia and Shang dynasties compared to the Gregorian calendar. This paper follows the definitions by Wang (1994) and Chang (1998) of the Yan and Xia calendar systems. According to them, during the Shang period, foxtail millet, broomcorn millet, and rice were sown in the Gregorian calendar June and harvested in late summer and autumn. Cannabis has a short-life-cycle which being sown during April and May and harvested in July. Wheat was the only crop sown in September and harvested next June (Table 2.3.7) (Zhang, 2016). However, those historical documents are with few mentions about the Xia period and none for the late Neolithic.

Table 2. 3. 7 Sowing and harvesting time in Shang based on historical documents

Sowing of crops	Season	Yan calendar	Xia calendar	Julia calendar	Harvesting of crops
	Spring	Sep	Jan	Feb	
	Spring	Oct	Feb	Mar	
Cannabis	Spring	Nov	Mar	Apr	
	Summer	Dec	Apr	May	
Broomcorn millet, foxtail millet, rice	Summer	Jan	May	Jun	Wheat
Soybean	Summer	Feb	Jun	Jul	Cannabis
	Autumn	Mar	Jul	Aug	Foxtail millet
Wheat	Autumn	Apr	Aug	Sep	Broomcorn millet
	Autumn	May	Sep	Oct	Rice, soybean
	Winter	Jun	Oct	Nov	
	Winter	Jul	Nov	Dec	
	Winter	Aug	Dec	Jan	

*Table 2.3.7 is based on Zhang JT (2016 Table 4-1).

Concerning harvesting time, archaeobotanical studies provide helpful information, in particular, arable weeds from archaeological sites (Hillman, 1981; Bogaard, 2004). Normally, arable weeds have their maturity times earlier or at the same time as crops. Thus, they can enter the settlements by being harvested together with crops. But it is also important to note that the seeding period of arable weeds is often longer than that of crops to increase propagation and spread rate. Therefore, some species can be used as indicators for the crop harvesting time, but only with an approximate range. In this research, the time interval is selected in which most arable weeds overlap. Due to the lack of information on biological and ecological

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features of ancient plants, here all the potential arable weeds and fruiting time in modern plants have been collected. Although ancient plants and modern plants are comparable, certain limitations should be noted, like the influence of herbicides on arable weeds in modern times. Table 2.3.8 shows that wheat should be harvested between May and June and rice should be harvested between August and November. It is difficult to separate the soybean arable weeds from millets arable weeds since they share similarities. The arable weeds show soybean/millets should be harvested in late summer and autumn. This result coincides with the historical records. Except for that, a large increase in wheat since Shang implies that there might be an increase in summer harvesting if compared to autumn harvesting.

Table 2. 3. 8 Ecological information for potential arable-weeds

	Latin name ⁴	English name	Fruiting time	Occurrence Frequency*
Wheat field weeds	<i>Erodium stephanianum</i>	Common Heron's Bill	Apr-Aug	Seldom
	<i>Galium tricorne</i>	Threecorn Bedstraw	Apr-Jun	Common
	<i>Galium aparine</i>	Tender Catchweed Bedstraw	May	Common
	<i>Arenaria serpyllifolia</i>	Creepingthymeleaf Sandwort	May	Common
	<i>Avena fatua</i>	Wild Oat	May-Jun	Common
	<i>Poa annua</i>	Annual Bluegrass	Mar-May	Common
	Latin name	English name	Fruits time	Occurrence Frequency
Paddy field weeds	<i>Juncellus serotinus</i>	Late Juncellus	Sep-Nov	Common
	<i>Pycreus sanguinolentus</i>	Bloodred Pycreus	Jul-Nov	Common
	<i>Polygonum lapathifolium</i>	Dockleaved Knotweed	Jul-Sep	Seldom
	<i>Scirpus juncooides</i>	Rushlike Bulrush	Aug-Nov	Common
	<i>Fimbristylis dichotoma</i>	Dichotomous Fimbristylis	Jul-Sep	Common
	<i>Scirpus triqueter</i>	Common Bulrush	Jun-Sep	Common
	<i>Lycopus lucidus</i>	Shiny Bugleweed	Aug-Nov	Seldom
	Latin name	English name	Fruits time	Occurrence Frequency
Soybean/millets field weeds	<i>Setaria viridis</i>	Green Bristlegrass	Autumn	Common
	<i>Amaranthus retroflexus</i>	Redroot Amaranth	Aug-Sep	Common
	<i>Xanthium sibiricum</i>	Siberian Cocklebur	Aug-Sep	Common
	<i>Solanum nigrum</i>	Black Nightshade	Sep-Oct	Common
	<i>Acalypha australis</i>	Copperleaf	Aug-Oct	Common
	<i>Portulaca oleracea</i>	Purslane	Autumn	Common
	<i>Amethystea caerulea</i>	Skyblue Amethystea	Sep-Oct	Seldom
	<i>Digitaria sanguinalis</i>	Common Crabgrass	Jun-Nov	Common

*Occurrence frequency is based on the modern investigation which means how often can you see those weed species in farming fields. The frequency information of occurrence and the plant nomenclature follows the *Chinese weed flora* (Li, 1998).

⁴ The scientific name of some species in the *Chinese weed flora* (Li, 1998) are updated to new ones according to the *Plant Plus of China* (see www.iPlant.cn) that hosted by the State Key Laboratory of Systematic and Evolutionary Botany Institute of Botany, the Chinese Academy of Sciences (LSEB, IB, CAS). They include *Galium tricorne*: *Galium tricorutum*; *Scirpus juncooides*: *Schoenoplectus juncooides*; *Juncellus serotinus*: *Cyperus serotinus*; *Scirpus triqueter*: *Schoenoplectus triqueter*; and *Xanthium sibiricum*: *Xanthium strumarium*.

Harvesting method

Harvesting method is part of the husbandry practices and it plays a key role in determining the degrees of weed infestation in archaeobotanical remains. With the weed records from ancient sites, harvesting methods could be explored (Hillman, 1981; Reynolds, 1985, 1993). Here, the average height of modern weeds from *Chinese weed flora* (Li, 1998) is carefully used to infer the harvesting technique in the past (Hillman, 1981:151). The arable weed species present in the samples have been classified into three categories, according to their mean height: ‘low’ is 0-40 cm, ‘medium’ is 40-80 cm and ‘high’ is above 80 cm. The climbing weeds like Mancurian Tubergourd *Thladiantha dubia*, Tender Catchweed Bedstraw *Galium aparine*, Threecorn Bedstraw *Galium tricornis* species are difficult to avoid even by ear-plucking and belong to high growth species (Zhang, 2010). The calculation is on species level (details see Table 2.3.9).

Table 2. 3. 9 Arable weeds used in exploring harvesting method

	Species name ⁵
Low (0-40cm)	Purslane <i>Portulaca oleracea</i> , Green Foxtail <i>Setaria viridis</i> , Common Crabgrass <i>Digitaria sanguinalis</i> , Rushlike Bulrush <i>Scirpus juncooides</i> , Dichotomous Fimbristylis <i>Fimbristylis dichotoma</i> , Creegoithymeleaf Sandwort <i>Arenaria serpyllifolia</i> , Common Heron’s Bill <i>Erodium stephanianum</i> , Distinct Pondweed <i>Potamogeton distinctus</i> , Annual Bluegrass <i>Poa annua</i> , Hairy Cupgrass <i>Eriochloa villosa</i> , Japanese Paspalum <i>Paspalum thunbergii</i> , Bloodred Pycreus <i>Pycreus sanguinolentus</i> , Carex diandra <i>Carex diandra</i> , Viola <i>Viola verecunda</i> , Rigescent Sedge <i>Carex rigescens</i>
Medium (40-80cm)	Cutleaf Groundcherry <i>Physalis angulate</i> , Digitaria Ciliaris <i>Digitaria chrysoblephara</i> , Garden Sorrel <i>Rumex acetosa</i> , Chinese Betony <i>Stachys chinensis</i> , Flowerofanhour <i>Hibiscus trionum</i> , Copperleaf <i>Acalypha australis</i> , European Verbena <i>Verbena officinalis</i> , Goosegrass <i>Eleusine indica</i> , Skyblue Amethystea <i>Amethystea caerulea</i> , Clavate Bentgrass <i>Agrostis matsumurae</i> , Common Bulrush <i>Scirpus triquetter</i> , Dockleaved Knotweed <i>Polygonum lapathifolium</i> , Late Juncellus <i>Juncellus serotinus</i> , Triangular Bulrush <i>Scirpus triangulatus</i> , Redroot Amaranth <i>Amaranthus retroflexus</i> , Common Russianthistle <i>Salsola collina</i>
High (above 80cm)	Siberian Cocklebur <i>Xanthium sibiricum</i> , Barnyardgrass <i>Echinochloa crus-galli</i> , Lambsquarters <i>Chenopodium album</i> , Chingma Abutilon Piemarker <i>Abutilon theophrasti</i> , Shiny Bugleweed <i>Lycopus lucidus</i> , Wild Oat <i>Avena fatua</i>
Climbing (high)	Mancurian Tubergourd <i>Thladiantha dubia</i> , Tender Catchweed Bedstraw <i>Galium aparine</i> , Threecorn Bedstraw <i>Galium tricornis</i>

Table 2.3.10 shows a low/medium harvesting level can be inferred for all cultural periods since there is a greater proportion of low/medium growing weeds in

⁵ The scientific name of some species in the *Chinese weed flora* (Li, 1998) are updated to new ones according to the *Plant Plus of China* (see www.iPlant.cn) that hosted by the State Key Laboratory of Systematic and Evolutionary Botany Institute of Botany, the Chinese Academy of Sciences (LSEB, IB, CAS). They include *Viola verecunda*: *Viola arcuata*; *Carex rigescens*: *Carex duriuscula*; *Digitaria chrysoblephara*: *Digitaria ciliaris*; *Agrostis matsumurae*: *Agrostis clavate*; *Scirpus triangulatus*: *Schoenoplectus mucronatus*.

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contrast to the low percentage of high growing weeds. The increase in the arable taxa with low/medium growing heights from the Late Neolithic to the Bronze Age might be indicative that partly harvesting of ear-level was applied in the Longshan period, but low-level harvesting became more important towards the Bronze Age. This can also be the clue of the high utility of straw since it was an important resource for animal fodder (Chen, 2007). Notably, social factors- tribute activity- should also be considered in this interpretation. During the Pre-Qin period (before 221 BCE), tributes to central settlements can be found in three forms: crops with stalks (*Heshu, Daohe*), hulled-grains (*Caomi*), and unhulled-grains (*Jingmi*) (Dai, 2018). In this case, the rise of low/medium arable weeds may due to the fact that tributary crops were increasingly paid with stalks, but this assumption would need straw remains for support. Noted also, a decrease in the percentage of high growing weed though time could be a hint for more intensive weeding activity of the high height weeds during the cropping.

Table 2. 3. 10 Arable weeds height (percentage)

	Periods	Low and medium	High
The Late Neolithic	Longshan	69.52	30.48
	Xinzhai	76.03	23.97
The Bronze Age	Erlitou	80.38	19.62
	Shang	97.06	2.94

* The calculation in Table 2.3.10 is based on absolute counts and the height of each plant species is the mean value = (the maximum height + the minimum height)/2.

Meanwhile, the agricultural tools from archaeological records are direct and persuasive evidence for exploring the harvesting method. However, unfortunately, so far there is no reference from archaeological research can be cited. Here, a table with the collection of knife and sickle finds is provided, but considering the systematic collection of all the sites requires elaborate works, only these sites analyzed in this paper are involved. Following Hillman (1981) and Reynolds (1985, 1993), many more and also lower as well as medium-growing weed plants and their seeds are collected by sickle than by knife-harvesting. In Table 2.3.11, a decreasing change in the ratio of knife to sickle quantities from Longshan to Shang can be observed. This corresponds with the results from archaeobotany, but a decent statistical analysis of agricultural tools with more sample volumes by archaeologists is called for.

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Table 2. 3. 11 The change of knife/sickle ratio through time

Periods	Sites	Knife	Sickle	Knife/Sickle	References
Longshan	Wangchenggang, Xinzhai, Zhengzhou Shang City, Guchengzhai, Huizui (2002-2003), Chengyao	88	9	9.7:1	The School of Archaeology and Museology in Peking University et al., 2007; ACAC-PK and Zhengzhou, 2008; The Henan Provincial Institute of Cultural Relics and Archaeology, 2001; The Henan Provincial Institute of Cultural Relics and Archaeology et al., 2002; The Institute of Chinese Academy of Social Sciences in Henan(first team), 2010; Zhao et al.,1982; The Institute of Archaeology, Chinese Academy of Social Sciences, 1999, 2014; The research Centre of the historical and cultural heritage in Zhengzhou University, 2015
Xinzhai	Xinzhai	43	12	3.6:1	
Erlitou	Wangchenggang, Erlitou, Xinzhai, Huizui (2002-2003), Nanwa	336	231	1.5:1	
Shang	Erlitou, Wangchenggang, Zhengzhou Shang City, Nanwa	35	48	1:1.4	

Intensification

‘Intensification’ is an increase in labour and/or capital inputs to a fixed area of land to increase or maintain production (Brookfield, 1972; Van der Veen, 2005). Manure can be an important indicator of the intensification of agriculture, because it is an example of applying increased input into a fixed area to increase/maintain production. Such soil amendment strategies can be detected through analysis of certain arable weeds since they can only or prefer to grow in nutrient-rich soil circumstances (Rösch, 1997). These types of weeds include threecorn bedstraw *Galium tricornis*, chingma abutilon piemarker *Abutilon theophrasti*, lambsquarters *Chenopodium album*, purslane *Portulaca oleracea*, and flowerofanhour *Hibiscus trionum*. It is clearly demonstrated that in the Xinzhai period, these weeds on nutrient-rich soils have the lowest percentage but increase in the Bronze Age. This might indicate that in the Bronze Age, there were proven agricultural techniques to keep high soil fertility, possibly by manuring (Fig. 2.3.4). Recent attempts at detecting manuring and watering regimes of crops by the use of stable nitrogen isotope($\delta^{15}\text{N}$) ratios in cereal grains have so far been successful (Bogaard et al., 2007). It can be a potential approach to confirm this conclusion in the future.

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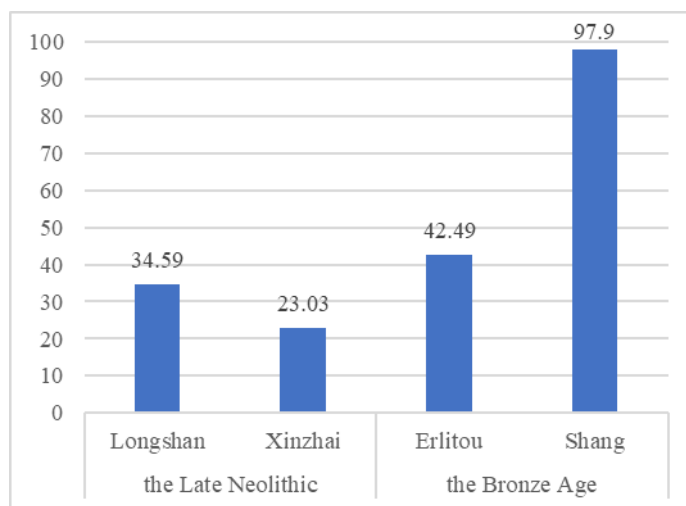


Figure 2. 3. 4 The percentage (%) of plant species that require nutrient-rich soil

Storage

It is striking that a huge amount of rice base or spikelet remains have been reported (Table 2.3.12). Rice husks so far only show in the Longshan period, the presence of rice husks in other periods cannot be excluded since husk can be easily destroyed during carbonization.

Table 2. 3. 12 Rice spikelet/base remains

	Period	Site/survey	Rice remains	Spikelet/base
The Late Neolithic	Longshan	Yin River Survey	41(with 10 rice husk fragments)	4
	Longshan	Wadian (2007-2008)	1144	More than 100
	Longshan	Wadian (2007, 2009)	1231	135
	Xinzhai	Xinzhai 2014	381	More than 50
The Bronze Age	Erlitou	Erlitou I	15	432
		Erlitou II	3234	4482
		Erlitou III	58	29
		Erlitou IV	2358	2289
	Shang	Erlitou	22	10

* These numbers in Table 2.3.12 are the absolute numbers of rice and rice spikelet/base.

Once processing activities are completed, crops should be stored in spikelet or as clean/semi-clean grains depending on the climatic conditions prevailing at the site's location (e.g. in areas with wet summer, spikelet storage might be preferred, Hillman, 1981) or/and social factors such as labour availability and tradition (Stevens, 2003; Fuller and Stevens, 2009). The climatic factor can be roughly excluded in this research since the climate from Longshan to Shang witnessed

warm, wet to cold, dry then back to warm, wet many fluctuations (Liu, 2005:27-32). The storage of rice in spikelet form seems to have no climatic preference. Therefore, social factors and labour organization might be the main factor for that.

The presence of rice base or spikelet remains, on the one hand, indicates that rice was stored at least sometimes in ear or in spikelet form which can keep longer preservation. On the other hand, it may reflect a labour mobilization strategy about rice processing. Rice spikelets or bases, which should be removed in the processing sequence, their presence implies some routine processing on-site. The advantage of this might have included lower labour demands during the busy periods of harvest, but create a great demand for labour after harvest and prior to consumption. Earlier regional compilations of archaeobotanical results (Fuller and Zhang, 2007; Song et al., 2017) already pointed out: diversification of crop-processing practices has already happened in different sites during the Longshan period. More restricted ability for mobilizing larger labour forces at harvest is only found at some sites. As in Table 2.3.12, enormous rice bases and spikelets are only found in Xinzhai site and Erlitou site but absent in other contemporary sites, this difference between sites might indicate the diversification in labour mobilization further increased in Xinzhai and Erlitou periods. As mentioned above, Xinzhai and Erlitou sites are both central settlements and both show the highest RI values of rice at each period. Rice, especially in northern China, was a scarce cereal resource. For ordinary people, rice was more difficult to get than millet. Eating rice is even recorded as a prestigious status symbol in historical documents (Zeng, 2016). Therefore, this particular storage method indicates that rice might be preferred by elites and they would like to keep longer preservation of rice and also have the ability to control labour mobilization for rice processing.

Conclusions

In the Zhengluo Region, foxtail millet was dominant from the Late Neolithic to the Bronze Age, with rice subdominant in the Longshan period and broomcorn millet subdominant since the Xinzhai period. In general, rice was decreasing throughout the whole time and wheat witnessed a dramatic increase in the Shang period. Different crop choices have been made from the Late Neolithic to the Bronze Age in the Zhengluo Region. For some reasons remaining to be investigated, more

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broomcorn millet was cultivated in the Xinzhai and Erlitou periods. Except for that, in the Bronze Age, probably more rice and wheat were produced because of more elaborate agricultural techniques, possibly including irrigation, manuring and spikelet-form storage method. Except for that, this study verifies the crops harvesting time in historical documents and also indicates that the removal of the high-height weed plants was more intensive in the Bronze Age, and the sickle-harvesting method was prevalent since the Late Neolithic.

The results of this research should be treated cautiously given the size of the analytical samples. More archaeobotanical flotation data is very welcomed to contribute to this research and a detailed investigation on the Xinzhai site is currently on the way. Samples lacking archaeological context information limit the significance of the conclusions drawn in this paper. More detailed archaeobotanical reports with raw data as an appendix are promoted. Also, as a pilot study, knife and sickle finds were collected from partial archaeological sites, a more elaborate collection work by archaeologists would be better to testify archaeobotanical results.

Acknowledgements

The research for this paper is supported by the China Scholarship Council (CSC) for a Ph.D. degree (State Scholarship Fund No.201706220058), the Graduate School of Human Development in Landscapes (GSHDL) at the Christian-Albrechts-University, Kiel, Germany and the China National Natural Science Foundation (41771230). The authors are grateful to Helmut Kroll, Jutta Kneisel, Anna E. Reuter for discussion of some of the issues considered here as well as for constructive comments for the RI and CA analyses.

Appendix III

Table III.1-III.2 (This appendix is only listed in this dissertation but not in the publication).

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2.4 Regional study on the Haidai Region

Societies under different farming systems have different resilience to climate changes (Weiss 2016, 2017; Cookson et al. 2019; Kleijne et al. 2019, 2020). Moreover, societies might pursue various adaptation strategies in the agricultural area to handle prolonged climatic events depending on existing environmental and cultural factors. In this section, by summarizing all available macro-botanical data concerning the agricultural economy from the East-Haidai and West-Haidai, it allows us to detect the differences and similarities in farming systems and cultivation regimes between these two regions.

In section 2.3, it has been proven that from the Late Neolithic to the Early Bronze Age, the Central Plain formed a farming system with relatively high production of water-requiring crop species (e.g. rice). However, in this section, different pictures have been described in the East-Haidai and West-Haidai. Water-requiring species either occupied a small proportion in the agricultural system through time in the West-Haidai or have witnessed a rapid decline in the East-Haidai. Moreover, unlike the irrigated wet rice farming in the Central Plain, current evidence shows in the Haidai Region, rice farming could be inferred as wet, paddy farming but possibly relied on naturally watered fields without irrigation. Direct evidence is the paddy features found at the Zhaojiazhuang and Taitou sites. They were formed in the patch of fields that utilized a natural water body and natural topography without any irrigation canals or ditches being found, although it might due to the limited excavation scales as the researchers claimed (Jin et al. 2007; Zheng et al. 2015). Besides, those charred rice grains found in the Liangchengzhen site are smaller (4x2 mm) than either wild rice or modern rice cultigens by morphological observations suggesting they were grown under water stress (Crawford et al. 2005), likely in seasonal wet-habitats, rather than in irrigation conditions. In this section, arable weeds associated with rice fields in the macro-botanical remains have been analyzed to further illustrate this topic. As a result, a rice system on a relatively dry ecological growing condition (equal to the intermediate rice category which depends on groundwater, seasonal flood, or rainfed from Weisskopf et al. 2014) has been suggested. Thus, in the research of the East-Haidai and West-Haidai, instead of irrigation technique, agricultural systems and cultivation regimes have been focused.

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By doing this, it argues that the different resilience in societies while facing huge climate changes could be reflected in the specific resilience of the rice farming system and millet farming system. Furthermore, different cultivation regimes have contributed to the social transformation as well. For these societies with intensive agricultural systems, if the intensification is depending on the inputs of extra labour rather than the innovation of techniques, it is not necessarily the case that the agricultural intensification is always connected with social development. In this research, the analysis of weed assemblages with their ecological information (life spans, living habitats, soil requirements) demonstrates that agricultural extensification in the West-Haidai actually offered more opportunities for social stability than the farming system which was more intensive in the East-Haidai. From this point of view, archaeological investigations on the settlement numbers and assessments of population also provide additional evidence. The migration of population from the East-Haidai to the more favourable ecological- areas since the Late Longshan period can therefore be considered together with the agricultural systems and the social transformations.

Understanding the collapse of the Longshan culture (2400-1800 cal. BCE) and the 2.2 ka BC event in the Haidai Region of China from an agricultural perspective

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This is the author’s original manuscript (AOM) of an article that after the peer review and was re-submitted to *Environmental Archaeology*, currently under review.

Abstract

The Haidai Region was important for early Chinese cultures that reached their prehistorical peak during the Longshan period (2400-1800 cal. BCE). However, the continuous development of Longshan society was interrupted since the Yueshi period (1800-1600 cal. BCE) in West-Haidai but in the Late Longshan phase (2100/2000-1800 cal. BCE) in East-Haidai. As archaeobotanical data accumulates, it is possible to conduct a comprehensive study on agriculture development, which is quite sensitive to climate change and also crucial to human society. Therefore, we conducted a synthetic analysis of macro-botanical remains from 25 Longshan sites using Representativeness Index (RI) and Correspondence Analysis (CA). We identified sub-regional differences in crop structures and cultivation regimes between West- and East-Haidai that offer new insights into social changes that arose after the 2.2 ka BC event. While facing abrupt cooling and drought, societies engaged in millet farming in West-Haidai showed much stronger resilience than those in East-Haidai that were occupied with rice farming. Moreover, to cope with environmental deterioration, West-Haidai inhabitants may have attempted to change cropping practices by exploiting previously uncultivated lands (extensive cultivation) whereas those in East-Haidai were preoccupied with intensive rice farming throughout the entire Longshan period and probably mitigated food shortages by population migration.

Keywords Haidai Region· Longshan period· Cultural collapse· 2.2ka BC event· Farming systems· Cultivation regimes

Introduction

In the face of climate change, especially abrupt climatic events, the role of ancient agriculture in the transformation of human societies is a topic of current debate (Wilkinson 1997; Weiss 2003, 2016, 2017; Petrie et al. 2017; Li et al. 2020). The global 2.2 ka BC event, commonly known as a sudden cooling and aridification event, had a well-documented influence on large parts of the world (Wang J et al. 2016; Ran and Chen 2019). Notably, societies with distinctive agricultural systems displayed different resilience after this climatic event (Weiss 2016, 2017; Cookson et al. 2019; Kleijne et al. 2019, 2020). Moreover, societies might have pursued various agricultural strategies to deal with this profound climate change depending on existing environmental and cultural conditions (Ristvet 2003; Riehl 2009; Clarke et al. 2016; Weiss 2016, 2017; Pokharia et al. 2017; Blanco-González et al. 2018; Cookson et al. 2019; Kleijne et al. 2019, 2020). Examples include adopting new drought-tolerant crop species, developing a greater diversity of wild resources, conducting intensive agriculture through the adoption of new techniques, practicing extensive agriculture through farmland expansion, and population migration to new ecological areas.

This 2.2 ka BC event was recorded by various climate archives such as ice-cores, speleothems, terrestrial, marine sediment cores, and others across China (Hong et al. 1997; Liu et al. 2000; Peng et al. 2005; Xu et al. 2010; Dykoski et al. 2005). It is expressed as a sudden cool and arid climatic-transformation in the Haidai Region (Gao et al. 2007; Chen and Wang 2012) which had significant influences on Late Neolithic Longshan societies (2400-1800 cal. BCE). As documented previously, this climatic event caused widespread environmental deterioration which further triggered massive rice farming abandonment, remarkable population shrinkage, and ultimately societal collapse (Qi et al. 2006; Gao et al. 2007; Peng et al. 2010). However, the social collapse was expressed differently between West- and East-Haidai. A social collapse along with the sudden decline in settlements occurred from the Late Longshan phase (2100/2000-1800 cal. BCE) in East-Haidai which emerged in the Yueshi period (1800-1600 cal. BCE) in West-Haidai (Liu 2005; Luan 2016; Zhang 2017; Han 2019). Furthermore, rice cultivation was not the main choice for all Longshan inhabitants in Haidai. Sub-regional variations in crop choice, especially in Shandong where has intensive archaeobotanical investigation,

have been frequently noted (Zhao 2004, 2006; Jin 2013; Ma and Jin 2017). It transpires that millet farming instead of rice farming played a more important role in many Longshan sites or sub-regions (Zhao 2004, 2006; Jin 2013; Ma and Jin 2017). Therefore, questions on how the climatic event differently affected agricultural systems and what the connections were between agriculture and social collapse (or societal resilience) demand answers. In the exploration of ancient agriculture and related human behaviours, plant remains documented by archaeobotanical work can provide persuasive evidence (Zhao 2011). Thus, we conducted a systematic compilation of archaeobotanical data from 25 Longshan sites into a solid database for a semi-quantitative approach to describe and compare sub-regional agricultural systems and their interactions with the 2.2 ka BC event. Besides, considering their potential for providing insights into the management of cultivation plots, a review of weed assemblages was performed as well.

The study area of Haidai

As a cultural and archaeological term, the “Haidai Region” has no precise geographic definition and covers different areas during different periods throughout the Neolithic and Bronze Age (Gao and Shao 1984). During the Longshan period, it reached its maximum expansion and included the modern Shandong province, the northern Huai river area in Anhui and Jiangsu provinces, the southern Liaodong Peninsula, and eastern Henan (Luan 1997; Fig. 2.4.1). The entire region includes two main topographic configuration types: 1. the central Tai-Yi mountain system; and 2. the surrounding plains. The former is marked by the Tai, Meng, Lu, and Yi mountains at >1000 m above sea level, and the latter comprises the Northwest, Southwest, Jiaolai, and Huaibei plains (Luan 1996). Based on archaeological and topographic information, we divided the Haidai Region into West-Haidai and East-Haidai by drawing a line through Wei river, Yi mountain, and Meng mountain spanning from northeast to southwest. West-Haidai includes the southern Liaodong Peninsula, western Shandong, and eastern Henan, while East-Haidai covers the eastern Shandong, northern Anhui, and northern Jiangsu (Fig. 2. 4.1).

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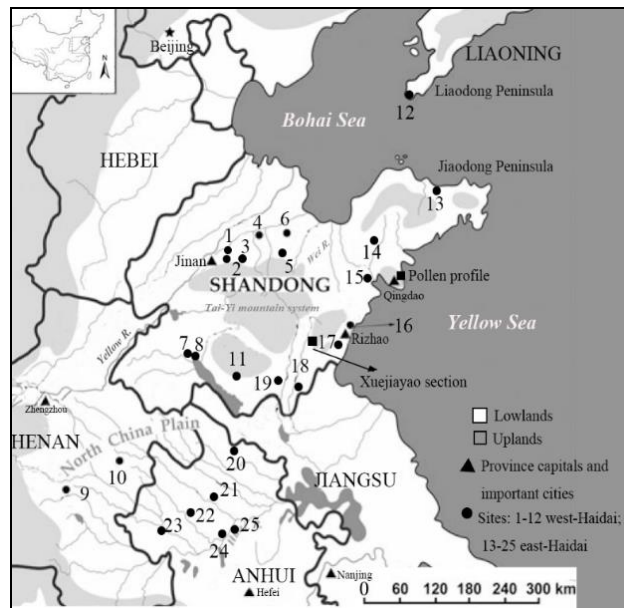


Figure 2. 4. 1 The location of the Haidai Region and the main sites mentioned in the text (site names see Table 2.4.1; modified from Underhill 2017)

Climatically, the Haidai Region belongs to the East Asian monsoon system zone (An et al. 2000; Liu and Chen 2012). By being dominated by warm and wet air masses from the tropical Pacific Ocean (summer monsoon) in summer and cold and dry Siberian air masses (winter monsoon) in winter, it exhibits a clear seasonality with hot, wet summers and cold, dry winters (Zhao 2005; Tarasov et al. 2009). The wet season generally spans an interval from May to September bringing up to 60% of the annual precipitation which coincides with the growth phase of rice (June to October) (Tarasov et al. 2009). Due to the topography, especially the lofty Tai-Yi mountain system in the middle, average annual precipitation follows a southeast-northwest gradient in Haidai (Jin 2013). For example, in Shandong, it gradually decreases from above 700 mm in the east to 600-700 mm in the middle, and to below 600 mm in the west (CAEC 1994). During the Longshan period, as revealed by pollen and charcoal analysis from archaeological settlements, the climate was likely similar with more humid conditions in the east and relatively drier conditions in the west (Jin 2009a). Moreover, with the weakening of the summer monsoon and its southern retreat from around 2200 cal. BCE, the maximum precipitation belt lay in the Yangtze river region which eventually led to cool and dry conditions in Haidai (Liu and Chen 2012). Local climatic indicators (locations see Fig. 2.4.1) are consistent with this conclusion (Gao et al. 2007; Chen and Wang 2012). Around 2200 cal. BCE, with the gradual $\delta^{13}\text{C}$ increase and a quick drop in median granule

content, a climate change from warm, humid to cool, dry can be observed in the Xuejiayao section from the Yi-Shu river basin (Gao et al. 2007). Likewise, a sharp drop in arboreal pollen falling to its lowest during 2550-1900 cal. BCE observed in a high-resolution pollen record in Qingdao infers a distinct cooling deterioration (Chen and Wang 2012). Overall during the Longshan period, the research area not only showed sub-regional differences in micro-climates due to topographic variations but also witnessed a shift to cooler and drier conditions under the abnormal movement of the monsoon system. These natural settings had a profound impact on human adaptation especially on ancient agriculture which is closely bound to environmental settings.

Materials and methods

To evaluate crop finds, and further reconstruct cultivation regimes, archaeobotanical flotation data were systematically collected from 25 Longshan sites (Table 2.4.1). Some archaeobotanical data mainly covered the early (2400-2100/2000 cal. BCE) or the late (2100/2000-1800 cal. BCE) phase of the Longshan period while others were defined simply as the Longshan period (2400-1800 cal. BCE) without the possibility of further differentiation. The majority of samples were derived from refuse pits and ditches (1251/1593), followed by those from cultural layers (107), houses (56), inside pots (55), and post-holes (55) (Appendix Table-IV.1). Among all the excavation features, refuse pits and ditches are such contexts where daily waste would have been mainly deposited and their contents mostly represent the waste from routine food preparation activities (Fuller et al. 2014). So, except for a small proportion (6.5%, 104/1593) of samples from impurity contexts (post-holes, burials, wall foundations, and kilns), most samples can be tentatively used to reflect ancient agriculture and related information.

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Table 2. 4. 1 Archaeobotanical data compiled for this paper

Sites in West-Haidai*	Period#	Archaeobotanical data references	Sites in East-Haidai*	Period#	Archaeobotanical data references
1.Ningjiabu	Early Longshan	Wei et al. 2018	13. Wutai	Early Longshan	Chen et al. 2019
2.Huangshangyuan	Longshan	Zhang F et al. 2018	14. Xuejiazhuang	Early Longshan	Jin et al. 2010
3.Pengjiazhuang	Longshan	Wu et al. 2010	15. Zhaojiazhuang	Early Longshan	Jin et al. 2011b
4.Dinggong	Longshan	Wu et al. 2018	16. Liangchengzhen	Longshan	Crawford et al. 2005
5.Fangjia	Early Longshan	Jin et al. 2011a	17. Liujiiazhuang	Early Longshan	AIHC-SU 2016
6.Tonglin	Longshan	Song 2007	18. Dongpan	Early Longshan	Wang et al. 2011
7.Shilipubei	Late Longshan	Guo et al. 2019	19.Houyangguan-zhuang	Early Longshan	Wang et al. 2013
8.Zhuanglixi	Late Longshan	Kong et al. 1999	20. Yangpu	Longshan	Cheng et al. 2016
9.Haojiatai	Longshan	Deng and Qin 2017	21. Luchengzi	Longshan	Wang Y et al. 2016
10.Pingliangcheng	Late Longshan	1. Deng and Qin 2017; 2. Zhao et al. 2019	22. Yuchisi	Longshan	Zhao 2010
11.Beitaishang	Longshan	Wang 2018	23. Gongzhuang	Early Longshan	Cheng et al. 2019
12.Wangjiacun	Early Longshan	Ma et al. 2015a	24. Yuhuicun	Late Longshan	Yin 2013
			25. Diaoyutai	Late Longshan	Zhang J et al. 2018

*Sequence numbers correspond to the location number in Fig. 2.4.1; # References for dating information are summarized in Appendix Table-IV.1.

While conducting an inter-regional comparison, sampling strategies and sample numbers among individual sites are often different. Because such differing data qualities may cause serious bias in weighting the importance of crop species among sites, we used the Representativeness Index (RI), an effective semi-quantitative approach, to make incomparable data comparable (Stika and Heiss 2013a,b; Effenberger 2018). We applied this RI method with a modified scoring system to Chinese databases (An et al. 2019; Table 2.4.2). Moreover, to ensure comparability, a series of standards were used for database harmonization: 1. all the mature and immature foxtail millets were included into *Setaria italica* category, and the same was applied to broomcorn millet (*Panicum miliaceum*); 2. most ubiquity information could be found in original reports, but when it was missing, a ubiquity < 25% was assumed to minimize representativeness. This method provides a measurement for the importance of specific crop species and also depicts the representativeness of the data (Effenberger 2018). Additionally, correspondence analysis (CA) was used to investigate the spatial and temporal variations of crop species among sites and sub-regions. The program used to carry out CA was

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CAPCA 2.1 (Kneisel 2010) and small samples with whole site RI values < 10 were excluded during the analysis.

Table 2. 4. 2 RI scoring system in this research

Factor	Ratios between different cereals (modification in this research) *		
X1	Foxtail millet (<i>Setaria italica</i>)	X2.4	Broomcorn millet (<i>Panicum miliaceum</i>)
X8	Rice (<i>Oryza sativa</i>)	X19	Wheat (<i>Triticum aestivum</i>)/ Barley (<i>Hordeum vulgare</i>)
Scores	<1000 Seeds and Fruits	>1000 Seeds and Fruits (from Effenberger 2018)	
1	<10	<10	
2	10-49	10-49	
3	50-99	50-99	
4	>100	100-499	
5	-	>500	
6	-	25-49%	
7	-	>50%	
Factors	Requirements per site (from Effenberger 2018)		
X2	>20 samples or >1000 liters of samples	X5	>100 samples
X4	>40 samples or >5000 liters of samples	X2	No requirement of above applies, but samples contain >10,000 finds
Scores	Ubiquity (modification in this research)		
X1	<25%	X4	50%~75%
X2	25%~50%	X5	>75%

*Ratios between different cereals—the weight of one thousand wheat (broomcorn millet, barley, rice) grains/ the weight of one thousand foxtail millet grains, grains are all without husks.

Results

Archaeobotanical remains associated with agricultural activities were summarized in two main categories in the following discussion: 1. crops and related exploitable species; and 2. weed seeds. Key results of crops and related exploitable species were obtained through the CA analysis based on RI values (Fig. 2.4.2a,b) whereas major conclusions on weeds were derived from absolute counts (Fig. 2.4.3).

Crops and related exploitable species

Following the definition of cultivated plants in Bronze Age Europe by Stika and Heiss 2013a, plant spectra included in crops primarily comprises three main groups: 1. cereals (grasses of the Poaceae family), 2. oilseeds, and 3. legumes/pulses (Fabaceae family) (Appendix Table-IV.2). Due to different preservation probabilities in the carbonization context, these groups have to be evaluated separately during RI analysis (Stika and Heiss 2013a,b). The most important cereal crops in the Bronze Age, according to the earliest available historical written records (e.g. Oracle inscription, Shijing), were most likely foxtail millet *Setaria italica*, broomcorn millet *Panicum miliaceum*, rice *Oryza sativa*, wheat *Triticum*

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aestivum, and barley *Hordeum vulgare* (Yang 1991; Song 2002; Ma et al. 2015b). These were the main contributions to human daily calorie intake (Stika and Heiss 2013a). Oilseeds of cannabis *Cannabis sativa* and sesame *Sesamum indicum* provided essential fatty acids crucial for human metabolism and hormonal balance (Stika and Heiss 2013a). Although the domestication history of both species in China is still inconclusive, a bunch of early finds of cannabis achenes (3000-2000 cal. BCE) (Long et al. 2017) and sesame seeds (3360-1900 BCE) (Qiu et al. 2012) has led many scholars to conclude that they were cultigens either locally cultivated (Chang 1986; Yang 1991; Crawford 2006) or imported from central Asia (Long et al. 2017) during the Longshan period. Besides, the utilization of purple perilla *Perilla frutescens* seeds for food oil and lighting fuel can be found in historical documents (e.g. *Qiminyaoshu*, *Mingyibielu*) (Miu and Miu 2009; Liu 2009), but the earliest mention as a cultigen is around 1900-1500 BCE (Crawford 2006). Therefore, it is still treated as an exploitable wild resource in the Longshan period. Legumes/pulses cover only one cultivar soybean *Glycine max* but the exploitation of its progenitor- wild soybean *Glycine soja* -can be traced back to 9000 BP and continued in the Longshan period (Crawford et al. 2005; Lee et al. 2011; Wu et al. 2013; Zong et al. 2017). Apart from their use as a source of calories and essential amino acids, legumes/pulses generally have high vegetable fat content (Stika and Heiss 2013a). As proposed by Zong and his colleagues (2017), selection for oil content probably played a vital role in soybean domestication as it has a significantly higher oil content than its wild counterpart. This trait leads to very low preservation potentials by charring (Fuller 2020) and eventually brings a similar bias with oilseeds. So, in this research, pulse and oilseed species were classified in one category as “oily seeds” and evaluated separately from cereals.

The CA analysis based on cereal RI values shows that wheat and barley are generally poorly represented compared to rice and two millet species (Fig. 2.4.2a). As exotic species from central Asia (Zhao 2015; Liu et al. 2017; Long et al. 2017, 2018), wheat and barley in this compilation of the Longshan period are quite early recordings from eastern China. Their appearance possibly shows a direct influence of central Asian pastoralist communities and indicates that the trans-Eurasia exchange or migration network through the steppe zone with this region had already been established during the third millennium BCE (Long et al. 2017, 2018).

However, existing radiocarbon dating directly on wheat grains shows that ten out of fourteen finds were actually intrusions from later periods, even including ones from modern times (Appendix Table-IV.3). This result strongly suggests that further radiocarbon dating is required to provide a better understanding of these exotic species in this region. Nevertheless, the CA analysis based on current data shows wheat and barley have an exclusively close association with the Yuchisi site (Fig. 2.4.2a). The Yuchisi site is special for its social function as an etiquette location for Xia leader *Yu* and his followers for sacrificial activities (He 2014; Wang and Xie 2014) and some plant remains were indeed derived from sacrificial activity-related contexts (sixteen samples from sacrifice pits and ditches) (Yin 2013; Appendix Table-IV.1). Thus, by being intimately connected with particular social activities or social groups, these exotic taxa likely reflect information beyond local agriculture. Besides, a clear separation of two distinct site groups can be found along Axis 1 (Fig. 2.4.2a). The West-Haidai sites are closely associated with two millet species at the positive end of Axis 1 supporting the notion that millet cultivation was a common feature of agriculture in this region. Conversely, the majority of East-Haidai sites were located at the negative end of Axis 1, along with rice, indicating rice dominated farming. Also, several outliers can be observed. Compared to the other West-Haidai sites, relatively larger amounts of rice were associated with Tonglin and Dinggong which are two regional centres (Sun 2013). As proposed by archaeologists, certain crops were produced more in certain settlements and intimately involved in economic exchange networks in Longshan times (Liu 2005; Sun 2013, 2020). Acting as regional centres, Tonglin and Dinggong were densely populated with enough labour to produce sufficient amounts of rice which may, in turn, have supported their key role in the exchange network. However, this phenomenon only occurred in the dry farming dominant West-Haidai but was absent in the rice farming prevalent East-Haidai where rice was very likely consumed as daily food. As shown in Fig. 2.4.2a, the central settlement of Liangchengzhen shows almost equivalent importance of rice with all the other ordinary settlements.

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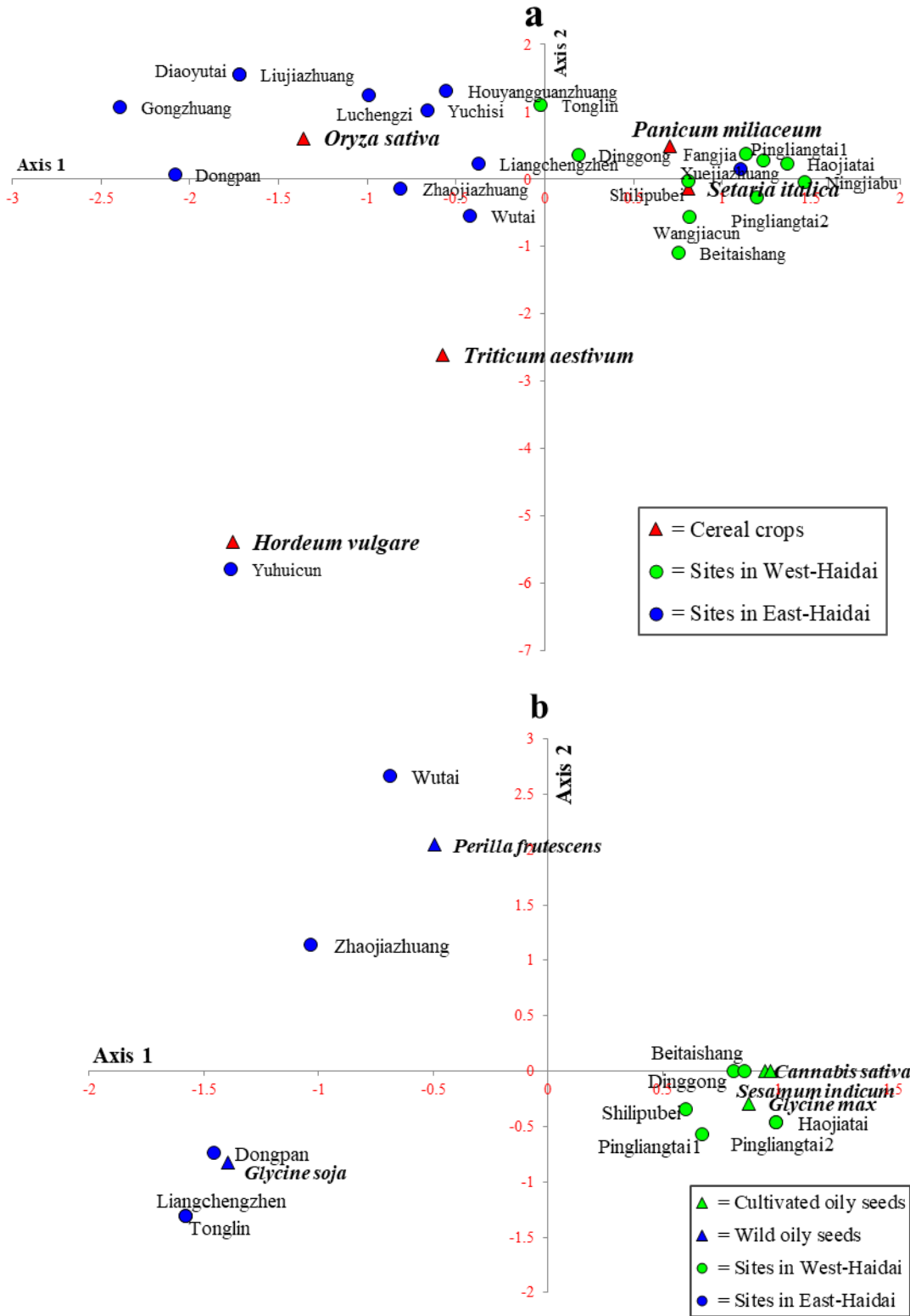


Figure 2. 4. 2 The CA plot of **a.** cereals and sites; **b.** oily seeds and sites on 1. and 2. principal axes in the Longshan period (based on RI values)

A clear separation of two distinct site groups can be found along Axis 1 in oily seeds as well (Fig. 2.4.2b). While most West-Haidai sites were characterized by cultivated oilseeds at the positive end of Axis 1, the East-Haidai sites were located

at the negative end of the axis, along with wild taxa. Diversification in the selection of wild species among settlements was also found in East-Haidai with some focused on the collection of *Perilla frutescens* (second quadrant) and the remainder devoted to *Glycine soja* (third quadrant). This diversification might be a consequence of different access to wild resources which were heavily dependent on natural conditions.

Weed seeds

Another common component found in macro-botanical assemblages was weeds. Weed remains, mainly those identified to species level, were divided into six categories based on their growing habitats (Li 1998; Fig. 2.4.3). Among them, arable weeds encompassed the taxa commonly found in modern farmlands. The remaining five categories were all deemed as non-arable weeds and included species originating from mountains, hills, forest edges, ruderal areas, riverbanks, and lakeshores. Weed species included in each category were listed in Appendix Tables-IV.4, IV.5. In the following discussion, non-arable weeds were treated the same as arable weeds for the exploration of agricultural activities, since both categories co-occurred in crop remains which is indicative of their tight connection to agricultural activities. Moreover, Fabaceae species dominate the non-arable weeds (1656/2715; Appendix Table-IV.5). Although they possibly entered settlements intentionally as gathered animal fodder (Jin et al. 2012), the strong C₄ signal in the diet of domestic animals (pigs and dogs) identified by stable isotope analysis excluded the large consumption of C₃ Fabaceae plants to local animals (Lanehart et al. 2011). Therefore, the presence of non-arable weeds was tentatively interpreted as intrusions in archaeobotanical assemblages during the growth or processing of crops. In both sub-regions, the proportion of arable weeds (71.8% and 84.9%) is significantly higher than non-arable weeds (28.2% and 15.1%). Moreover, ignoring those weeds that are unable to be differentiated, the majority of non-arable weeds are from ruderal areas (41% and 54.2%), followed by those from hillside grasslands and woodlands (35.6% and 9%).

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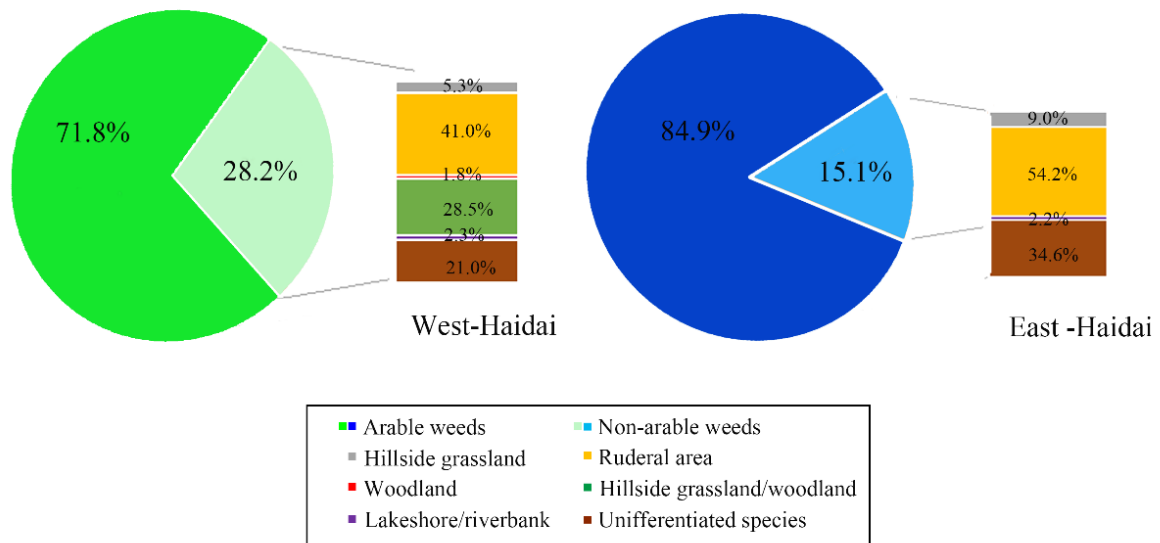


Figure 2. 4. 3 Proportions of weed remains by their growing habitats (species in each category see Table S4, S5; based on absolute counts)

Discussion

Favourable environmental conditions may have boosted ancient farming and therefore increased food availability to support a complex society, while adverse conditions may have undermined production and human society living conditions or exacerbated social stresses which eventually led to severe crises or collapses of social-culture systems (Yang et al. 2017). Located in the monsoon zone, the strength of the monsoon system is the primary determinant of precipitation (An et al. 2000; Zhao 2005; Tarasov et al. 2009), and therefore, has been one of the most important factors affecting vegetation, river systems, and ecological adaptations undertaken by Haidai inhabitants. With the southward retreat of the summer monsoon, the 2.2 ka BC event brought far less precipitation, a decline in the average annual temperature (AAT), and an earlier arrival of winter in Haidai. This most likely triggered a profound impact on local agriculture which further influenced the trajectory of social development. Our analysis indicates that while climate being transformed into drier and cooler conditions, West-Haidai and East-Haidai societies witnessed different societal changes through different crop structures and cultivation regimes.

Regional differences in crop structure

To interpret social transformation after the climatic event from an agricultural

perspective, we initially conducted a diachronic analysis of crop structure (Fig. 2.4.4). The results lend strong support for distinct regional differences between East- and West-Haidai. In East-Haidai, the high representativeness of rice both in the Early and Late Longshan phase provides a strong indication that this region was dominated by rice cultivation throughout the entire period. Meanwhile, West-Haidai agriculture was characterized by two highly drought-tolerant millet species from the Early to the Late Longshan phase. In non-mechanized societies, natural conditions set a basic requirement and limitation for agriculture (Wilkinson 1997), so natural factors might account for the distribution pattern. Located in an arid and semi-arid region, water availability in Haidai is (and likely was) a major constraint for crop choice (Wagner and Tarasov 2014). Importantly, archaeological evidence of rice fields suggests that Haidai Longshan rice was highly likely cultivated in a paddy system but relied heavily on natural water without any artificial irrigation (Jin et al. 2007; Zheng et al. 2015). The analysis of rice field weeds with 69.9% (1766/2526) from dry rice fields and 30.1% (760/2526) from wet rice fields also reveals an ecological condition comparable to the modern Indian “semi-wet rice” category (groundwater, rainfed, or seasonal floods water supply) (Weisskopf et al. 2014; Appendix Table-IV.4). On this precondition, natural precipitation determined rice cultivation in Haidai. As mentioned above, with a well-pronounced precipitation gradient from east to west, the humid East-Haidai therefore offered a more favourable rice growing habitat. Comparatively, because foxtail millet and broomcorn millet have a wide ecological amplitude, they can grow in a broad array of natural conditions which allows them to maintain stable production, even under extreme physical conditions. So, millet cultivation was preferred in West-Haidai where natural water resources were limited.

Crop structure has a profound impact on the formation of societies. With high-yield production that is twice that of millet (Fuller et al. 2011), rice farming once offered a solid foundation for the unprecedented flourishing of Longshan culture in East-Haidai. Archaeological investigation suggests that this region formed the most complex four-level settlement hierarchies with a large mono-centre in the whole Haidai Region since the Early Longshan time (Liu 2005). However, this flourishing could only be sustained under favourable climatic conditions. From the Late Longshan phase, shortly after the 2.2 ka BC event, East-Haidai societies

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began to show a period of collapse. Rice is a drought-susceptible species and therefore very sensitive to climate stress (Fuller et al. 2011), and since less rainfall was available during the rice growing season and the rice growth period was shortened by earlier winter arrival after the climatic event, rice productivity declined significantly. This food shortage intensified the conflicts between population growth and food distribution. Archaeological investigations show that there was a large-scale population movement from east to west in the Haidai Region since the Late Longshan phase (Luan 2016). A possible interpretation is under the environmental and food stress, East-Haidai inhabitants simply migrated to more favourable areas, which in this case, would be West-Haidai. Moreover, loss of labour would have increased the stress on construction and maintenance of rice fields. In contrast, dry millet farming guaranteed more stable returns in the unfavourable West-Haidai environment and provided a strong subsistence base for social stability.

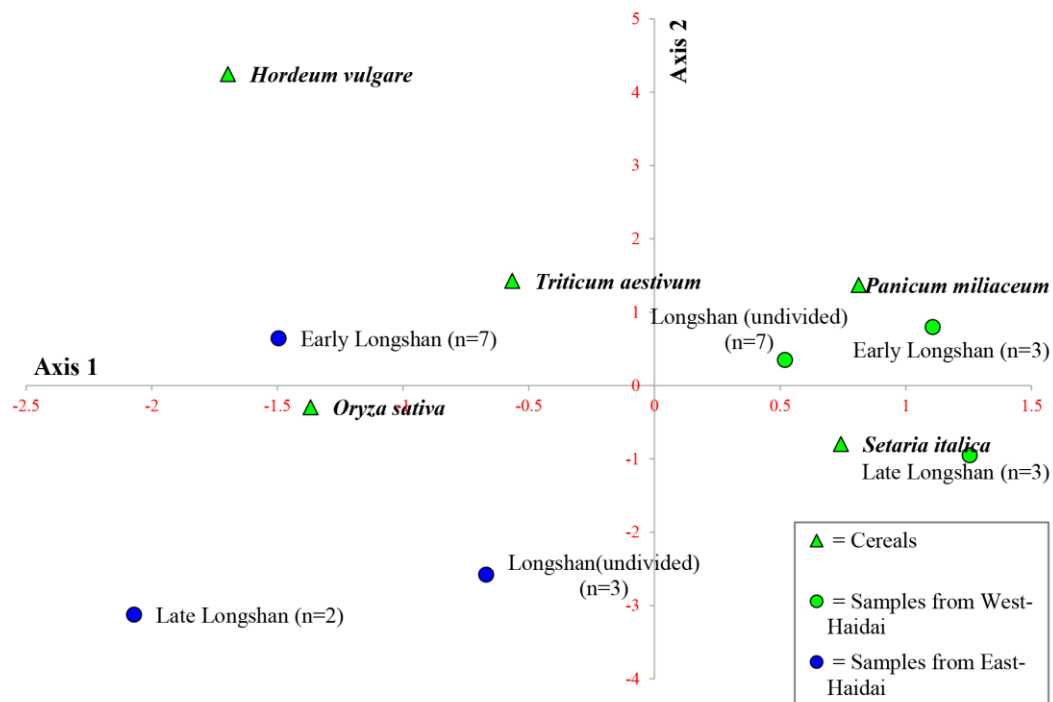


Figure 2. 4. 4 The CA plot of cereals and samples from different phases on 1. and 2. principal axes (wheat and barley from Yuchisi are excluded since they are more indicative of exchange network instead of local agriculture; based on RI values)

Furthermore, the dependency on wild oily resources in East-Haidai may also have accelerated social decline since wild resources are more easily threatened by

external climatic factors. The CA plot clearly shows that in contrast to West-Haidai inhabitants, who started to pay more attention to cultigens since the Late Longshan phase, those in East-Haidai most likely maintained their collection of wild oily seeds throughout the entire Longshan period (Fig. 2.4.5). This shifting focus on cultivars in West-Haidai perhaps guaranteed a far more stable food supply for societies when coping with the climate change. A similar pattern was observed in the cultivation of legumes/pulses. Compared to its wild counterpart, domesticated soybean was never a priority in East-Haidai but was quite important in West-Haidai since the Late Longshan phase (Fig. 2.4.5), which may indicate nutrition replacement. A good example is by the time agricultural practices arrived, perhaps due to the availability of protein from animal production (e.g. meat, milk, cheese), there was a loss of pulse cultivars in northern Europe (Kirleis 2004; Kirleis et al. 2012; Whitehouse and Kirleis 2014). Soybeans and seafood can be substituted for each other nutritionally since they both contain high protein levels (40% in soybeans) (Singh et al. 2007). Compared to inland West-Haidai, coastal sites in East-Haidai were close to readily accessible seafood and high seafood consumption was already observed prior to the Dawenkou period (4100-2400 cal. BCE) (Jin 2009b). For example, in the Beiqian site, seafood (probably shellfish and fish) made up the highest proportion of the human diet (44%) while terrestrial C₄ plants and mammals contributed only 34% and 22%, respectively (Wang et al. 2012). The protein demand, therefore, was probably met through seafood and wild soybeans consumption without further motivation for soybean domestication in East-Haidai. This pattern of food use had severe limitations as the availability of wild resources can be easily impacted by external factors.

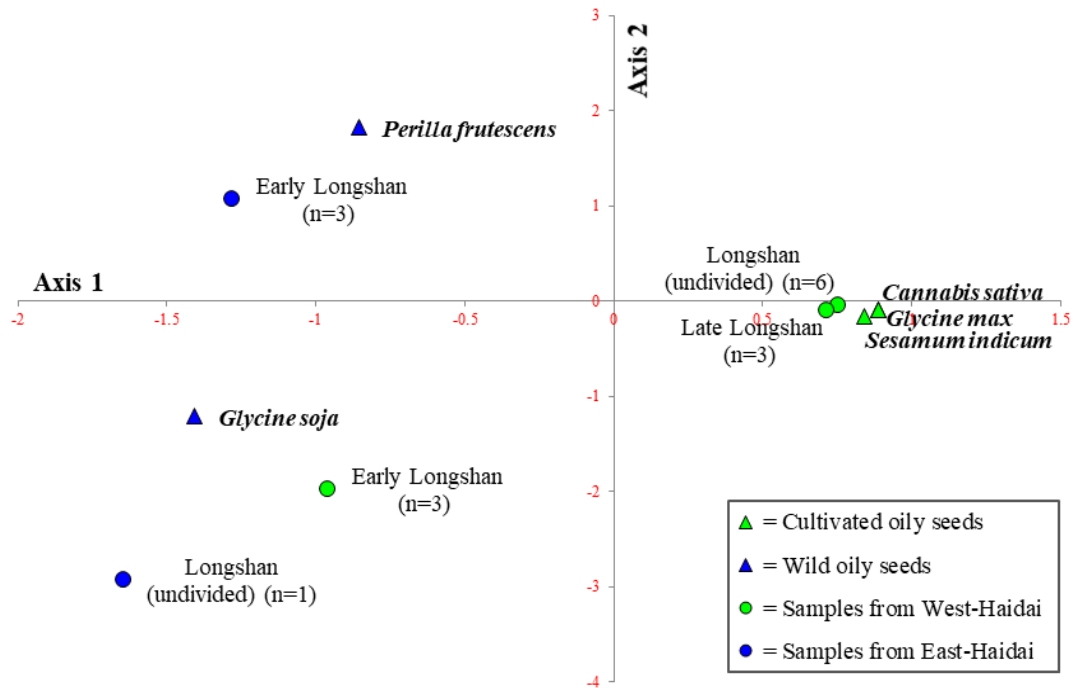


Figure 2. 4. 5 The CA plot of oily seeds and samples from different phases on 1. and 2. principal axes (based on RI values)

Regional differences in cultivation regime

Weeds can be used as indicator species for extensive or intensive cultivation regimes (Wasylikowa 1981; Rösch 1998; Bogaard 2002, 2004; Bogaard and Jones 2007; Kreuz and Schäfer 2011). In the Hambach forest in southwestern Germany, observations on extensive shifting cultivation plots indicate that the weed flora associated with recently cleared plots and managed with no or little tillage and weeding was likely to be dominated by perennial taxa, particularly woodland perennials. Conversely, dominance by annual taxa represented a more intensive regime and probably indicated long-established cultivation plots on regularly disturbed soils or with only short fallow periods (Bogaard 2002, 2004; Bogaard and Jones 2007). By utilizing weed life spans, soil requirements, and growth habitats, we were able to investigate sub-regional differences in cultivation regimes.

In East-Haidai, the dominance of annual weeds (generally > 90%) both in the Early and Late Longshan phase suggests that those cultivation plots were quite possibly established on regularly disturbed soils (Fig. 2.4.6a). The minimum time required for weed floras to develop was estimated to be at least ten years or more, given that the six-year-old Hambach forest experiment plots on shifting cultivation were still

dominated by perennials, despite increasingly intensive tillage measures (Bogaard 2002). Thus, rather than transient plots that were cultivated for a few years only, East-Haidai cultivation plots were maintained for an extended time as long-established plots. Accordingly, rather than adopting new agricultural strategies to fit changing environmental conditions, East-Haidai inhabitants maintained intensive rice farming for a long time. In fact, it wasn't until the subsequent Yueshi culture, that millet cultivation finally replaced rice farming (Chen 2012). This conclusion is further supported by the proportion of fertile-soil arable weeds (Fig. 2.4.6b). A basic principle in long-term utilization of farming fields is to maintain soil fertility, as once farmlands lose their fertility, they are more likely to experience regular fallow periods or to be abandoned. A common way to replenish "tired soil" is manuring, which simultaneously offers ideal conditions for those arable weeds that prefer fertile soils. Nowadays, arable weeds that commonly grow on nitrogen-rich soils include indicator species such as *Chenopodium album*, *Acalypha australis*, and *Hibiscus trionum* (Appendix Table-IV.4). They comprised 41.8% (758/1814) and 14.3% (9/63) of arable weeds in East-Haidai during the Early and Late Longshan phase, much higher than 29% (43/145) and 5.7% (51/899) in West-Haidai. Moreover, *Portulaca oleracea* (736) and *Amaranthaceae* (253) weeds were also recovered at the Wutai site but were removed from the database by Chen and his colleagues (2019). They concluded that sophisticated manuring was impossible for Longshan inhabitants, and therefore abundant finds of nutrient-loving weeds were impossible. However, our analysis supports a nutrient-rich soil condition in East-Haidai and also the presence of both taxa during the Longshan period. With those finds from the Wutai site, the proportion of indicator species in the Early Longshan phase would be even higher in East-Haidai. So, on the condition of maintaining soil fertility in the farmlands, long-term intensive cultivation in East-Haidai was very likely.

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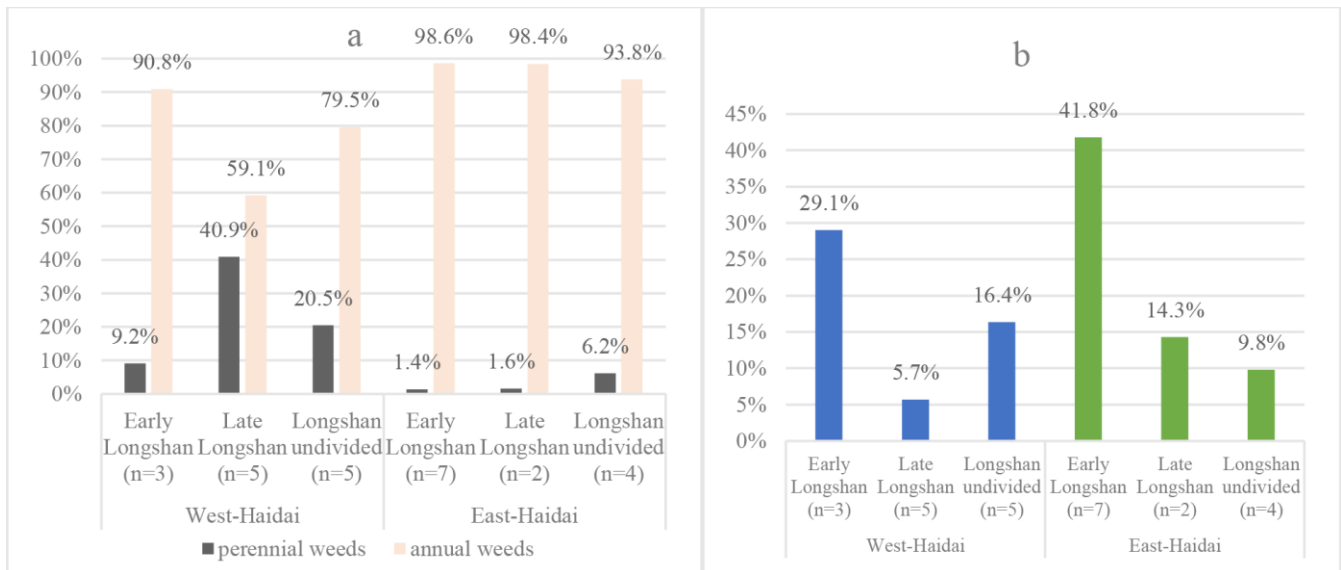


Figure 2. 4. 6 The proportions of weeds in different categories based on **a.** life span and **b.** soil nutrition in different periods in West- and East- Haidai (based on absolute counts)

Compared to annual weeds only in East-Haidai, a relatively higher percentage of perennials were noticed in West-Haidai and also with a remarkable increase from the Early (9.2%) to Late (40.9%) Longshan phase (Fig. 2.4.6a). As mentioned above, perennials are more likely to occur on recently cleared plots with little or no tillage, and so this might indicate more extensive cultivation in West-Haidai. Therefore, unlike East-Haidai inhabitants who were preoccupied with rice farming, those in West-Haidai may have changed to more extensive cropping practices to cope with alternative climatic conditions. As it has long been proven, extensive cultivation (e.g. slash-and-burn agriculture) usually causes deforestation and creates open lands in the vicinity of settlements (Behre 1981; Tarasov et al. 2006). For example, the deforestation in northeastern China during the Yangshao period (ca. 5000-3000 BCE) was triggered by an increase in slash-and-burn agriculture (Ren 2002; Ren and Beug 2002). Current biome reconstructions suggest a similar deduction of woody plants at many West-Haidai sites since the Late Longshan phase, such as at Yuchisi (Xu et al. 2011) and Yuhuicun (Zhao et al. 2013). However, although pollen records indicate increases in herbaceous plants, due to the low-resolution identification of cereals, it is difficult to find direct evidence of crop cultivation. Other factors such as paleoclimatic shifts are also unable to be excluded for this vegetation transformation. However, our research, on archaeobotanical remains can offer complementary evidence. Perennial weeds that originated from woodlands, hillside grasslands and mountainous areas increased

from 6.7% (2/31) in the Early Longshan to 30.1% (125/390) in the Late Longshan (Appendix Table-IV.5). More importantly, they were found together with crop remains in archaeological settlements which points to a clear connection between forest clearance and crop cultivation. Based on these indicators, it might be feasible to count agricultural expansion as one reason for the deforestation shortly after the climatic event.

Moreover, broomcorn millet and soybean might have been used as pioneer species for newly cultivated plots. Due to its shorter life cycle (60 plus days) and higher survival rates in poor soils (Weisskopf 2010), broomcorn millet was recorded as a pioneer species in extensive cultivation of new areas, such as during the initial development of agriculture in Northern China, extensive cultivation was observed with wide planting of broomcorn millet in the Early Yangshao phase (5000-4200 BCE) (Zhao 2017; Li et al. 2021). Notably, broomcorn millet cultivation was closely related to foxtail millet expansion according to historical documents (Qiminyaoshu, Shi and Tan 2015). Foxtail millet and broomcorn millet show clearly synchronized high proportions in West-Haidai (Fig. 2.4.4), and therefore might indicate that broomcorn millet has been used as a pioneer for the constant expansion of foxtail millet farming. Besides, legumes/pulses are nitrogen-fixing plants that have great potential in preventing nitrate loss which is one of the limiting nutrients for plant growth (Smartt 1990). Thus, growing legumes/pulses can help to replenish “tired” soils, either in crop rotation to reduce fallow times or to expand farmlands onto more marginal soils (Fuller 2020). In West-Haidai, soybean cultivation became prevalent since the Late Longshan (Fig. 2.4.5) but the remarkable decline in the proportion of fertile-soil species from 29.1% to 5.7% shows no attempt to reduce fallow time to recover soil fertility. This strengthening soybean cultivation, therefore, was more likely to improve marginal soils for new cultivation. Also, with the increase in dry and cool conditions, plenty of previously wet lowlands became available for cultivation (Jin and Wang 2011). These previous lowlands were intentionally exploited by West-Haidai residents as shown by the increasing number of settlements in former marshlands (Guo et al. 2013) and the abundant finds of marsh habitat plants (e.g. reed *Phragmites australis*, sedge plants) in archaeological sediments from Chengziya and Heze mound (Gudui) sites (Jin 2008; Jin and Wang 2011). These previously wet lowlands may also have

provided ideal rice growing conditions. Perennials that are commonly found in rice fields accounted for 51.8% (43/83) of arable weeds in West-Haidai and perennials from riverbanks and lakeshores (n=52) were found only in West-Haidai (Appendix Table-IV.4, IV.5). These results indicate that activities related to rice field expansion were most likely conducted in West-Haidai. In summary, West-Haidai residents might have consciously exploited previously uncultivated plots for rice and foxtail millet cultivation along with pioneer species soybean and broomcorn millet.

Conclusions

Agriculture in Neolithic societies was very susceptible to environmental changes. The 2.2 ka BC event exerted a crucial influence on the ecological system and further impacted local farming systems and social stabilities. However, agriculture was not the only factor driving social and cultural change; religion, politics, and trade also interacted to increase the resilience of human societies. But we can say with a surety that agriculture accelerated social change in the Haidai Region. In a broad scope of different social changes in the Haidai Region after the 2.2 ka BC event, different crop structures and cultivation regimes were adopted between East- and West-Haidai, and can therefore, be discussed together. Under environmental deterioration, millet dry farming displayed much stronger resilience than rice farming. Due to a dependency on intensive rice farming and the collection of wild oily seed resources, East-Haidai was more vulnerable to the rapid climate change. Moreover, using population migration to mitigate food stress aggravated its situation. On the contrary, West-Haidai societies were more resilient as they relied primarily on drought-resistant millet dry farming as well as constant exploitation of previous lowlands and uncultivated plots. This led to better food security, allowed farmers to withstand harvest failures and overcame the increased population migration pressure from East-Haidai.

As a pilot study, our research represents the first comprehensive analysis of Longshan crop and weed assemblages of the Haidai Region. Sub-regional variations of crop structures were highlighted and the analysis of weed remains provided new insights into the past management of cultivation plots. However, as another vital factor for ancient farmers while practicing agricultural activities, the

micro-environment around settlements was neglected in our current research. For instance, northwest Shandong sites were mostly located on piedmont plains while those in southwest Shandong were surrounded by lakes and marshes, however, we treated both as West-Haidai in our analysis. Furthermore, the identification of weed remains in some cases was not detailed enough and hindered our analysis. It is not our intention to judge the quality of previous data, but certainly to encourage researchers to provide more detailed information (e.g. sampling contexts, specific identification of weed remains) about their raw data. We acknowledge and also expect that subsequent recovery of archaeobotanical remains in this region will improve future findings.

Acknowledgements

This research is financially supported by the China National Natural Science Foundation (41771230) to GY Jin and the China Scholarship Council (CSC) for gaining a Ph.D. degree (Fund No.201706220058) to JP An. Research facilities are provided by the Young Academy of the Cluster of Excellence ROOTS (EXC 2150) at Kiel University. For the support with study methods used in this paper, JP An wants to thank Dr. Jutta Kneisel for leading her into the CA method, Dr. Helmut Kroll for inspirations on understanding weed ecology, Dr. Anna E. Reuter for useful introduction on the RI analysis, and Robert Hoffman for Oxcal software instruction. The authors are also grateful to PD Dr. Mara Weinelt, Anna M. Wierzgoń, and Songtao Chen for adding their inspiring insights to the discussion and constructive comments on some of the issues considered in this paper. Thanks to the primary language polishing by Roisin O'Droma and Andreas Mercke, and expert linguistic services by EditSprings. Finally, this paper has been greatly improved by anonymous peer reviewers.

Appendix IV

Table IV.1-IV.5

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3. Synthesis of the main results and future perspectives

3.1 An overview of the results

On the background of different social changes from the Late Neolithic to the Early Bronze Age in the Central Plain, West-Haidai, and East-Haidai, this research tries to reveal more information relating to the subsistence base of societies-the agricultural economy-through archaeobotanical remains. It proves that these three regions formed different agricultural patterns and developed different agricultural strategies to cope with climatic fluctuations, which in turn, has a profound influence on the social transformation.

Different choices in crop species among regions from the Late Neolithic to the Early Bronze Age

Based on the RI values of cereal crops in the Central Plain (section 2.3), East-Haidai and West-Haidai (section 2.4), regional comparative research, thus, can be conducted. In the results, the East-Haidai witnessed a shift from being dominated by rice farming in the Late Neolithic to being dominated by millet farming in the Early Bronze Age, the West-Haidai formed millet-dominated farming and the importance of millet kept increasing from the Late Neolithic to the Early Bronze Age, and the Central Plain developed a farming system with a stable combination of both dry and water-requiring crop species through the time.

In these different variations of farming systems, a diachronic difference can be noticed in the selection of crop species, among which the changes in rice and wheat are the most significant (Fig. 3.1.1). From the Late Neolithic to the Early Bronze Age, rice experienced a more or less stable production with a slight increase from the period of Xinzhai to Erlitou in the Central Plain while the West-Haidai and East-Haidai both showed a decline in the proportion, especially in the East-Haidai. More importantly, under the cool and dry climatic condition during the Erlitou/Yueshi period, rice had a higher proportion in the Central Plain than the other two regions (Fig. 3.1.1a). The investigation of the landscape evolution and rice planting in the Central Plain shows at least since the Erlitou period, rice can be planted not only in plain areas with fertile soil and ample water but also in the Loess Plateau valley which has a relatively tough ecological condition (Li and Zhang 2020). Natural conditions set a basic foundation for agriculture but the

3.Synthesis of the main results and future perspectives

adoption of agricultural techniques can shift the border of limits and potentials. According to the conclusions in this research, it is feasible to argue that the practice of irrigation in rice farming might have helped to overcome the ecological limitations. Rice, thus, managed to be cultivated under an unfavourable climatic condition in all kinds of landscapes, including the Loess Plateau valley.

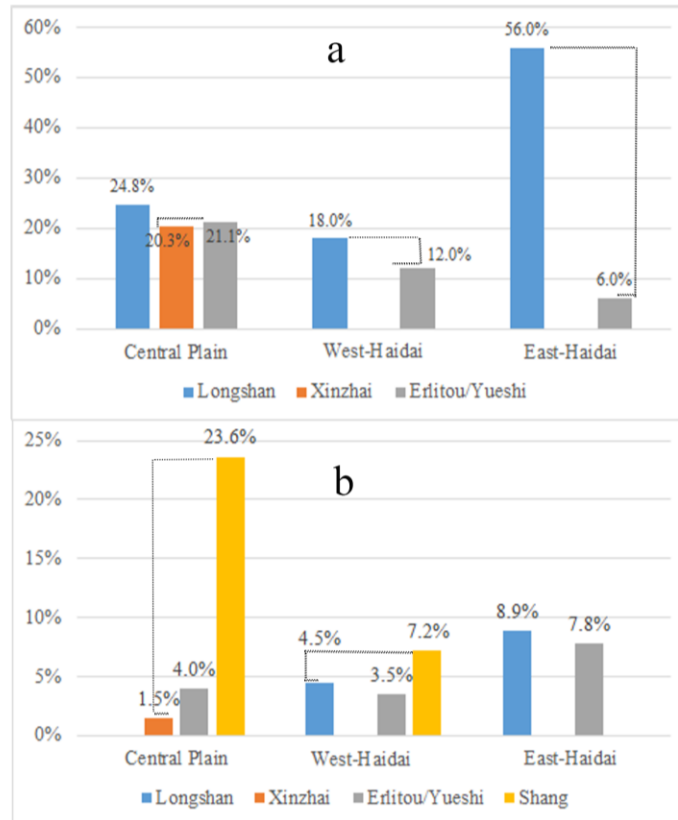


Figure 3. 1. 1 **a.** the proportion of rice from Longshan to Erlitou/Yueshi period in each region; **b.** the proportion of wheat from Longshan to Shang period in each region

Meanwhile, an increasing trend of wheat can be seen in both Central Plain and West-Haidai, but it is more remarkable in the Central Plain (Fig. 3.1.1b; Appendix Table-VI.1). Without considering the controversial wheat finds in the Longshan period in the Central Plain, for wheat, from the introduction to becoming a prominent food, it took only approximately 200 years through Erlitou to Shang in the Central Plain. This process cost far less time than in the Haidai Region where the establishment of wheat as a major crop took around 1400 years from Longshan to the Western Zhou (1046-771 cal. BCE), although wheat has been imported into the Haidai Region far earlier in the Longshan period (Zhao 2011; Chen 2016; An et al. 2016, 2019; Guo and Jin 2019; Zhong 2020). As proven by historical documents

3.Synthesis of the main results and future perspectives

and weeds ecological information (An et al., 2019), wheat in China is defined as a winter crop. Thus, its vegetation period shows huge conflicts with the local climate. North China exhibits clear seasonality with cold, dry winters and hot, wet summers under the East Asian monsoon system. The wet season lasts from May to September, with a remarkable maximum of precipitation in July-August (An et al. 2000; Zhao 2005). This climatic condition fits more for summer crops which rely on summer monsoonal rainfall but is unfavourable for winter crops since March to May is the water demanding phase of wheat (Fig. 3.1.2). Therefore, this large-scale cultivation of wheat in the Shang period is inevitably associated with the development of the irrigation system. This assumption can be further confirmed by historical records from the Shang period: large-scale irrigation facilities were constructed and managed in the Shang period (Zhou 2000; Chen 2007; Han 2012). From this point of view, this remarkable increase of wheat in the Central Plain during the Shang period can be attributed to the mastery of irrigation techniques.

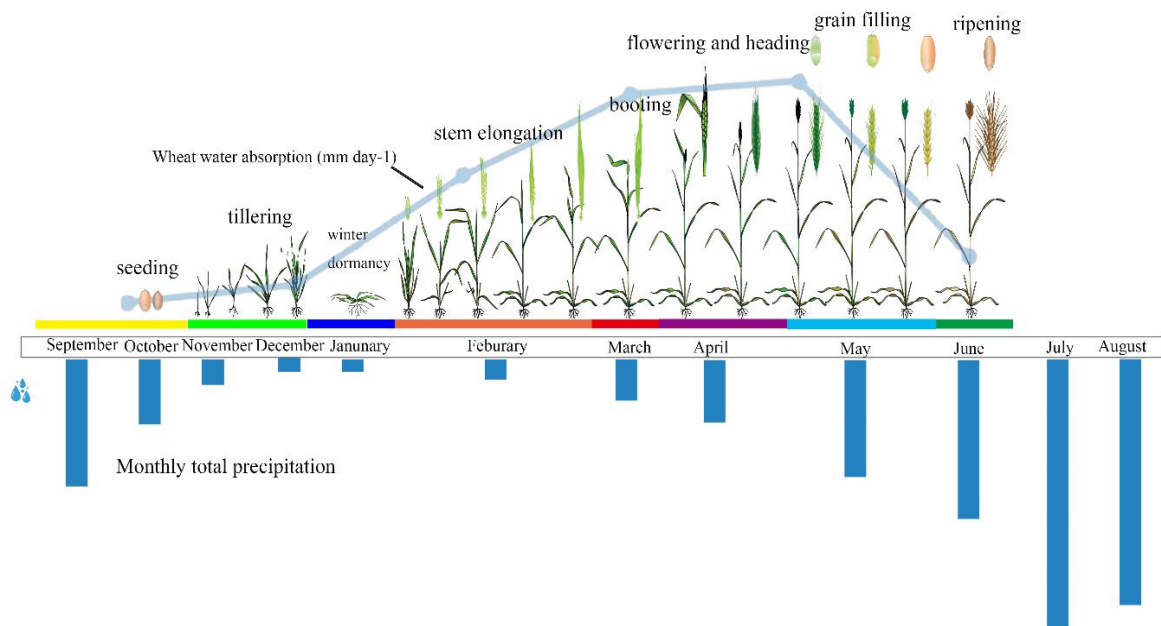


Figure 3. 1. 2 Information of wheat growth phases, water requirement, and precipitation in research areas (precipitation information from Jing et al 2016; wheat water absorption from Sarto et al. 2017; wheat growth stages from Lollato 2018; wheat harvesting and sowing time from Han 2012 and An et al. 2019)

Different cultivation settings in rice farming among regions from the Late Neolithic to the Early Bronze Age

The examination of different archaeobotanical proxies in weed floras as a means of inferring the ecological settings of rice has been used in the Xinzhai site (section 2.1), the West-Haidai and the East-Haidai (section 2.4). Here, with the same analysis of the Central Plain, regional differences can be recovered. In the investigation of the ecological setting of rice farming, analysis of phytolith remains such as the case study on the Xinzhai site is an effective method (Weisskopf et al. 2014; Weisskopf et al. 2015; An et al. under review), however, when phytolith remains are not available, weed finds in macro-botanical remains can be used as alternative indicators (Fuller and Qin 2009; Weisskopf et al. 2014).

A survey of weeds from modern various rice cultivation regimes in India suggested that rice typically grows in two contrasting micro-niches or eco-types: wet systems with standing water for much of the growth cycle, found in lowland irrigated paddies and terraced systems, and upland rainfed dry fields, including some shifting cultivation systems (Fuller et al. 2010; Weisskopf et al. 2014). Moreover, these different rice-growing habitats differ to varying degrees in weed taxa (Weisskopf 2011). While some species of genera such as *Echinochloa* sp., wild *Oryza* sp., and *Cyperus* sp. are ubiquitous to all systems, some taxa such as *Eleocharis* sp. are restricted to wetter and irrigated systems, and some species like *Chloris barbata* and *Brachiaria reptans* are unlikely to thrive in a wetter environment but on an upland dry condition (Thompson 1996; Weisskopf 2010; Weisskopf et al. 2014). In archaeological contexts, macro-botanical remains could pick out different floras of weeds, thus, can be used to distinguish different ecological environments. In the case studies of the Neolithic, Chalcolithic and Iron Age/Early Historic sites in Ganges and Orissa, India, by examining the weed floras associated with rice, Fuller and Qin (2009) have pointed out that the early exploitation and cultivation of annual wild rice and perennial wild rice occurred at differing ecological settings with one focused in perennial wetlands and the other seasonal fluctuating monsoonal wetlands, and further revealed a clear shift from dry rice to wet rice in the ecological niche of rice farming through time (Fuller and Qin 2009; Fuller et al. 2010). In the research areas of this project, different weed assemblages highlight the regional variations of wet and dry rice farming as well.

3.Synthesis of the main results and future perspectives

In the Central Plain, from the Longshan to the Erlitou period, weeds from dry rice fields have never been so important, instead, they were only minor components (less than 10%) in the weed assemblage. The East- and West-Haidai, on the opposite, both comprise more weeds from dry rice fields from Longshan to the Yueshi period (Table 3.1.1). This difference in the composition of weeds clearly indicates different ecological settings of rice farming among regions. The presence of some weeds related to wet rice in the West-Haidai may be down to the tendency for the utilization of previous lowlands for new rice fields rather than to the development of true wet-field, irrigated rice systems. Combined with the phytolith results in the Xinzhai site, it is possible to infer that an irrigated rice farming could be carefully traced back to the Longshan period and also inherited to the Erlitou period in the Central Plain. However, in the West-Haidai and the East-Haidai, no evidence shows a farming system with wet rice. As testified by other researchers (Fuller and Qin 2009; Qin 2012), during 4000-2000 BCE, the spread of rice out of the Yangtze River towards the Central Plain and the Haidai Region appears to have occurred only after rice was fully domesticated and labour-intensive paddy-field cultivation was finally established. It is, thus, no surprise if the intensive rice farming with the irrigation technique has been spread into the other regions in a package rather than rice *per se*. However, current results only highlight the possible absorption of wet rice and its associated irrigation system in the Central Plain but only rice itself in the Haidai Region.

Table 3. 1. 1 Counts and percentages of rice field weeds in different ecological categories

Family	Species	Wet rice*	Dry rice*	Long shan	Xin Zhai	Er litou	Long shan	Yue Shi	Long Shan	Yue Shi
Region				Central Plain			West-Haidai		East-Haidai	
Poaceae	<i>Poa annua</i>		Dry rice	3			7		2	14
	<i>Eleusine indica</i>		Dry rice	3	2	1	818	27	791	3
	<i>Echinochloa crus-galli</i>	Wet rice		118	265	90	52	8	8	
	<i>Echinochloa sp.</i>	Wet rice	Dry rice	77	12	142	581	54	55	
Portulacaceae	<i>Portulaca oleracea</i>		Dry rice	5	2		34			
Cyperaceae	<i>Cyperus iria</i>		Dry rice		52		61	20	46	1
	<i>Cyperus serotinus</i>	Wet rice			78			10	6	
	<i>Scirpus triqueter</i>	Wet rice		8						
	<i>Carex diandra</i>	Wet rice		7	3					
	<i>Schoenoplectus juncooides</i>	Wet rice		44	188	13	4			
	<i>Pycreus sanguinolentus</i>	Wet rice			98					
	<i>Fimbristylis dichotoma</i>	Wet rice		2			42	1		
	<i>Polygonum lapathifolium</i>		Dry rice	2			17	5		
Proportion		Wet rice		67%	90%	42%	7%	11%	1%	0%
			Dry rice	5%	8%	0.4%	57%	46%	93%	100%
			Wet/dry rice	29%	2%	58%	36%	43%	6%	0%

*Wet and dry rice field weeds follow Fuller and Qin 2009, Table 2, Weisskopf 2011, Table 4.1, and Weisskopf et al. 2014, Fig. 2. Archaeobotanical data compiled in this analysis can be found in Table 1.5.1.

3.Synthesis of the main results and future perspectives

About this, social (e.g. ruler preference, population density), cultural (e.g. cultural traditions, individualism), and ecological factors (e.g. precipitation, micro-environments) could have all played important roles. Here, different planting landforms can be highlighted as one of the potential ecological factors through the evidence of arable weeds. According to the weed assemblage derived from the modern upland and lowland rice fields in Indonesia (Soerjani et al. 1987), weed floras associated with rice from archaeological contexts can be carefully grouped and attributed to different planting landforms (Table 3.1.2). Weeds that come from upland landforms are more visible in both West-Haidai and East-Haidai than in the Central Plain, on the contrary, those weeds that are commonly found in lowlands are more representative in the Central Plain (Table 3.1.2). Upland terraced systems represent an extreme form of landscape modification that allows the extension of irrigated rice to higher elevations (Soerjani et al. 1987; Weisskopf et al. 2014). Thus, the cultivation of wet rice on uplands could have led to a more challenging circumstance for ancient inhabitants in the Haidai Region. Even in the Central Plain where irrigation was highly likely to be practiced since the Longshan period, it is at least until the Erlitou period, wet rice finally can be practiced in some extreme forms of landscapes (Li and Zhang 2020). Thus, when it comes to the adoption of irrigation systems, different planting landforms should be considered.

Table 3. 1. 2 Counts and percentages of rice field weeds in different cultivation settings

Species	Cultivation settings*	Longshan	Xinzhai	Erlitou	Longshan	Yueshi	Longshan	Yueshi
Region		Central Plain			West-Haidai		East-Haidai	
<i>Eleusine indica</i>	Upland	3	2	1	818	27	791	3
<i>Portulaca oleracea</i>	Upland	5	2		34			
<i>Polygonum lapathifolium</i>	Upland	2			17	5		
<i>Poa annua</i>	Upland	3			7		2	14
<i>Echinochloa</i> sp.	All type of rice fields	77	12	142	581	54	55	
<i>Cyperus iria</i>	All type of rice fields		52		61	20	46	1
<i>Scirpus triqueteter</i>	Lowland irrigated, tidal rice field	8						8
<i>Echinochloa crus-galli</i>	Lowland irrigated	118	265	90	52	8	8	541
<i>Schoenoplectus juncooides</i>	Lowland irrigated/tidal	44	188	13	4			249
<i>Pycnus sanguinolentus</i>	Lowland irrigated/tidal/rainfed		98					98
<i>Carex diandra</i>	/	7	3					10
<i>Fimbristylis dichotoma</i>	/	2			42	1		45
<i>Cyperus serotinus</i>	/		78			10	6	94
Proportion	Upland	5%	1%	0.4%	54%	26%	87%	94%
	All type	29%	9%	57.7%	40%	59%	11%	6%
	Lowland irrigated/tidal/rainfed	63%	79%	41.9%	3%	6%	1%	
	/	3%	12%		3%	9%	1%	

*The information of rice cultivation setting from Soerjani et al. 1987; Archaeobotanical data compiled in this analysis can be found in Table 1.5.1.

Different roles of agriculture among regions from the Late Neolithic to the Early Bronze Age

With the information of different crop choices, different cultivation settings of rice, and also further conclusions about cultivation regimes (intensification or extensification), population migration and so on, different social transformations in these three regions can be discussed together with climate changes from an agricultural perspective.

In the Central Plain, irrigation technique has played an important role in the stability of agricultural production as well as social development (Fig. 3.1.3). Advanced irrigation technique ensured the successful planting of water-demanding crop species in unsuitable climatic conditions such as the cultivation of rice in cool and dry Erlitou period and the widespread of the new irrigation-required species wheat in the Shang period. Furthermore, because of the intensive inputs of labour and time in the creation and maintenance of irrigation facilities and paddy fields, irrigation-required species might have been part of the prestige goods and have been exchanged among elite individuals. It is reflected as material wealth representing by labour-intensive irrigated rice was closely related and concentrated in small groups of elites in the Xinzhai and Erlitou periods. By more or less exclusively producing or consuming prestige food, the status of elites or central settlements, in turn, could have been guaranteed.

Besides, central settlements invested a large amount of labour in the irrigation system, thus, less labour might have been available for the cultivation of other crops which might have led to the favour of those crop species with shorter growing periods and less investment of labour such as broomcorn millet during the Xinzhai and Erlitou periods (see section 2.3). Besides, the less available labour also impacted the labour distribution in the crop processing which directly caused a labour shortage during the harvesting season and eventually led to a preference for crop processing on small household units after the storage. This emphasis on small social units shows huge differences from the egalitarian communal- society in the Middle Neolithic Yangshao period. It means the change in agricultural activities has prolonged influences on the organization of the whole society. Therefore, the Central Plain, according to the archaeobotanical investigation in this research, appears to have witnessed a stable and continuous social complexity through the

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Late Neolithic and Early Bronze Age.

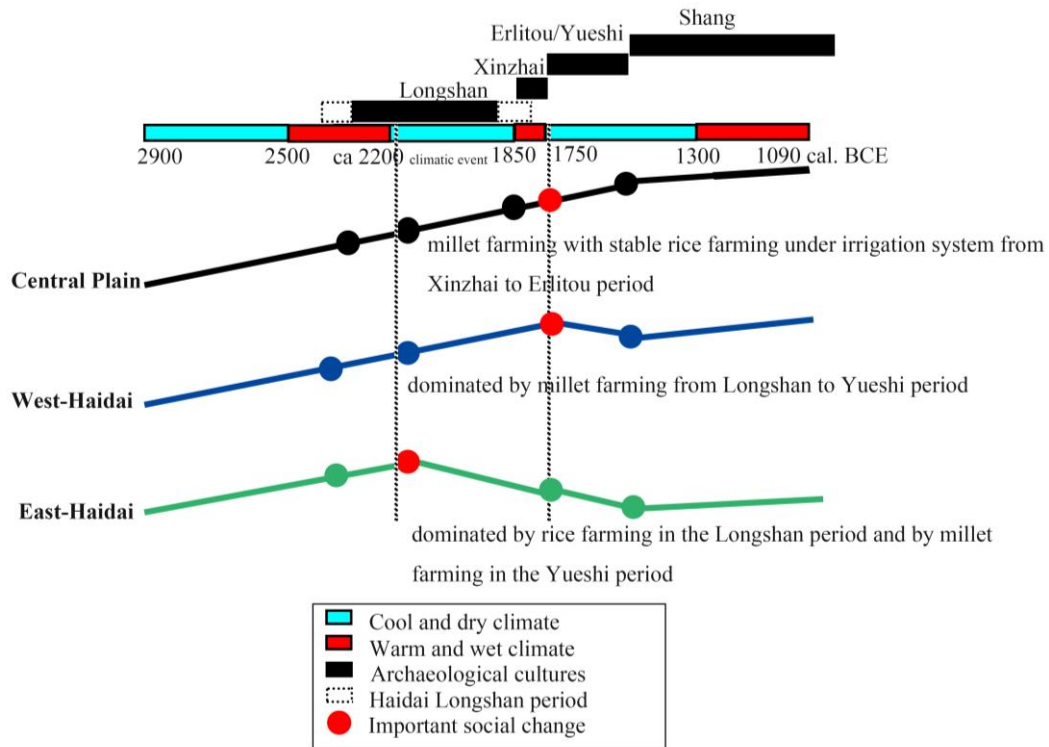


Figure 3. 1. 3 Combination of social changes, climatic conditions, and agricultural information (drawn by JP An)

The West-Haidai and East-Haidai Region, in the contrast, have paid less effort in the development of the irrigation system. Their rice farming was highly dependent on natural water bodies and natural precipitation. Rather than agricultural techniques, the different farming systems and different cultivation regimes in the West- and East-Haidai have been considered as main reasons underlying the social changes (Fig. 3.1.3). The millet farming dominant West-Haidai shows longer social resilience than the rice farming dominant East-Haidai. It has been interpreted from the different characteristics of the millet farming system and rice farming system. Wet rice farming which depends on natural water resources was more easily influenced by external factors such as the unstable climatic condition, thus, more fragile than millet dry farming. Moreover, even though under the cooler and drier climate after the 2.2 ka BC event, rice showed a trend of decline in the production, East-Haidai inhabitants kept the rice farming system through the whole Longshan period rather than adopting new agricultural strategies to fit into changing environmental conditions. Instead, to solve the conflict between population and food distribution caused by the less productive rice farming, migration with a large-

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scale population from the east-Haidai to the west-Haidai occurred since 2100/2000 BCE. This loss of labour, in turn, increased the stress on the construction and maintenance of rice paddy fields. In the contrast, West-Haidai records a set of adaptations in agriculture to the climate change. The inhabitants may have attempted to change cropping practices by the extensification of farming areas. They practiced extensive cultivation to exploiting uncultivated fields into new cultivation plots of rice and millet at differing environmental-settings. This kind of agricultural extensification with millet dry-farming serving as a subsistence base shows much more advantages while facing climatic fluctuations, thus, have supported the social stability until the Yueshi period. However, in West-Haidai and East-Haidai, both of their agricultures have focused on the shift to more drought-intolerant crop species and eventually formed a mono-crop millet farming system in the Early Bronze Age Yueshi period, this agricultural response to the climate change is the biggest difference from the multi-crop farming system with advanced irrigation techniques in the Central Plain.

To summary, current results support the idea that agriculture has played an important role in the social transformation in ancient China. It is feasible to highlight the contribution of agricultural techniques especially the irrigation system in the development of social hierarchy and social complexity in the Central Plain. Compared with the West-Haidai and East-Haidai of which dealing with the environmental deterioration by shifting to drought-intolerant crop species, the agricultural system in the Central Plain showed great advantages and provided more possibilities to develop a highly complex society.

3.2 Future prospects

As summarized in section 3.1, this research has obtained a bunch of new information about ancient agriculture underlying the emergence of the earliest states in China, but as a preliminary framework, more studies are definitely required to rich current conclusions. First, the investigation of crop water regimes in Haidai Region is limited by lacking first-hand samples from one individual site. It can be foreseen that such a case study will help us to gain new insights into this region. Moreover, from the date of publication until today, new archaeobotanical data from research areas (Longshan Wangqidang site; Erlitou Erlitou site; Shang

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Xiaoshuangqiao, Liujiashuanbei, Dasikong, Xinanzhuang) (Wang et al. 2018; Zhong et al. 2018, 2019; Zhao and Liu 2019) have been continuously published by peer researchers. With more data available, it is possible that current conclusions can be further confirmed or revised. Also, a labour-intensive irrigation system is only part of agricultural intensification, other agricultural techniques such as manuring are only briefly discussed through weed ecological information in the current research. More direct and stronger evidence can be obtained by many other methods. For instance, recent attempts at detecting manuring (Bogaard et al. 2007, 2013) and water regimes of crops (Ferrio et al. 2005; Wallace et al. 2013) by the analysis of stable isotope ($\delta^{15}\text{N}$, $\delta^{13}\text{C}$) ratios in cereal grains have so far been successful. From this point of view, further analyses with various methods can be applied to improve current knowledge.

Lastly, this Ph.D. research has only solved a small corner of the whole puzzle of ancient agriculture but reveals more opportunities in using archaeobotanical remains in the discussion of certain social topics. Examples include a further investigation on the impact of different water conditions on archaeobotanical assemblages in millet *Setaria italica/Panicum miliaceum* fields, a systematic ethnographic-observation on the processing of soybean *Glycine max* with a practical standard to distinguish each processing step, and a pilot research of the initial introduction time of new crop species with weed ecological information. In the research of Central Plain, whether or not wheat *Triticum aestivum* has been imported to this region during the late 3rd millennium BCE remains a key point for the development of a multi-cropping system. It can be tentatively detected through a chronological comparison of weed floras tracing back to the 4th millennium BCE or even earlier. By compiling a list of common weeds recovered from archaeological sites, together with ecological information pertinent to when and how they first spread into arable fields, it is possible to detect the exchange of crop species between regions. Comparable cases studies are the identification of weed floras into ‘indigenous species’ and ‘introduced species’ covering a long time scale in the British Isles (Stevens and Fuller 2018) and the classification of weed finds into ‘apophytes’ and ‘anthropochres’ of the early Neolithic Bandkeramik culture in Central Europe (Kreuz and Schäfer 2011). Adverse growth cycles of winter crops (exotic wheat) and summer crops (local millet, soybean) even bring advantages in

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such research in China. With different ecological characters and reproductive strategies, it should be easy to identify the newly introduced weed species (winter-annuals) from native species of autumn seedling (summer-annuals). A systematic analysis of weed finds that covers the whole Neolithic in the Central Plain therefore can show great potential regarding this topic. Predictably, more pieces in the whole puzzle can be solved through archaeobotanical investigations and this better understanding of ancient agriculture can further add new insights into the full picture of ancient societies.

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5. Zusammenfassung

Die langfristigen Reaktionen und Anpassungen früherer Gesellschaften und ihrer Landwirtschaft an klimatische Veränderungen ist Gegenstand globaler Debatten. Das Hauptziel dieser Forschungsarbeit ist es, die Rolle der Landwirtschaft bei sozialen Transformationen innerhalb eines relativ weiten Zeitrahmens vom Spätneolithikum bis zur frühen Bronzezeit in der Region des chinesischen Central Plain (Spätneolithikum: Longshan-Zeit 2300-1900 v. Chr., Xinzhai-Zeit 1850-1750 v. Chr.; frühe Bronzezeit: Erlitou-Zeit 1750-1550 cal v. Chr., Shang-Zeit 1550-1046 v. Chr.) und in der Region Haidai (Spätneolithikum: Longshan-Zeit 2400-1800 v. Chr.; frühe Bronzezeit: Yueshi-Zeit 1800-1450 cal v. Chr., Shang-Zeit 1550-1046 v. Chr.) zu untersuchen.

Der Hintergrund dieses Themas ist, dass es in dieser Zeit in den Forschungsregionen sowohl bedeutende kulturelle Entwicklungen, als auch schwerwiegende Änderungen des Klimas gab. Kulturell folgte die Chieftdom-ähnliche spätneolithische Longshan-Kultur dem Trend des Zusammenbruchs um 2100/2000 v. Chr. in der Region Ost-Haidai und um 1800 v. Chr. in der Region West-Haidai. Die Longshan-Kultur in der Region des Central Plain überstand jedoch den Zusammenbruch und trat um 1750 v. Chr. in eine neue Ära der staatlichen Organisations-Ebene ein. Paläoklimatisch war der Forschungszeitraum durch mehrere klimatische Schwankungen charakterisiert, insbesondere durch das anhaltende Abkühlungs- und Dürreereignis um 2200 v. Chr. Der bemerkenswerte Rückgang von Niederschlag und Temperatur nach dem Klimaereignis von 2200 v. Chr. wirkte sich eindeutig auf die natürlichen Bedingungen für die Landwirtschaft aus. Dies hatte auch direkte Auswirkungen auf die Fähigkeit einer Gesellschaft stabile und vorhersehbare Getreideerträge zu erzielen. Diese Umstände waren offenbar limitierende Faktoren für die soziale Entwicklung in diesen Forschungsregionen. Es gibt jedoch keine einfache Korrelation zwischen günstigen klimatischen Bedingungen und der Entwicklung sozialer Komplexität oder umgekehrt. Es gibt zahlreiche Fälle, in denen sich komplexe Gesellschaften an Orten entwickelten, an denen Umweltfaktoren nicht optimal zu sein schienen, wie beispielsweise in dieser Forschungsarbeit gezeigt, die Entstehung des ersten Staates in der Region des Central Plain. Ein solcher Fall zeigt, dass es von großem Wert ist,

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das Verhältnis von sozialen Transformationen und Klimaveränderungen neu zu betrachten. In dieser Doktorarbeit wurde die Landwirtschaft ausgewählt, um soziale Entwicklungen von spätneolithischen Gesellschaften neu zu bewerten, da sie an der Ausgestaltung der Gesellschaft durch Anpassung und Überwindung von Umwelt- und Klimabeschränkungen und -potentialen maßgeblich beteiligt war.

Wir wissen jedoch überraschend wenig über die Rolle der Landwirtschaft, die diesen sozialen Veränderungen zugrunde lag. Obwohl China für seine zahlreichen historischen Dokumente bekannt ist, entspringt das früheste Dokument in Form von Inschriften auf Knochen oder Schildkrötenpanzern der Shang-Zeit (1550-1046 cal v. Chr.). Daher begann die zuverlässige Aufzeichnung des frühesten Chinas in der Shang-Zeit, während für das Spätneolithikum (ca. 2500-1800 v. Chr.) und die Erlitou-Periode (1750-1550 cal v. Chr.) bisher keine Dokumente bekannt sind. In dieser Hinsicht können Pflanzenreste, die über archäobotanische Arbeiten erschlossen werden, direkte Hinweise auf die antike Landwirtschaft liefern. Frühere archäobotanische Untersuchungen deuten darauf hin, dass die Region des Central Plain in der Frühbronzezeit ein einzigartiges Mischkultur-System mit Reis (*Oryza sativa*), Sojabohnen (*Glycine max*), Fuchsschwanzhirse (*Setaria italica*), Rispenhirse (*Panicum miliaceum*) und dem neu eingeführten Saatweizen (*Triticum aestivum*) entwickelt hat. Diese Art der Pflanzenkombination zeigte sich als deutlich vorteilhafter gegenüber Monokultur-Systemen, wie dem Hirse-Trockenanbau in der Haidai Region und wurde daher als einer der Hauptgründe für den kulturellen Wohlstand in der Region des Central Plain angesehen. In dieser Hypothese wurde jedoch der Umweltfaktor bisher nicht mit einbezogen. In einer Zeit ungünstiger Umweltbedingungen mit einem kalten und trockenen Klima ist eine Verlagerung zu Dürre toleranteren Pflanzenarten zu erwarten. Ein Beispiel hierfür ist die überwiegende Präferenz des Hirseanbaus während der Yueshi-Zeit in den Regionen Ost-Haidai und West-Haidai. Nichtsdestotrotz blieb die Produktion von Nassreis in der Region des Central Plain während der Erlitou-Zeit stabil.

Natürliche Bedingungen bilden das Fundament der Landwirtschaft, jedoch kann die Einführung neuer landwirtschaftlicher Strategien und Techniken die Grenzen der Möglichkeiten verschieben. Dies führt zur Überwindung von Limitationen und der Eröffnung neuer Potentiale. Die landwirtschaftliche Situation hinter dem Aufstieg und dem Niedergang neolithischer Kulturen in China steht derzeit noch zur Diskussion.

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Darüber hinaus wurde der soziale Zusammenbruch während der Yueshi-Zeit, der simultan sowohl in der Region West-Haidai, als auch in der Ost-Haidai Region stattfand noch nie separat und differenziert betrachtet, sondern immer nur als ein einziges zusammenhängendes Phänomen beschrieben. Auf Grundlage dieser ursprünglich undifferenzierten Betrachtung basierte die Theorie, dass der soziale Wandel auf den Niedergang des Reisanbaus in Longshan zurückzuführen ist. Der soziale Zusammenbruch ereignete sich jedoch früher in Ost-Haidai als in West-Haidai. Noch wichtiger ist, dass diese beiden Regionen während der Longshan-Zeit unterschiedliche landwirtschaftliche Systeme bildeten.

Auf Grundlage dieser Bedingungen zielt dieses Forschungsprojekt darauf ab, die Landwirtschaft differenziert in der Region des Central Plain und in der Region Haidai über das Spätneolithikum bis zur Frühbronzezeit aufzudecken. Hierbei liegt ein besonderer Schwerpunkt auf der sozialen Komplexität in der Region des Central Plain. Diese Arbeit soll dazu beitragen, ein neues Verständnis dafür zu gewinnen, warum der früheste Staat ursprünglich nur aus einer begrenzten Region in der Region des Central Plain hervorgegangen ist, sich jedoch nicht mehrere Staaten gleichzeitig über viele Regionen wie der Haidai Region entwickelten. Um die damalige Landwirtschaft zu untersuchen, wurden in dieser Doktorarbeit eine Zusammenstellung früherer archäobotanischer Daten und eine Analyse neuer archäobotanischer Proben der Stätte in Xinzhai durchgeführt. Anstatt einen umfassenden Überblick über die gesamte Region des Central Plain zu geben, konzentriert sich diese Studie zunächst auf eine bestimmte Fallstudie - der Stätte in Xinzhai. Hierbei liegt der Fokus auf der Xinzhai-Zeit (1850-1750 v. Chr.), die kurz nach dem Klimaereignis von 2,2 ka v. Chr. und vor der Entstehung des ersten Staates in der Region des Central Plain liegt. Während der Xinzhai-Zeit war diese Stätte die größte ummauerte Siedlung ihrer Zeit und fungierte auch als eines der regionalen Zentren der Region des Central Plain. Deshalb ist dieser Ort für das Thema dieser Forschung von besonderer Bedeutung und es bietet sich eine gute Gelegenheit, neue Einblicke in die Landwirtschaft in zentralen Siedlungen zu gewinnen. Die Ergebnisse werden in Form einer kumulativen Dissertation präsentiert, die aus vier Arbeiten besteht. Diese Artikel werden im folgenden Teil einzeln vorgestellt.

Zeitschriftenbeitrag 1 - Untersuchung des Bewässerungssystems in der Xinzhai-

Zeit

In dem ersten dieser vier Beiträge *“Identifizierung des Bewässerungssystems und seiner Assoziation mit Erntehierarchien in der Xinzhai-Zeit (1850-1750 v. Chr.): Eine Fallstudie von der Stätte Xinzhai“* wurde das Wassermanagement in verschiedenen Getreidefeldern durch die Analyse von 59 Phytolithproben untersucht. Zur Unterscheidung von Bewässerungssystemen wurden Korrespondenzanalysen verschiedener ökologischer Phytolithkategorien an einzelnen Proben und Verhältnisanalysen von Sensitiven zu Festen (*S:F Verhältnis*) Morphotypen durchgeführt. Beide Methoden zeigen eine klare Trennung zwischen den Proben: die Phytolithkategorien, die auf trockene Bedingungen hinweisen, sind in den Hirse-dominanten Proben häufiger vorhanden, während die Nassindikatoren, häufiger in den Reis-dominanten Proben vorkommen. Darüber hinaus weisen die Reis-dominanten Proben, höhere *S:F* Verhältnisse auf, als die Hirse-dominanten Proben. Nach dem Vergleich mit modernen indischen und früheren chinesischen archäologischen Proben scheinen Reis und Hirse in unterschiedlichen ökologischen Umgebungen angebaut zu werden. Reis wurde während der Vegetationsperiode unter einem Bewässerungssystem mit einer intensiven Wasserversorgung angebaut. Auch die feuchten Reisunkräuter sind in dem Gemenge der Unkraut-Funde dieses Standortes häufiger anzutreffen, als die typischen Reisunkräuter im Trockenanbau-Regenfeldbau. Dies bestätigt auch ein Anbauverfahren für Reis unter Bewässerungs- oder Feuchtgebietsbedingungen. Im Gegensatz dazu wurde Hirse in Regenfeldbau angebaut und erhielt im Sommer unter dem Sommer-Monsunsystem ihre maximale Wasserversorgung.

Dieses Ergebnis wird weiter verwendet, um die Reiskonzentration in zentralen Siedlungen zu interpretieren. In der Xinzhai-Zeit wurde inzwischen ein räumliches Verteilungsmuster von Reis entdeckt. Ein relativ höheres Vorkommen von Reis in der zentralen Siedlung und im Wohngebiet der Eliten oder Geistlichen an der Stätte Xinzhai ist beim Vergleich von Phytolithen und makrobotanischen Überresten sehr gut zu erkennen. In Kombination mit den Ergebnissen stabiler Isotopenanalysen von menschlichen und tierischen Proben scheint Reis von Eliten oder Geistlichen in zentralen Siedlungen genutzt worden zu sein, während Hirse in großem Umfang als gemeinsames Lebensmittel für normale Bewohner oder als Futtermittel für Haustiere gelagert wurde. Basierend auf diesen Schlussfolgerungen kann die

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soziale Bedeutung verschiedener Bewässerungssysteme in der Xinzhai-Zeit zusammen mit den an sozialen Hierarchien geknüpften Pflanzenarten bewertet werden. Aufgrund des zusätzlichen Arbeits- und Zeitaufwandes bei der Bewässerung, ist Reis zu einem Prestige-Lebensmittel geworden und eng mit dem Vorhandensein von Eliten oder Geistlichen und regionalen Zentren verbunden. Hirse währenddessen wurde als allgemeines Lebens- und Futtermittel, sowie als Sicherheitsnahrungsmittel für ärmere Bevölkerungsschichten und ihre Nutztiere eingesetzt, weil sich der Regenfeldbau wesentlich weniger arbeits- und zeitintensiv gestaltete. In einfachen Gesellschaften liegt der Schwerpunkt auf der Menge der Lebensmittel, während in stark hierarchischen Gesellschaften der Schwerpunkt mehr auf Exoten und einer differenzierten Küche (niedrige und hohe Küche) liegt. Daher wird sich in der Xinzhai-Zeit wahrscheinlich eine sehr hierarchische Gesellschaft gebildet haben, da die Eliten einen Schwerpunkt auf das Luxusprodukt Reis legten.

Zeitschriftenbeitrag 2 - Modell der Pflanzenverarbeitung in der Xinzhai-Zeit

Das Bewässerungssystem hatte nicht nur Auswirkungen auf die Hierarchie der Kulturen, sondern kann auch große Auswirkungen auf die Arbeits- und Sozialorganisation haben. Der arbeitsintensive Anbau von bewässertem Reis erfordert einen hohen Arbeitsaufwand während des gesamten Produktionszyklus, von der Vorbereitung der Felder, über die Aussaat, bis hin zum Umsetzen von Jungpflanzen. Dieser Arbeitsaufwand muss in der Regel mit den anderen landwirtschaftlichen Tätigkeiten in Einklang gebracht werden, da die Umsetzung einer Nassreiskomponente erhebliche Auswirkungen auf alle anderen Aspekte des landwirtschaftlichen Zyklus hat. Dieser Faktor verlangt, dass eine Siedlung eines angemessenen sozialen Systems bedarf, um massive Arbeitskräfte organisieren, Kooperationsprojekte durchführen und einen intensiven Reisanbau mit einem Bewässerungssystem betreiben zu können. In nicht mechanisierten frühen Gesellschaften sind die Landwirtschaft und die damit verbundenen Aktivitäten wichtige Bereiche, in denen Bedarf an gegenseitiger Unterstützung zwischen menschlichen Gruppen (z. B. Haushalten) bestand. Dies schuf eine stetig wiederkehrende Situation aus der sich komplexe arbeitsorganisatorische und soziale Beziehungen innerhalb dieser Gesellschaften entwickelten.

Durch die Analyse der Lagerungsform von Kulturpflanzen und des

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Pflanzenverarbeitungsmodells ist es somit möglich, die Form der Arbeit und der sozialen Organisation in einer Siedlung aufzudecken. In der zweiten Veröffentlichung "*Verständnis der Erntemodelle und ihrer sozialen Bedeutung in der Xinzhai-Zeit (1850-1750 v. Chr.): Eine Fallstudie von der Stätte Xinzhai*" wurden 220 makrobotanische Proben und 59 Phytolithproben verwendet, um das Pflanzenverarbeitungsmodell an der Stätte Xinzhai und ihre weiteren Indikationen in den Arbeits- und Sozialorganisationen zu untersuchen. Die ethnografische Beobachtung der Verarbeitung von kleinschaliger Hirse in Indien und China, der Reisverarbeitung in Thailand und China, sowie der Sojabohnenverarbeitung in Indien wurde verglichen und bei der Differenzierung der Verarbeitungsschritte für Nutzpflanzen berücksichtigt. Die Ergebnisse zeigen, dass keine der Pflanzen in dieser Siedlung vollständig verarbeitet wurde: die Anzahl der reifen/entspelzten Hirsekörner gegenüber den unreifen/ungeschälten Hirsekörnern, die hohe Anzahl großer und schwergewichtiger Unkräuter in den Unkrautfunden, und die höhere Anzahl der Schalenfunde gegenüber den Blättern/Stängeln-Funden in der Phytolithenanalyse deuten darauf hin, dass Hirse möglicherweise in Ährchenform gelagert wurde. Ebenso deuten der hohe Prozentsatz an Reisspreu und unreifen Reiskörnern in vielen Proben, die große Menge an kleinen Ackerunkräutern und das Vorhandensein eines hohen Anteils an Phytolith-Morphotypen aus Blättern und Stängeln darauf hin, dass Reis wahrscheinlich als ganze Pflanzen gelagert wurde. Eine Korngrößenanalyse mit einem hohen Prozentsatz an kleinen Sojabohnen zeigt, dass Sojabohnen am wahrscheinlichsten vor dem Grobsieben gelagert wurden.

Für die Einwohner von Xinzhai waren der späte Sommer und Herbst (von August bis Oktober) mit der Erntezeit der Sommerkulturen (Fuchsschwanzhirse, Rispenhirse, Reis und Sojabohnen) die geschäftigsten Perioden für landwirtschaftliche Tätigkeiten. Daher könnte es zu dieser Zeit zu einem Arbeitskräftemangel für die Ernte und weitere Verarbeitungsschritte gekommen sein. Diese Art von Verarbeitungsmodell unterscheidet sich erheblich von den anderen Stätten in der Xinzhai-Zeit. Beispielsweise in der Stätte Dongzhao wurde Reis als entspelztes Getreide gelagert, nachdem der größte Teil der Verarbeitung wahrscheinlich auf kommunaler Basis durchgeführt wurde. Dies bedeutet, dass es während der Xinzhai-Zeit eine Differenzierung der sozialen Organisation gab, wobei

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sich einige der Stätten auf kleine Haushalte konzentrierten, während die anderen sich auf die zentralisierten kommunalen Gesellschaften konzentrierten. Dieses Muster unterscheidet sich von der einheitlichen zentralen Organisation von Arbeitskräften und groß angelegten kommunalen Aktivitäten in der Yangshao-Zeit (5000-2500 v. Chr.), ähnelt jedoch der Differenzierung, die in der Longshan-Zeit (2300-1900 v. Chr.) begann und bis in die Erlitou-Shang-Zeit (1750-1046 v. Chr.) anhielt. Die Ergebnisse dieser Forschung bestätigen, dass der Prozess des Zuwachses an sozialer Komplexität in der Region des Central Plain kontinuierlich und ohne Unterbrechung stattfand.

Zeitschriftenbeitrag 3 - Regionale Untersuchung der Landwirtschaft in der Region des Central Plain

Mit den Ergebnissen der Xinzhai-Zeit, die in den letzten beiden Arbeiten dargestellt wurden, kann eine chronologische Veränderung in der Region des Central Plain mit der Kombination aller verfügbaren archäobotanischen Daten aus früheren Studien diskutiert werden. Die dritte Veröffentlichung *“Wechsel der Pflanzenarten und landwirtschaftlichen Praktiken vom Spätneolithikum zur Frühbronzezeit in der Region Zhengluo (Central Plain), China“* dient als regionaler Überblick über archäobotanische Daten in der Region des Central Plain. Eine Ansammlung verkohlter Pflanzenreste von acht Longshan-Zeit Stätten, fünf Xinzhai-Zeit Stätten, sieben Erlitou-Zeit Stätten und neun Stätten der Shang-Zeit wurde gesammelt und mit der semi-quantitativen Methode Repräsentativitätsindex (RI), sowie mit der multivariaten statistischen Methode Korrespondenzanalyse (CA) analysiert.

Die Ergebnisse zeigen, dass eine gewisse Kontinuität des spätneolithischen Agrarsystems bis in die frühe Bronzezeit besteht: Fuchsschwanzhirse blieb während des gesamten Zeitraumes das Hauptgetreide. Es gab unabhängig vom abrupten Klimaereignis um 2200 v. Chr. eine stabile Produktion von Reis von der Longshan- bis zur Erlitou-Zeit. Reis hatte auch eine besondere Bedeutung für die zentralen Siedlungen während der Xinzhai- und Erlitou-Zeit. Allerdings waren auch gewisse Veränderungen spürbar. Während der Zeit von Xinzhai und Erlitou wurde eine größere Menge Rispenhirse gepflanzt. Der Anbau von Rispenhirse auch in armen Böden erfordert weitaus weniger Arbeitsaufwand. Die Präferenz dieser Pflanzenart könnte sich aus der Überlegung ergeben, Arbeitsressourcen und

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landwirtschaftliche Zyklen in Einklang zu bringen. Ihre Verwendung erhöht die Möglichkeit, in kurzer Zeit relativ stabile landwirtschaftliche Erträge zu erhalten (für Rispenhirse beträgt die Zeit für die Kultivierung nur 60 Tage) und dabei weniger Arbeitsaufwand betreiben zu müssen. Eine weitere Veränderung war, dass der Anbau und die Bedeutung von Saatweizen in der Shang-Zeit merklich zunahm. Tatsächlich weist Saatweizen in der Region des Central Plain im Vergleich zur Region Haidai während der Shang-Zeit ausschließlich große Häufigkeiten und hohe Mengen auf. Von der Einführung bis zur allgemeinen Bekanntheit dauerte es für den Saatweizen in der Region des Central Plain ungefähr 200 Jahre, über die Erlitou- bis zur Shang-Zeit. Jedoch benötigte dieser Prozess in der Region Haidai ungefähr 1400 Jahre, von der Longshan- bis in die Westliche Zhou-Zeit (1046-771 v. Chr.). Nach den historischen Unterlagen wurde Saatweizen zumindest in der Shang-Zeit als Winterernte beschrieben, und diese Schlussfolgerung wurde durch den Zeitplan für den Jahresgang der Unkräuter bestätigt, der aus der Analyse von Weizenfeldunkräutern in dieser Untersuchung abgeleitet wurde. Daher ist das Sommer-Monsunklima mit den meisten Niederschlägen in der Sommersaison für Winterkulturen unvorteilhaft, da März bis Mai die Phase mit dem höchsten Wasserbedarf von Saatweizen ist. Somit ist der großflächige Anbau von Saatweizen unweigerlich mit dem Bewässerungssystem verbunden. Angesichts all dieser Bedingungen, bei der Erklärung dieses landwirtschaftlichen Musters und der landwirtschaftlichen Veränderungen in dieser Region wurde ein Schwerpunkt auf die Bewässerungstechnik vorgeschlagen. Die Praxis des Bewässerungssystems garantierte die stabile Produktion von Reis unter dem schwankenden Klima, machte ihn zu einem Prestigeträchtigen Lebensmittel, veranlasste die Landwirte andere Kulturpflanzenarten (z. B. Rispenhirse) mit geringerem Arbeitsaufwand anzubauen und beschleunigte auch die Etablierung von Saatweizen in einem lokalen Anbausystem. Darüber hinaus hat die Bewässerungstechnik in der Region des Central Plain eine wichtige Rolle für die landwirtschaftliche- sowie für die soziale Entwicklung gespielt. Sie bot eine stabile Existenzgrundlage für die Bevölkerung und ihre soziale Entwicklung.

Zeitschriftenbeitrag 4 - Regionale Untersuchung der Landwirtschaft in der Haidai Region

Während die Region des Central Plain ausschließlich mit der Entstehung des ersten

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Staates im Jahr 1750 v. Chr. in die neue Ära eintrat, zeichnete sich in der Region Haidai ein anderes Bild, wobei die Longshan-Kultur um 2100/2000 v. Chr. im Ost-Haidai und um 1800 v. Chr. im West-Haidai zusammenbrach. Im vierten und letzten Artikel *“Verstehen des Zusammenbruchs der Longshan-Kultur und des Klimaereignisses von 2,2 ka BCE in der Region Haidai, China aus landwirtschaftlicher Perspektive”* wurden vergleichende Untersuchungen zur Landwirtschaft durchgeführt. Landwirtschaftliche Muster und Anbaustrategien wurden durch die systematische Analyse der archäobotanischen Makroresten von 25 Longshan-Stätten und 9 Yueshi-Stätten in dieser Region bewertet. Es zeigt sich, dass Ost-Haidai und West-Haidai während der Longshan-Zeit unterschiedliche Anbausysteme entwickelten, wobei Ost-Haidai vom Reisanbau und West-Haidai vom Hirse-Trockenanbau dominiert wurde. In Vergleich zu Hirse ist der dürreanfällige Reis deutlich empfindlicher gegenüber Klimastress. Darüber hinaus könnte in der Region Haidai, wie aus der Unkrautansammlung und der Rekonstruktion von Reisfeldern an den Stätten Zhaojiazhuang und Taitou hervorgeht, der Reisanbau als feuchter Reisanbau angesehen werden, der jedoch höchstwahrscheinlich auf natürlich bewässerten Feldern ohne Bewässerung beruhte. Unter der Umweltverschlechterung nach 2200 v. Chr. war Reis etwas leicht weniger produktiv, während der Hirse-Trockenanbau stabile Erträge liefern konnte. Dieser Unterschied im landwirtschaftlichen System kann als einer der Faktoren angesehen werden, der vor dem Hintergrund des Klimawandels die verschiedenen sozialen Veränderungen verursachte.

Bei der Analyse von Unkräutern auf der Grundlage der Informationen über die Lebensdauer, den Bodenbedarf und dem Habitat dieser Unkräuter, wurden außerdem subregionale Unterschiede im Anbau festgestellt. In Ost-Haidai deuten die Dominanz der einjährigen Unkräuter und der hohe Anteil an Indikatoren für fruchtbaren Boden darauf hin, dass die Einwohner das Reisanbausystem bis zur Yueshi-Zeit (1800-1450 v. Chr.) beibehielten, anstatt neue landwirtschaftliche Strategien zu entwickeln, um sich an veränderte Umweltbedingungen anzupassen. Darüber hinaus stellt sich heraus, dass seit 2100/2000 v. Chr. eine Migration einer großen Bevölkerung von Ost-Haidai nach West-Haidai stattgefunden hat, um die durch den Klimawandel verursachten Probleme im Zusammenhang mit der Bevölkerung und ihrer Nahrungsknappeit zu lösen. Der Verlust von

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Arbeitskräften erhöhte jedoch wiederum die Belastung der verbliebenen Arbeiter für den Bau und die Instandhaltung der Reisfelder. Im Gegensatz dazu gab es für die Bewohner von West-Haidai Anreize, die Anbaupraktiken durch die Ausweitung der landwirtschaftlichen Flächen zu ändern. Dies wird durch den hohen Anteil an mehrjährigen Pflanzen in landwirtschaftlichen Flächen, sowie außerhalb von Äckern, also an Waldrändern, im Grünland und in Berggebieten angezeigt. Darüber hinaus wurde extensive Landnutzung praktiziert, um je nach Umgebungsbedingungen nicht kultivierte Felder in neue Anbauflächen für Reis und Hirse umzuwandeln. Zum Beispiel wurden mit der Zunahme trockener und kühlerer Bedingungen viele frühere feuchte Niederungen in verfügbare Anbauflächen umgewandelt. Reichlich vorhandene mehrjährige Unkräuter aus Reisfeldern deuten darauf hin, dass diese früheren Niederungen möglicherweise als ideale Anbauflächen für neue Reisfelder genutzt wurden. Demnach lässt sich sagen, dass in der Region Haidai Gesellschaften mit unterschiedlichen Anbausystemen und verschiedenen Anbaustrategien im landwirtschaftlichen Bereich eine unterschiedliche Widerstandsfähigkeit gegenüber dem anhaltenden Klimaereignis aufweisen.

Schlussfolgerungen und Ausblick

Zusammenfassend ist der soziale Wandel vom Spätneolithikum bis zur frühen Bronzezeit eine komplexe Frage, bei der viele Faktoren zusammenwirken und in Betracht gezogen werden müssen. Die Ergebnisse der aktuellen Forschung stützen die Theorie, dass die Landwirtschaft als einer der wichtigsten Faktoren eine Rolle bei der sozialen Transformation im frühen China gespielt hat. Es ist naheliegend, den Beitrag landwirtschaftlicher Techniken, insbesondere des Bewässerungssystems, zur Entwicklung der sozialen Hierarchie und der sozialen Komplexität in der Region des Central Plain hervorzuheben. Die Landwirtschaft war nicht nur eine Existenzgrundlage der gesamten Gesellschaft, sondern war höchstwahrscheinlich auch für das Austauschnetzwerk der Eliten oder Geistlichen von großer Bedeutung. Anders als in der Region des Central Plain bemühten sich die Menschen in West-Haidai verstärkt um den Anbau von Hirse-Arten. Das durch Reisanbau- dominierte Ost-Haidai reagierte auf die Umweltverschlechterung durch die Umstellung auf dürreverträgliche Pflanzenarten und die Etablierung eines Hirse-Anbausystems. Verglichen mit dem Monokultur-Anbausystem in Ost-Haidai

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und West-Haidai zeigte das Gemenge-Anbausystem mit fortschrittlichen Bewässerungstechniken in der Region des Central Plain große Vorteile und bot mehr Möglichkeiten, sich auf ein komplexe staatliche Strukturen zu etablieren.

Diese Forschung trägt eine Reihe neuer Informationen über die antike Landwirtschaft bei, die helfen die Entstehung der frühesten Staaten in China zu erklären und zu verstehen. Sie bilden jedoch einen vorläufiger Rahmen und es sind weitere Forschungen erforderlich, um ein umfassendes Verständnis zu erlangen. Aktuelle Arbeiten können noch weiter gehen, indem weitere Untersuchungen archäobotanischer Makroreste integriert werden und insbesondere mit Phytolith-Analysen zum Nachweis des Bewässerungssystems von Reisfeldern zusammengeführt werden. Darüber hinaus kann die Analyse stabiler Isotopenverhältnisse in Getreidekörnern ebenfalls zum Nachweis von Bewässerungssystemen für Kulturpflanzen, sowie zum Nachweis anderer landwirtschaftlicher Techniken wie dem Ausbringen von Dünger beitragen. Unter diesem Gesichtspunkt könnten zukünftig viele weitere Analysen durchgeführt werden, um das aktuelle Wissen auszuweiten und zu untermauern.

Appendix I

Table I. 1 Radiocarbon dating results

Lab code	Sampling pits	Dating materials	Conventional ¹⁴ C age BP ($\pm 1\sigma$)	Calibrated 95% range (cal. BCE) *
KIA-55209	H37(2)	<i>O. sativa</i>	3409 \pm 26	1865-1622
KIA-55210	H67 (2)	<i>O. sativa</i>	3515 \pm 27	1922-1749
KIA-55208	H51(4)	<i>G. max</i>	3457 \pm 26	1881-1689
KIA-55211	H84 (10)	<i>Weeds</i>	3485 \pm 35	1900-1692
KIA-55214	H50 (2)	<i>Legumes</i>	3470 \pm 35	1890-1688
KIA-55213	H100 (1)	<i>G. max</i>	3450 \pm 35	1882-1640

*AMS ¹⁴C dating was conducted by the Leibniz Laboratory for Radiometric Dating and Stable Isotope Research at Kiel University, Germany (year 2019) and the calibration work were done with the OxCal program 4.4, working with the IntCal 20.

Table I. 2 Phytolith finds in the Xinzhai site (absolute counts)

Code	Morphotypes in ICPN 2.0	Morphotypes in ICPN 1.0	H84	H50	H95	H37	H100	H143	H51	H165	H67
Single cells											
Fixed or passive (short grass cells)											
RON	Rondel	Rondel	32	15	5	6	9	7	20	25	5
TOW_RON	Tower rondel	Tower rondel	10	9	2	3	2	4	5	9	2
BIL	Bilobate	Bilobate	597	309	98	118	71	338	256	308	205
CRO	Cross	Cross	303	99	32	44	32	134	95	92	41
SAD	Saddle	Saddle	69	19	15	8	23	35	23	36	17
POL	Polylobate	Polylobate	11	6	0	1	5	3	4	3	0
Sensitive or active (long grass cells and stomata)											
ELO_BOA	Elongate board	Elongate board	61	22	35	8	8	9	41	29	43
ELO_PSI	Elongate psilate	Elongate psilate	1289	355	111	108	85	287	461	301	318
ELO_SIN	Elongate sinuate	Elongate sinuate	206	49	67	7	15	58	137	30	77
ELO_CRE	Elongate crenate	Elongate crenate	7	1	19	0	0	0	14	0	0
STO	Stomata	Stomata	30	4	16	3	2	5	30	2	14
ELO_ECH	Elongate echinate	Elongate echinate	541	237	94	115	69	115	214	296	114
Potential crops phytoliths											
ELO_DEN	Elongate dendritic (wheat inflorescence)	Elongate dendritic	12	21	5	8	0	10	7	13	8
BUL_FL_A_FL_A	Bulliform flabellate with flanges (rice leaf)		43	22	16	18	13	8	88	37	7
DOU	Double-peaked (rice husk)		86	25	15	10	13	18	13	17	35
Dicots											
POY	Polyhedral		44	13	14	4	5	0	15	12	14

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SPH_ECH	Spheroid echinate	Globular echinate	8	5	3	1	0	0	4	6	5
SPH_PSI	Spheroid psilate	Globular psilate	2	3	0	3	0	0	4	3	6
Others											
TRA	Tracheid	Tracheid	113	28	10	10	17	37	30	18	8
TRZ	Trapezoid	Trapeziform	27	14	1	13	3	13	48	13	1
ACU_BUL_1	Acute bulbosus	Acicular hair cell	348	101	34	87	44	141	257	111	60
ACU_BUL_2	Acute bulbosus	Unciform hair cell	167	72	29	23	28	73	141	108	63
PSI_ELL	Psilate ellipsoid		5	1	4	0	5	2	6	2	0
PSI_OBL	Psilate oblong		5	2	0	1	2	0	9	0	1
BUL_FLA_SHI	Bulliform flabellate in shield shape		5	0	0	0	4	1	2	0	0
BUL_FLA	Bulliform flabellate	Cuneiform bulliform	216	74	48	19	23	36	172	107	25
BLO	Blocky	Parallepipedal bulliform	1050	300	164	123	67	302	405	287	142
CON	Conical Type (Cyperaceae husk)		36	6	9	3	2	3	6	6	12
LOG_ROD	Long rod (Cyperaceae leaf/stem)		19	3	9	1	1	1	2	4	5
GEN	Geniculate	Irregular long cell	17	2	8	5	2	8	19	7	5
SPO_SPI	Sponge spicules	Sponge spicules	155	19	11	3	11	20	47	15	17
DIA	Diatom	Diatom	26	18	5	2	3	9	17	16	7
POL_GRA	Pollen grain		7	2	0	0	0	6	8	0	1
UND	Undefined		49	31	10	3	16	3	28	15	19
Silica skeletons											
Monocots											
SKE_VER_BIL		Skeleton with vertically arranged bilobates	50	18	5	3	2	10	10	4	16
SKE_PAR_BIL		Skeleton with parallelly arranged bilobates	65	3	0	4	1	9	14	2	12
SKE_PAP		Skeleton with papillae (foxtail millet husk)	6	2	0	0	2	16	2	2	2
SKE_BLO	Skeleton with blocky	Skeleton with stacked/parallepipedal bulliforms	130	56	3	68	34	70	63	21	14
SKE_ELO_CRE		Skeleton with elongate crenate	3	13	3	0	1	0	1	1	6
SKE_COL_Ω		Silica skeleton with Ω-type ending of columellate long cells (foxtail millet husk)	30	110	6	50	3	14	4	68	22
SKE_COL_η		Silica skeleton with η-type ending of columellate long cells (broomcorn millet husk)	30	56	2	6	16	4	1	55	16
SKE_COL		Silica skeleton with columellate long cells	84	54	19	54	9	88	39	24	27
SKE_ELO_SIN		Skeleton with sinuate Long cells	92	105	28	15	7	30	3	28	18
SKE_ELO_ECH		Skeleton with echinate Long cells	309	68	29	12	17	41	85	33	64
SKE_ELO_DEN		Skeleton with dendritic Long cells (wheat husk)	2	1	0	1	0	0	0	2	0
SKE_ELO_PSI		Skeleton with psilate Long cells	46	4	1	0	1	0	30	6	11
Dicots											
FAV_AGG		Favose aggregates	11	10	4	2	1	1	10	4	9
MUL_JIG		Multi-cell phytolith with jigsaw-puzzle	4	1	1	0	2	1	1	1	0

Appendix

Table I. 3 Arable weeds in macro-botanical remains from the Xinzhai site with different excavation seasons (absolute counts)

	Xinzhai year 2016	Xinzhai year 2018	Xinzhai year 2014
References	This research	This research	Zhong et al. 2016
<i>Setaria viridis</i>	764	291	292
<i>Digitaria sanguinalis</i>	1746	710	94
<i>Acalypha australis</i>	5	1	8
<i>Cirsium arvense</i>		1	
<i>Portulaca oleracea</i>	2		
<i>Suaeda glauca</i>		1	
<i>Chenopodium album</i>	160	771	314
<i>Galium tricorntutum</i>	2	1	
<i>Hibiscus trionum</i>		1	
<i>Abutilon theophrasti</i>		2	2
<i>Malva cathayensis</i>		2	
<i>Oxalis corniculata</i>	1		
<i>Cyperus iria</i>	33	19	
<i>Polygonum aviculare</i>	1	2	
<i>Physalis angulate</i>	1		
<i>Plantago asiatica</i>	6		
Millet field weeds	2721	1802	700
	Xinzhai year 2016	Xinzhai year 2018	Xinzhai year 2014
<i>Echinochloa crus-galli</i>	135	141	1
<i>Cyperus serotinus</i>	39		39
<i>Schoenoplectus juncooides</i>	109	75	4
<i>Carex diandra</i>			3
<i>Cyperus iria</i>	33	19	
<i>Pycreus sanguinolentus</i>	55	41	2
<i>Eleusine indica</i>	2		
<i>Physalis angulate</i>	1		
Rice field weeds	374	276	49

Table I. 4 Sensitive and fixed morphotypes in each sample (absolute counts)

		Sample(g)	Rice (grains/g)	Sensitive	Fixed	S:F ratio
Rice	H84	0.00853	26698	2134	1072	1.99
	H95	0.00153	20274	342	157	2.18
	H51	0.00996	11500	897	413	2.17
	H67	0.00286	18900	566	286	1.98
Millet	H50	0.00744	6700	668	475	1.41
	H37	0.00421	7616	241	183	1.32
	H100	0.00331	8154	179	144	1.24
	H143	0.00425	8225	474	531	0.89
	H165	0.00708	7896	658	477	1.38

Appendix

Table I. 5 The collection of S:F ratios from archaeological sites and their indications in water regimes

Site	Cultural period	Absolute date (BCE or cal. BCE)	S:F ratio	Indication	References
Shunshanji	Shunshanji I	6500-6000 cal. BCE	1.04±0.19	Drier, lowland rainfed rice field	Luo et al. 2021
	Shunshanji II		1.49±0.55	Wetter, manipulate drainage	Luo et al. 2021
	Shunshanji III	6000-5500 cal. BCE	1.33±0.52		Luo et al. 2021
Hanjing	Shunshanji I	6500-6000 cal. BCE	1.09±0.45	Drier, lowland rainfed rice field	Luo et al. 2021
	Shunshanji II		1.40±0.32	Wetter, manipulate drainage	Luo et al. 2021
	Shunshanji III	6000-5500 cal. BCE	1.38±0.18		Luo et al. 2021
Baligang	Yangshao/Pre-Yangshao	4300-3500 BCE	1.7/ 3.92/ 2.2	Wet, wild rice setting	Weisskopf et al. 2015a
	Qujialing	3000-2500 BCE	0.91	Drier, drainage, irrigated in early growth and dried out	Weisskopf et al. 2015a
	Shijiahe	2500-2300 BCE	1.74	Wetter, irrigation to later during growth	Weisskopf et al. 2015a
	Longshan	2300-1800 BCE	0.96	Mixed, less intensive rice regime	Weisskopf et al. 2015a
	Erlitou	1800-1500 BCE	2.04		Weisskopf et al. 2015a
Zhuzhai	Peiligang	6500-5000 cal. BCE	0.92	Dry field	Wang et al. 2018
	Yangshao	4500-3000 cal. BCE	0.46	Dry field	Wang et al. 2018
	Shang	1600-1000 cal. BCE	0.39	Dry field	Wang et al. 2018
Dahecun	Yangshao	5000-3000 cal. BCE	0.19	Dry field	Wang et al. 2019
Yingyang	Yangshao	5000-3000 cal. BCE	0.93	Dry field	Wang et al. 2019
Maanhe	Yangshao	5000-3000 cal. BCE	0.64	Dry field	Wang et al. 2019
Caiyuangou	Yangshao	5000-3000 cal. BCE	0.44	Dry field	Wang et al. 2019
Tianluoshan	Early Hemudu	4800-4300 BCE	2.0-2.5	Wet, a setting where wild rice occurs	Weisskopf et al. 2015b
Caoxieshan	Late Hemudu	3950-3700 BCE	0.5-1.0	Drier; rainfed or decrue fields	Weisskopf et al. 2015b
Maoshan	Liangzhu	3000-2300 BCE	1.0-1.3	Wetter, irrigated paddy systems	Weisskopf et al. 2015b
Baligang	Yangshao	4900-3000 cal. BCE	Rice: 2.35	Wet	Weisskopf 2017
Baligang	Longshan	3000-1850 cal. BCE	Rice: 1.05	Dry	Weisskopf 2017
Xipo	Yangshao	4900-3000 cal. BCE	Rice: 0.99	Not irrigated but managed	Weisskopf 2017
Xipo	Yangshao	4900-3000 cal. BCE	Millet: 0.59	Dry	Weisskopf 2017
Huizui	Yangshao	4900-3000 cal. BCE	Rice: 3.92	Irrigated paddy fields	Weisskopf 2017
Huizui	Yangshao	4900-3000 cal. BCE	Millet: 1.61	Wet, rainfed, fits Paleo-ecological environment	Weisskopf 2017
Huizui	Erlitou/Shang	1850-1100 cal. BCE	Rice: 0.52	Drier	Weisskopf 2017
Huizui	Erlitou/Shang	1850-1100 cal. BCE	Millet: 0.34	Drier	Weisskopf 2017

Appendix

Table I. 6 Finds of phytolith (absolute counts) and charred cereal remains (counts, ubiquities and RI values) in different sites of the Xinzhai period

Sites	Sample volume	Information	Foxtail millet		Broomcorn millet	Rice			Wheat	Reference
Phytolith			SKE_C OL_Ω	SKE_PAP	SKE_COL_η	DOU	BUL_FLA _FLA	SKE_PRA_BIO	ELO_DEN/SKE_ ELO_DEN	
Xinzhai (2007)	1 sample from exploratory trench		504			4	16		10	Yao et al. 2007
Xinzhai (2018)	59 samples from 9 relic units		307	22	206	232	252	110	90	This study
Dongzhao	36 samples from 28 relic units		450		963	170	27	27	61	Luo et al. 2018
Macro-botanical remains			Foxtail millet		Broomcorn millet	Rice			Wheat	Reference
Xinzhai (year 2000)	10	Count	354		98	423				ACAC-PK and Zhengzhou 2008
		Proportion	40%		11%	48%				
		Ubiquity	40%		20%	80%				
		RI value	8		4	35				
Xinzhai (year 2016)	108	Count	13198		1735	3112			1	An et al. forthcoming
		Proportion	73%		10%	17%			0.006%	
		Ubiquity	97%		67%	72%			1%	
		RI value	150		100	140			10	
Xinzhai (year 2018)	60	Count	8590		445	3075				An et al. forthcoming
		Proportion	71%		4%	25%				
		Ubiquity	98%		60%	72%				
		RI value	120		80	112				
Xinzhai (year 2014)	109	Count	5887		1035	381			1	Zhong et al. 2016
		Proportion	81%		14%	5%			0.01%	
		Ubiquity	99%		83%	44%			1%	
		RI value	175		125	60			10	
Dongzhao	37	Count	2325		175					Yuan 2016
		Proportion	93%		7%					
		Ubiquity	55%		55%					
		RI value	56		32					
Huadizui	30	Count	1228		179	397				Tang et al. 2018
		Proportion	68%		10%	22%				
		Ubiquity	73%		53%	67%				
		RI value	60		32	56				
Zhengzhou Shang City	4	Count	125		35					Jia et al. 2018
		Proportion	78%		22%					
		Ubiquity	100%		50%					
		RI value	20		12					

Appendix

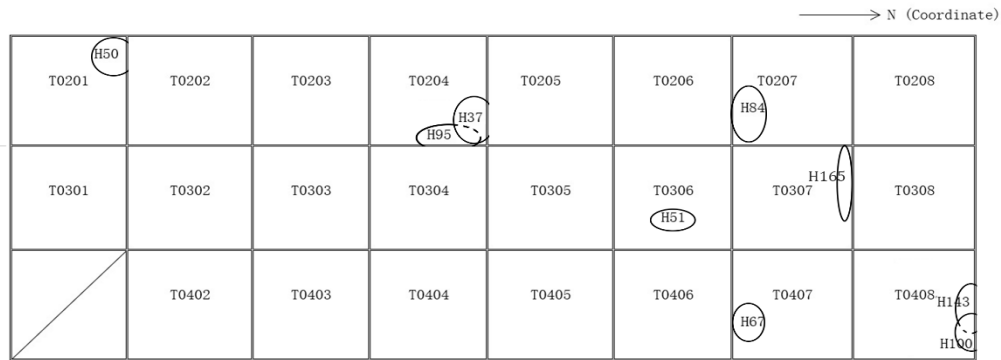


Figure I. 1 The spatial distribution of phytolith samples on the excavation plan

Pits	Sampling details in each pit	Layers	Depth(cm)	Samples	Description
H84				P21*	Modern field soil
		H 8 4 ①	0-10	P19, P20	Light grey soil, contain red burned soil grains
		H 8 4 ② a	10-20	P18	Light grey soil
		H 8 4 ② b	10-20	P17	Light grey soil
		H 8 4 ③	20-30	P16	Grey soil with red burned grains
		H 8 4 ④	30-40	P15	Light grey soil with dark grey and yellow layers inside
		H 8 4 ⑤	40-50	P14	Light grey soil with white grains
		H84⑥	50-60	P13	Light grey mix with dark grey soil
		H84⑦	60-70	P12, P11	Light grey soil with yellow grains
		H84⑧	70-110	P10, P9	Grey soil
		H84⑨	110-120	P8	Dark grey soil
		H84⑩	120-161	P7, P6, P5, P4	Light grey soil
H84⑪	161-251	P3	Light grey soil, contain dark grey grains		
H84⑫	251-281	P2, P1	Aqua soil, contain yellow points		
				P0*	Natural subsoil

H37		①	0-40	P3	Grey and brown soil
H95		②	40-92	P2	Grey loose soil
		③	92-117	P1	Steel grey soil with yellow grains
H95		①	0-100	P2	Brown-earth soil contain burned black and red soil grains
		②	100-157	P1	Black and red layers landslide from east to west

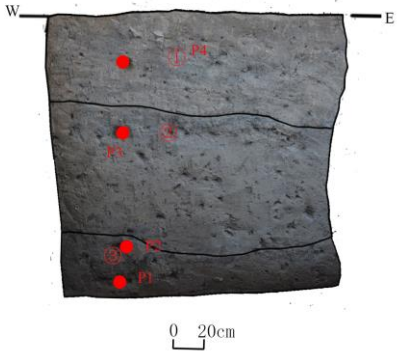
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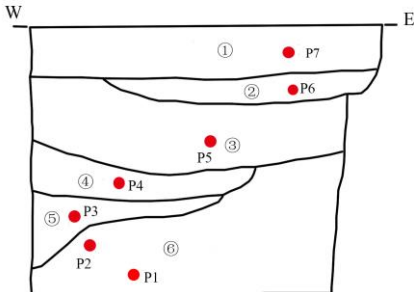
H51		①	0-30	P9	Brown-earth, dense soil
		②	30-70	P8	Brown-earth, loose soil
		③	70-120	P6, P7	Grey and black silty soil, contain red burned grains
		④	120-210	P3, P4, P5	Black silty soil
		⑤	210-280	P1, P2	Brown-earth soil, contain red burned grains and the bottom has processing marks

H165		①	0-25	P7*	Modern filed soil
		②	25-45		Yellow, disturbed soil, historical period
		H165	45-130	P6	White clay, Xinzhai phase
				P5	White clay, Xinzhai phase
				P4	Greyish silty layer, contain many burnt-soil grains, Xinzhai phase
				P3	Red silty layer, contain many burnt-soil grains, Xinzhai phase
				P2, P1	Grey silty layer, Xinzhai phase

H100		①	0-55	P2	Grey and black soil
H143		②	55-125	P1	Grey soil, contain yellow grains
		①	0-240	P6	Grey soil
		②	240-280	P1, P2, P3, P4, P5	Grey soil, contain red, black and grey layers

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H67		①	0-65	P4	Grey silty soil with a thin black soil layer as boundary
		②	65-150	P3	Grey silty soil with a thin black soil layer as boundary
		③	150-190	P1, P2	Grey silty soil, bottom has processing marks

H50		①	0-45	P7	Grey silty soil, contain yellow and burned red grains
		②	45-80	P6	Light grey, dense soil with yellow grains, pit wall has processing marks
		③	80-125	P5	Light grey, loose soil with yellow grains, pit wall has processing marks
		④	125-145	P4	Red soil, pit wall has processing marks
		⑤	143-163	P3	Dark grey soil
		⑥	163-213	P1, P2	Grey silty soil with burned black and red grains

*Sample P0,P21 with H84 and P7 with H165 is collected as a comparative sample but not included in the final analysis.

Figure I. 2 Detailed archaeological information of each phytolith samples

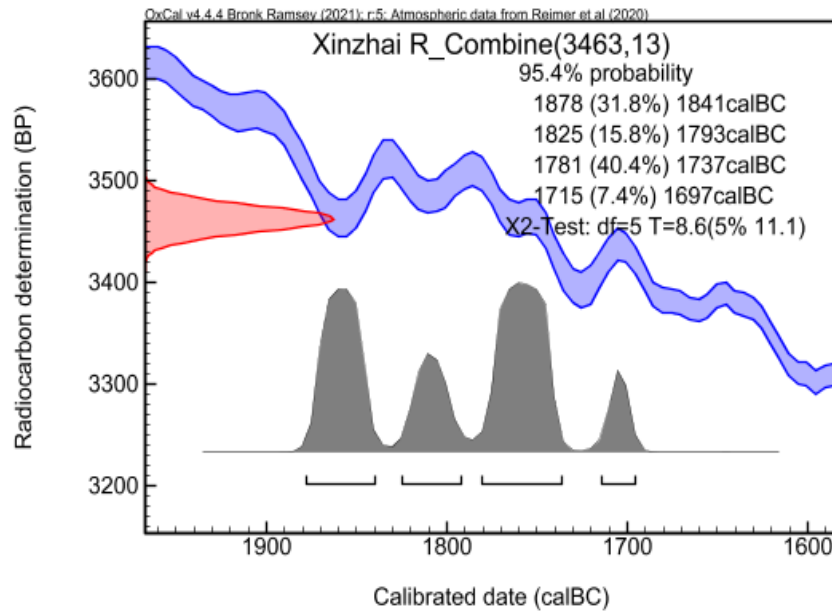


Figure I. 3 Oxcal plot of the combined radiocarbon dates of the Xinzhai site

Appendix

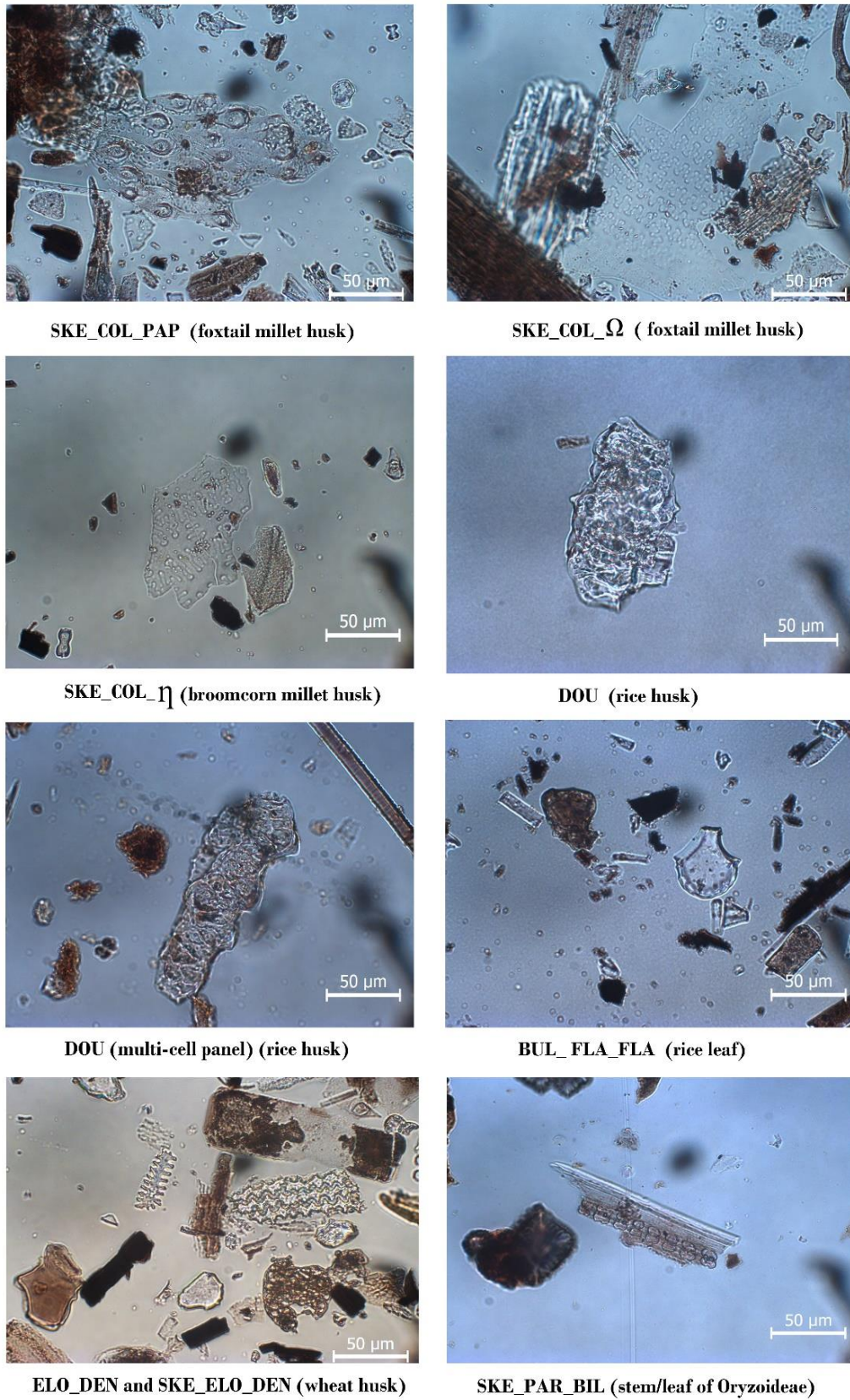


Figure I. 4 Main phytolith morphotypes from cereals (photographed by JP An)

Appendix

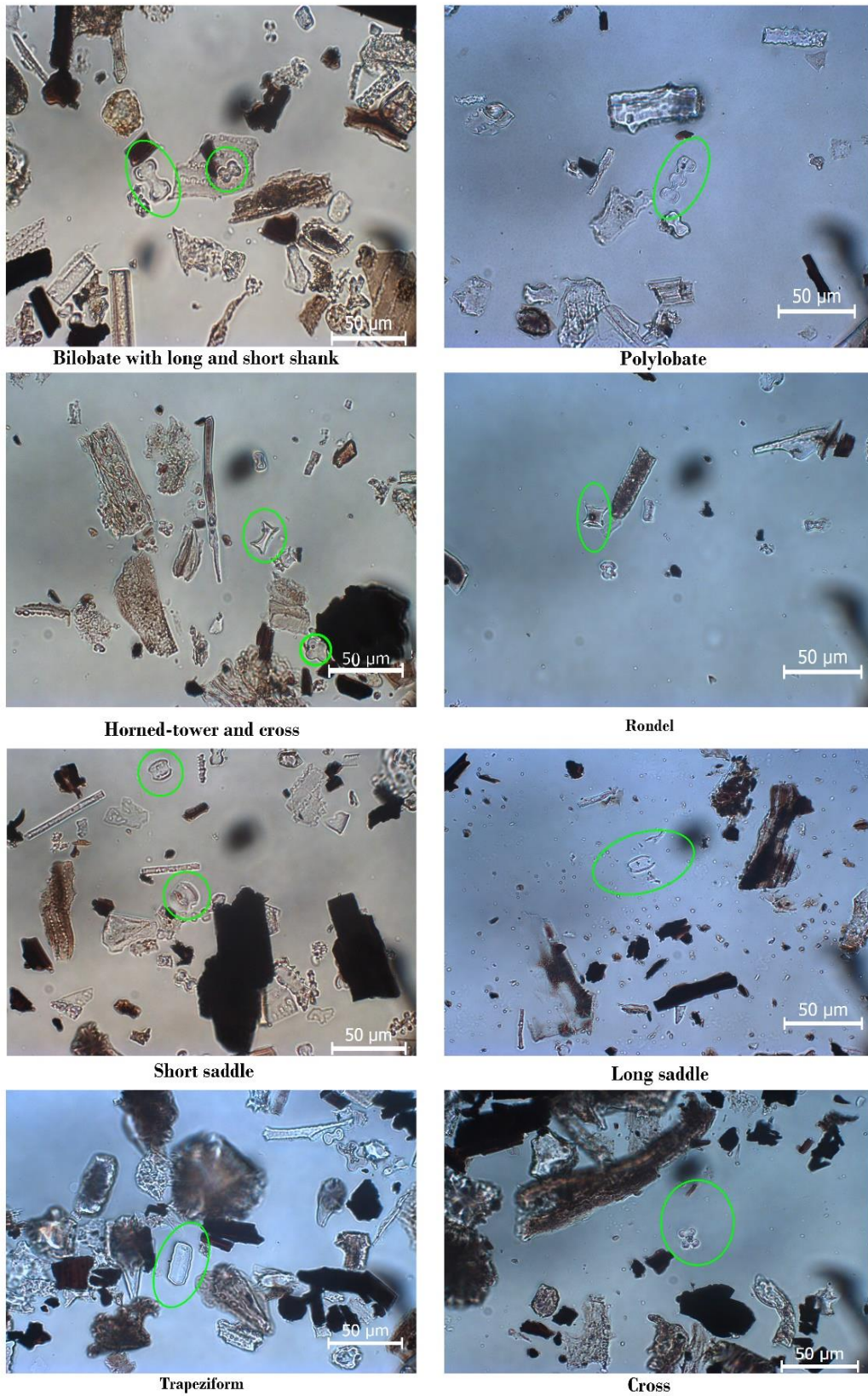


Figure I. 5 Main phytolith morphotypes indicative of dry conditions (photographed by JP An)

Appendix

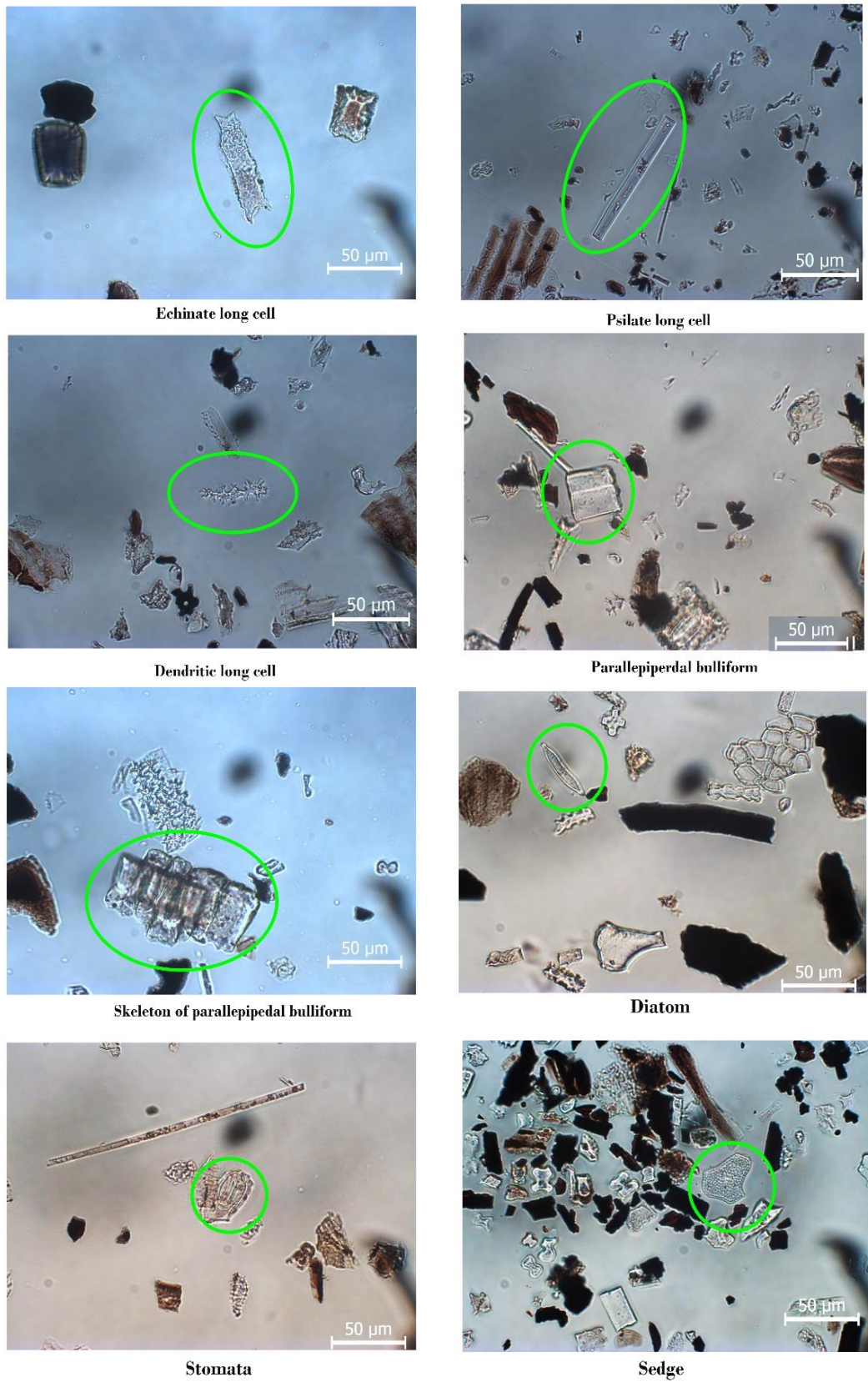


Figure I. 6 Main phytolith morphotypes indicative of wet conditions (photographed by JP An)

Appendix II

Table II. 1 Sampling details of macro-botanical remains and phytoliths in the Xinzhai site

Materials	Huikeng (pit)*	Detailed information of each pit	Sample volumes [#]
Phytolith	H84 ^c	281 cm deep, 12 layers, in trench T0207	20 samples
	H37 ^a	117 cm deep, 3 layers, in trench T0204	3 samples
	H67 ^c	190 cm deep, 3 layers, in trench T0407	4 samples
	H50 ^c	213 cm deep, 4 layers, in trench T0201	7 samples
	H143 ^c	280 cm deep, 2 layers, in trench T0408	6 samples
	H95 ^a	157 cm deep, 2 layers, in trench T0204	2 samples
	H100 ^a	125 cm deep, 2 layers, in trench T0408	2 samples
	H51 ^c	280 cm deep, 5 layers, in trench T0306	9 samples
Macro-botanical remains	H165 ^b	130 cm deep, homogeneous unit, in trench T0307	6 samples
	168 pits, soil volume in total 1986 liters		220 samples

* H is the abbreviation of *Huikeng*. It means pit. In the case of this study, it means refuse pits;

Sampling method of each pit: a. based on sub-layers; b. isometric sample collection (every 20 cm); c. combined sub-layers with isometric sample collection;

Each phytolith sample contains around 250 g soil and each flotation sample contains around 10 liters of soil.

Table II. 2 Macro-botanical finds in the Xinzhai site from different excavation seasons (absolute counts)

Family	Scientific name*	Year 2016(n=108)	Year 2018(n=60)	Total (n=168)	Height [#]	Growing habits ¹	Categori es ²
Crops (29118)							
	<i>Setaria italica</i>	13198	8040	21238			
	<i>S. italica with husks</i>	3789	1896	5685			
	<i>S. italica (immature)</i>	10877	5107	15984			
	<i>Panicum miliaceum</i>	1735	445	2180			
	<i>P. miliaceum with husks</i>	247	115	362			
	<i>P. miliaceum (immature)</i>	56	113	169			
	<i>Oryza sativa</i>	2112	3075	5187			
	<i>O. sativa (immature)</i>	267	668	935			
	<i>O. sativa with husks</i>	107	465	572			
	<i>Glycine max</i>	349	163	512			
	<i>G. max (small)</i>	107	67	174			
	<i>Triticum aestivum</i>	1		1			
Arable weeds (8204)							
Poaceae	<i>Echinochloa crus-galli</i>	135	141	276	H	Wet rice	SFH
	<i>Setaria viridis</i>	764	291	1055	M	Millet	SFH
	<i>Digitaria sanguinalis</i>	1746	710	2456	L	Millet	SFH
	<i>Eleusine indica</i>	2		2	H	Millet/Dry rice	SFH
	<i>Panicoideae</i> grasses	2036	1011	3047	/	/	/
Euphorbiaceae	<i>Acalypha australis</i>	5	1	6	M	Millet	BFH
Asteraceae	<i>Cirsium arvense</i>		1	1	M	Millet	SHH
Portulacaceae	<i>Portulaca oleracea</i>	2		2	L	Millet/Dry rice	SFH
Chenopodiaceae	<i>Suaeda glauca</i>		1	1	H	Wheat/Millet	BFH
	<i>Chenopodium album</i>	160	771	931	H	Millet	SFH
Rubiaceae	<i>Galium tricorntutum</i>	2	1	3	/	Wheat/Millet	SFH
Malvaceae	<i>Hibiscus trionum</i>		1	1	M	Millet	SHH
	<i>Abutilon theophrasti</i>		2	2	M	Millet	SHH
	<i>Malva cathayensis</i>		2	2	H	Millet	SHH
Oxalidaceae	<i>Oxalis corniculata</i>	1		1	L	Millet	SFH
Cyperaceae	<i>Schoenoplectus juncooides</i>	109	75	184	L	Wet rice	SFL
	<i>Cyperus iria</i>	33	19	52	L	Millet/Dry rice	SFL
	<i>Pycrus sanguinolentus</i>	55	41	96	M	Wet rice	SFH
	<i>Cyperus serotinus</i>	39		39	H	Wet rice	SFH
Polygonaceae	<i>Polygonum aviculare</i>	1	2	3	L	Wheat/Millet	SFH

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Solanaceae	<i>Physalis angulate</i>	1		1	M	Millet/ Dry rice	BFH
Plantaginaceae	<i>Plantago asiatica</i>	6		6	L	Millet	SFH
Other weeds (858)							
Poaceae	<i>Lolium</i> sp.	13	1	14			
Solanaceae	<i>Solanum nigrum</i>	1	1	2			
	<i>Physalis alkekengi</i>	1		1			
Cyperaceae	<i>Schoenoplectus mucronatus</i>	14	12	26			
	<i>Amethystea caerulea</i>	3	1	4			
Fabaceae	<i>Senna tora</i>	2		2			
	<i>Lespedeza bicolor</i>	21	6	27			
	<i>Melilotus officinalis</i>	678	26	704			
	<i>Kummerowia striata</i>	1	2	3			
	<i>Astragalus scaberrimus</i>	1		1			
	<i>Glycine soja</i>	25	21	46			
Lamiaceae	<i>Perilla frutescens</i>	5	7	12			
	<i>Leonurus japonicus</i>	1		1			
	<i>Stachys chinensis</i>		1	1			
	<i>Ajuga</i> sp.	2	4	6			
Polygonaceae	<i>Rumex acetosa</i>	8		8			
Cucurbitaceae	<i>Thladiantha dubia</i>	5	9	14			
Violaceae	<i>Viola</i> sp.	12	11	23			
Hydrocharitaceae	<i>Najas marina</i>	1		1			
Verbenaceae	<i>Vitex negundo</i>	2	2	4			
Fleshy fruits (36)							
	Rosaceae (<i>Cerasus</i> sp.)	1		1			
	Rosaceae (<i>Amygdalus</i> sp.)	1	2	3			
	Rosaceae (<i>Malus</i> sp.)	2	1	3			
	Rhamnaceae (<i>Ziziphus</i> sp.)	4	19	23			
	Vitaceae (<i>Vitis bryoniifolia</i>)	4	2	6			
Others							
	Animal dropping (?)	12		12			
	Nutshells	37	4	41			
	Tree bracts	1	3	4			
	Rice bases	664	795	1459			
	Millet bulks	3		3			
	Unknown	27	22	49			
	Unidentifiable	3	6	9			

* The nomenclature of species is updated according to *Plant Plus of China* (see www.iPlant.cn) that hosted by the State Key Laboratory of Systematic and Evolutionary Botany Institute of Botany, the Chinese Academy of Sciences (LSEB, IB, CAS).

Height- H (high): above 80 cm, M (middle): 40-80 cm, L (low): below 40 cm.

1. Living habits- common in Rice: rice field, Millet: millet dry field, Wheat: wheat field, /: unidentifiable. Ecological information of rice fields see Soerjani et al. (1987).

2. Weed categories follow (Reddy 1994): small-free light (SFL), small-free heavy (SFH), small-headed light (SHL), small-headed heavy (SHH), big-free light (BFL), big-free heavy (BFH), big-headed light (BHL), and big-headed heavy (BHH).

Appendix

Table II. 3 Phytolith finds in the Xinzhai site (absolute counts)

Code	Morphotypes in ICPN 2.0	Morphotypes in ICPN 1.0	H84	H50	H95	H37	H100	H143	H51	H165	H67
Single cells											
Fixed or passive (short grass cells)											
RON	Rondel	Rondel	32	15	5	6	9	7	20	25	5
TOW_RON	Tower rondel	Tower rondel	10	9	2	3	2	4	5	9	2
BIL	Bilobate	Bilobate	597	309	98	118	71	338	256	308	205
CRO	Cross	Cross	303	99	32	44	32	134	95	92	41
SAD	Saddle	Saddle	69	19	15	8	23	35	23	36	17
POL	Polylobate	Polylobate	11	6	0	1	5	3	4	3	0
Sensitive or active (long grass cells and stomata)											
ELO_BOA	Elongate board	Elongate board	61	22	35	8	8	9	41	29	43
ELO_PSI	Elongate psilate	Elongate psilate	1289	355	111	108	85	287	461	301	318
ELO_SIN	Elongate sinuate	Elongate sinuate	206	49	67	7	15	58	137	30	77
ELO_CRE	Elongate crenate	Elongate crenate	7	1	19	0	0	0	14	0	0
STO	Stomata	Stomata	30	4	16	3	2	5	30	2	14
ELO_ECH	Elongate echinate	Elongate echinate	541	237	94	115	69	115	214	296	114
Potential crops phytoliths											
ELO_DEN	Elongate Dendritic (wheat inflorescence)	Elongate dendritic	12	21	5	8	0	10	7	13	8
BUL_FLA_FLA	Bulliform flabellate with flanges (rice leaf)		43	22	16	18	13	8	88	37	7
DOU	Double-peaked (rice husk)		86	25	15	10	13	18	13	17	35
Dicots											
POY	Polyhedral		44	13	14	4	5	0	15	12	14
SPH_ECH	Spheroid echinate	Globular echinate	8	5	3	1	0	0	4	6	5
SPH_PSI	Spheroid psilate	Globular psilate	2	3	0	3	0	0	4	3	6
Others											
TRA	Tracheid	Tracheid	113	28	10	10	17	37	30	18	8
TRZ	Trapezoid	Trapeziform	27	14	1	13	3	13	48	13	1
ACU_BUL_1	Acute bulbosus	Acicular hair cell	348	101	34	87	44	141	257	111	60
ACU_BUL_2	Acute bulbosus	Unciform hair cell	167	72	29	23	28	73	141	108	63
PSI_ELL	Psilate ellipsoid		5	1	4	0	5	2	6	2	0
PSI_OBL	Psilate oblong		5	2	0	1	2	0	9	0	1
BUL_FLA_SHI	Bulliform flabellate in shield shape		5	0	0	0	4	1	2	0	0
BUL_FLA	Bulliform flabellate	Cuneiform bulliform	216	74	48	19	23	36	172	107	25

Appendix

BLO	Blocky	Parallelepipedal bulliform	1050	300	164	123	67	302	405	287	142
CON	Conical Type (Cyperaceae husk)		36	6	9	3	2	3	6	6	12
LOG_ROD	Long rod (Cyperaceae leaf/stem)		19	3	9	1	1	1	2	4	5
GEN	Geniculate	Irregular long cell	17	2	8	5	2	8	19	7	5
SPO_SPI	Sponge spicules	Sponge spicules	155	19	11	3	11	20	47	15	17
DIA	Diatom	Diatom	26	18	5	2	3	9	17	16	7
POL_GRA	Pollen grain		7	2	0	0	0	6	8	0	1
UND	Undefined		49	31	10	3	16	3	28	15	19
Silica skeletons											
Monocots											
SKE_VER_BIL		Skeleton with vertically arranged bilobates	50	18	5	3	2	10	10	4	16
SKE_PAR_BIL		Skeleton with parallelly arranged bilobates	65	3	0	4	1	9	14	2	12
SKE_PAP		Skeleton with papillae	6	2	0	0	2	16	2	2	2
SKE_BLO	Skeleton with blocky	Skeleton with stacked/parallelepipedal bulliforms	130	56	3	68	34	70	63	21	14
SKE_ELO_CRE		Skeleton with elongate crenate	3	13	3	0	1	0	1	1	6
SKE_COL_Ω		Silica skeleton with Ω-type ending of columellate long cells	30	110	6	50	3	14	4	68	22
SKE_COL_η		Silica skeleton with η-type ending of columellate long cells	30	56	2	6	16	4	1	55	16
SKE_COL		Silica skeleton with columellate long cells	84	54	19	54	9	88	39	24	27
SKE_ELO_SIN		Skeleton with sinuate Long Cells	92	105	28	15	7	30	3	28	18
SKE_ELO_ECH		Skeleton with echinate Long Cells	309	68	29	12	17	41	85	33	64
SKE_ELO_DEN		Skeleton with dendritic Long Cells	2	1	0	1	0	0	0	2	0
SKE_ELO_PSI		Skeleton with psilate Long Cells	46	4	1	0	1	0	30	6	11
Dicots											
FAV_AGG		Favose aggregates	11	10	4	2	1	1	10	4	9
MUL_JIG		Multi-cell phytolith with jigsaw-puzzle	4	1	1	0	2	1	1	1	0

Appendix

Table II. 4 Measurement data of rice grains, millet grains and related weed seeds (mm)

Mature and immature rice grains			Mature and immature millet grains			Common rice field weeds		
Species	Length	Width	Species	Length	Width	Species	Length	Width
<i>Oryza sativa</i>	5.28	2.66	<i>Setaria italica</i>	1.51	1.37	<i>Echinochloa crus-galli</i>	2.18	2.16
<i>Oryza sativa</i>	5.14	2.8	<i>Setaria italica</i>	1.25	1.09	<i>Echinochloa crus-galli</i>	2.12	1.98
<i>Oryza sativa</i>	5.29	2.72	<i>Setaria italica</i>	1.2	0.75	<i>Echinochloa crus-galli</i>	2.02	1.89
<i>Oryza sativa</i>	4.53	2.27	<i>Setaria italica</i>	1.25	0.64	<i>Echinochloa crus-galli</i>	2.32	2.23
<i>Oryza sativa</i>	4.22	2.22	<i>Setaria italica</i>	1.21	0.65	<i>Echinochloa crus-galli</i>	2.04	1.78
<i>Oryza sativa</i>	4.44	2.31	<i>Setaria italica</i>	1.13	1.1	<i>Echinochloa crus-galli</i>	2.16	2.14
<i>Oryza sativa</i>	4.17	2.34	<i>Setaria italica</i>	1.72	1.71	<i>Echinochloa crus-galli</i>	2.13	2.09
<i>Oryza sativa</i>	4.29	2.12	<i>Setaria italica</i>	1.76	1.7	<i>Echinochloa crus-galli</i>	2.23	2.07
<i>Oryza sativa</i>	4.33	2.59	<i>Setaria italica</i>	1.7	1.56	<i>Echinochloa crus-galli</i>	2.11	2.07
<i>Oryza sativa</i>	4.18	2.47	<i>Setaria italica</i>	1.7	1.74	<i>Echinochloa crus-galli</i>	2.23	2.19
<i>Oryza sativa</i>	4.93	2.7	<i>Setaria italica</i>	1.86	1.64	<i>Echinochloa crus-galli</i>	2.1	1.91
<i>Oryza sativa</i>	4.7	2.34	<i>Setaria italica</i>	1.77	1.75	<i>Echinochloa crus-galli</i>	2.11	1.89
<i>Oryza sativa</i>	4.32	2.29	<i>Setaria italica</i>	1.26	1.25	<i>Echinochloa crus-galli</i>	2.18	2.13
<i>Oryza sativa</i>	4.5	2.22	<i>Setaria italica</i>	1.28	1.16	<i>Echinochloa crus-galli</i>	2.19	2.11
<i>Oryza sativa</i>	4.4	2.41	<i>Setaria italica</i>	1.2	1.18	<i>Echinochloa crus-galli</i>	2.18	2.17
<i>Oryza sativa</i>	4.4	2.1	<i>Setaria italica</i>	1.29	1.19	<i>Echinochloa crus-galli</i>	2.18	2.16
<i>Oryza sativa</i>	4.7	2.4	<i>Setaria italica</i>	1.3	0.67	<i>Echinochloa crus-galli</i>	1.99	1.97
<i>Oryza sativa</i>	4.6	2.2	<i>Setaria italica</i>	1.24	0.8	<i>Echinochloa crus-galli</i>	2.26	2.17
<i>Oryza sativa</i>	4.5	2.1	<i>Setaria italica</i>	1.21	1.08	<i>Echinochloa crus-galli</i>	2.22	2.1
<i>Oryza sativa</i>	3.9	2.1	<i>Setaria italica</i>	1.37	1.11	<i>Echinochloa crus-galli</i>	2.12	2.05
<i>Oryza sativa</i>	4.7	2.5	<i>Setaria italica</i>	1.51	1.37	<i>Echinochloa crus-galli</i>	2.15	1.88
<i>Oryza sativa</i>	5.2	2.5	<i>Setaria italica</i>	1.25	1.09	<i>Schoenoplectus mucronatus</i>	2.28	1.32
<i>Oryza sativa</i>	4.6	2.2	average value of <i>S. italica</i>	1.41	1.21	<i>Schoenoplectus mucronatus</i>	1.7	1.2
<i>Oryza sativa</i>	4.8	2.34	standard deviation of <i>S. italica</i>	0.23	0.37	<i>Schoenoplectus mucronatus</i>	1.99	1.26
<i>Oryza sativa</i>	4.4	2	<i>Immature Setaria italica</i>	1.2	0.75	<i>Schoenoplectus mucronatus</i>	2.02	1.34
<i>Oryza sativa</i>	4.7	2.3	<i>Immature Setaria italica</i>	0.99	0.85	<i>Schoenoplectus mucronatus</i>	1.97	1.27
<i>Oryza sativa</i>	4.88	2.51	<i>Immature Setaria italica</i>	0.76	0.56	<i>Schoenoplectus mucronatus</i>	1.8	0.99
<i>Oryza sativa</i>	4.44	2.39	<i>Immature Setaria italica</i>	0.87	0.71	<i>Najas marina</i> *	2.67	1.6
<i>Oryza sativa</i>	5.01	2.57	<i>Immature Setaria italica</i>	0.91	0.81	<i>Schoenoplectus juncooides</i>	1.29	0.97
<i>Oryza sativa</i>	4.97	2.67	<i>Immature Setaria italica</i>	0.93	0.83	<i>Schoenoplectus juncooides</i>	2	1.47

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<i>Oryza sativa</i>	4.75	2.57	<i>Immature Setaria italica</i>	0.99	0.79	<i>Schoenoplectus juncooides</i>	1.67	1.27
<i>Oryza sativa</i>	4.68	2.6	<i>Immature Setaria italica</i>	0.65	0.54	<i>Schoenoplectus juncooides</i>	1.99	1.65
<i>Oryza sativa</i>	5.13	2.56	<i>Immature Setaria italica</i>	0.78	0.61	<i>Schoenoplectus juncooides</i>	2.13	1.74
<i>Oryza sativa</i>	4.73	2.95	<i>Immature Setaria italica</i>	0.77	0.65	<i>Schoenoplectus juncooides</i>	2.11	1.67
<i>Oryza sativa</i>	4.69	2.33	<i>Immature Setaria italica</i>	0.98	0.73	<i>Pycreus sanguinolentus</i>	1.2	0.89
<i>Oryza sativa</i>	4.94	2.38	<i>Immature Setaria italica</i>	1	0.79	<i>Pycreus sanguinolentus</i>	0.8	0.67
<i>Oryza sativa</i>	4.97	2.88	<i>Immature Setaria italica</i>	0.91	0.77	<i>Pycreus sanguinolentus</i>	1.56	0.87
<i>Oryza sativa</i>	4.7	2.84	<i>Immature Setaria italica</i>	0.88	0.63	<i>Pycreus sanguinolentus</i>	1.35	1.12
<i>Oryza sativa</i>	4.61	2.49	<i>Immature Setaria italica</i>	0.87	0.67	<i>Pycreus sanguinolentus</i>	0.92	0.63
<i>Oryza sativa</i>	4.97	2.53	<i>Immature Setaria italica</i>	0.9	0.71	<i>Pycreus sanguinolentus</i>	1.5	0.91
<i>Oryza sativa</i>	4.83	2.67	<i>Immature Setaria italica</i>	0.83	0.69	<i>Pycreus sanguinolentus</i>	1.22	0.97
<i>Oryza sativa</i>	4.87	2.44	<i>Immature Setaria italica</i>	0.84	0.57	<i>Pycreus sanguinolentus</i>	1.24	0.97
<i>Oryza sativa</i>	4.33	2.58	<i>Immature Setaria italica</i>	1.11	0.82	<i>Pycreus sanguinolentus</i>	0.97	0.61
<i>Oryza sativa</i>	4.61	2.76	<i>Immature Setaria italica</i>	0.87	0.75	<i>Pycreus sanguinolentus</i>	0.87	0.75
<i>Oryza sativa</i>	4.9	2.73	<i>Immature Setaria italica</i>	0.89	0.6	<i>Pycreus sanguinolentus</i>	1.13	0.86
<i>Oryza sativa</i>	4.67	2.76	average value of immature <i>S. italica</i>	0.90	0.71	Common millet field weeds		
<i>Oryza sativa</i>	4.88	2.61	standard deviation of immature <i>S. italica</i>	0.12	0.10	<i>Digitaria sanguinalis</i>	1.87	1.16
<i>Oryza sativa</i>	4.78	2.78	<i>Panicum miliaceum</i>	1.83	1.77	<i>Digitaria sanguinalis</i>	1.89	1.12
<i>Oryza sativa</i>	4.73	2.65	<i>Panicum miliaceum</i>	2.1	1.8	<i>Digitaria sanguinalis</i>	1.98	1.13
<i>Oryza sativa</i>	5.05	2.64	<i>Panicum miliaceum</i>	1.91	1.74	<i>Digitaria sanguinalis</i>	1.92	1.06
<i>Oryza sativa</i>	4.56	2.36	<i>Panicum miliaceum</i>	2.05	2.03	<i>Digitaria sanguinalis</i>	1.87	1.17
<i>Oryza sativa</i>	4.78	2.54	<i>Panicum miliaceum</i>	2.11	1.81	<i>Digitaria sanguinalis (with husk)</i>	1.87	1.32
<i>Oryza sativa</i>	4.77	2.54	<i>Panicum miliaceum</i>	2.05	1.74	<i>Digitaria sanguinalis (with husk)</i>	1.83	1.23
<i>Oryza sativa</i>	4.45	2.68	<i>Panicum miliaceum</i>	1.96	1.7	<i>Digitaria sanguinalis (with husk)</i>	1.59	1.17
<i>Oryza sativa</i>	4.67	2.78	<i>Panicum miliaceum</i>	1.94	1.69	<i>Digitaria sanguinalis</i>	1.88	1.2
<i>Oryza sativa</i>	4.93	2.44	<i>Panicum miliaceum</i>	1.98	1.7	<i>Digitaria sanguinalis</i>	1.78	1.04
<i>Oryza sativa</i>	5.02	2.57	<i>Panicum miliaceum</i>	2.21	1.82	<i>Setaria viridis</i>	1.46	0.73
<i>Oryza sativa</i>	4.56	2.66	<i>Panicum miliaceum</i>	1.91	1.72	<i>Setaria viridis</i>	1.21	0.89
<i>Oryza sativa</i>	4.89	2.56	<i>Panicum miliaceum</i>	1.94	1.69	<i>Setaria viridis</i>	1.41	0.95
<i>Oryza sativa</i>	4.96	2.62	<i>Panicum miliaceum</i>	2.25	1.91	<i>Setaria viridis</i>	1.56	0.98
<i>Oryza sativa</i>	4.78	2.83	<i>Panicum miliaceum</i>	2.23	1.92	<i>Setaria viridis</i>	1.6	0.91
<i>Oryza sativa</i>	4.89	2.81	<i>Panicum miliaceum</i>	2.01	1.74	<i>Setaria viridis</i>	1.44	0.98
<i>Oryza sativa</i>	4.83	2.74	<i>Panicum miliaceum</i>	2.14	1.77	<i>Setaria viridis</i>	1.38	0.7

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<i>Oryza sativa</i>	4.94	2.66	<i>Panicum miliaceum</i>	1.96	1.68	<i>Setaria viridis</i>	1.52	0.93
<i>Oryza sativa</i>	4.77	2.41	<i>Panicum miliaceum</i>	2.04	1.93	<i>Setaria viridis</i>	1.37	0.71
<i>Oryza sativa</i>	4.61	2.5	<i>Panicum miliaceum</i>	2.07	1.95	<i>Setaria viridis</i>	1.46	0.92
<i>Oryza sativa</i>	4.78	2.86	<i>Panicum miliaceum</i>	2.17	1.87	<i>Setaria viridis</i>	1.59	1
<i>Oryza sativa</i>	4.72	2.84	<i>Panicum miliaceum</i>	2.07	1.79	<i>Chenopodium album</i>	0.9	0.79
<i>Oryza sativa</i>	4.61	2.47	average value of <i>P. miliaceum</i>	2.04	1.80	<i>Chenopodium album</i>	0.91	0.85
<i>Oryza sativa</i>	4.88	2.45	standard deviation of <i>P. miliaceum</i>	0.11	0.10	<i>Chenopodium album</i>	1.22	1.03
average value of <i>O. sativa</i>	4.7	2.5	<i>Immature Panicum miliaceum</i>	1.17	1.08	<i>Chenopodium album</i>	0.89	0.84
standard deviation of <i>O. sativa</i>	0.3	0.2	<i>Immature Panicum miliaceum</i>	1.31	1.11	<i>Chenopodium album</i>	0.94	0.91
<i>Immature Oryza sativa</i>	4.61	2.03	<i>Immature Panicum miliaceum</i>	1.17	1.09	<i>Chenopodium album</i>	0.94	0.92
<i>Immature Oryza sativa</i>	4.16	1.45	<i>Immature Panicum miliaceum</i>	1.18	1.11	<i>Chenopodium album</i>	0.94	0.8
<i>Immature Oryza sativa</i>	4.15	1.55	<i>Immature Panicum miliaceum</i>	1.41	1.33	<i>Chenopodium album</i>	0.95	0.89
<i>Immature Oryza sativa</i>	4.21	1.37	<i>Immature Panicum miliaceum</i>	1.01	0.98	<i>Chenopodium album</i>	0.9	0.8
<i>Immature Oryza sativa</i>	4.68	1.67	<i>Immature Panicum miliaceum</i>	1.11	1	<i>Chenopodium album</i>	0.82	0.75
<i>Immature Oryza sativa</i>	3.23	1.87	<i>Immature Panicum miliaceum</i>	1.14	1.06	<i>Chenopodium album</i>	0.82	0.75
<i>Immature Oryza sativa</i>	4.6	1.84	<i>Immature Panicum miliaceum</i>	1.19	1.06	<i>Chenopodium album</i>	0.89	0.8
<i>Immature Oryza sativa</i>	4.58	1.9	<i>Immature Panicum miliaceum</i>	1.21	1.08	<i>Chenopodium album</i>	1.24	1.13
<i>Immature Oryza sativa</i>	4.71	1.67	<i>Immature Panicum miliaceum</i>	1.15	0.99	<i>Oxalis corniculata</i>	1.5	0.92
<i>Immature Oryza sativa</i>	3.93	1.89	<i>Immature Panicum miliaceum</i>	1.09	1.01	<i>Cyperus iria</i>	1.04	0.49
<i>Immature Oryza sativa</i>	4.19	1.76	<i>Immature Panicum miliaceum</i>	1.21	1.12	<i>Amethystea caerulea</i>	1.23	0.83
<i>Immature Oryza sativa</i>	4.47	1.88	<i>Immature Panicum miliaceum</i>	1.28	1.13	<i>Amethystea caerulea</i>	2	1.04
<i>Immature Oryza sativa</i>	4.57	1.85	<i>Immature Panicum miliaceum</i>	1.3	1.21	<i>Amethystea caerulea</i>	1.96	0.99
<i>Immature Oryza sativa</i>	3.98	1.62	<i>Immature Panicum miliaceum</i>	1.12	1.04	<i>Acalypha australis</i>	1.67	0.7
<i>Immature Oryza sativa</i>	4.76	1.59	<i>Immature Panicum miliaceum</i>	1.11	0.87	<i>Cirsium arvense</i>	3.15	1.2
<i>Immature Oryza sativa</i>	4.58	1.76	<i>Immature Panicum miliaceum</i>	1.08	1.02	<i>Suaeda glauca</i>	1.06	1.03
<i>Immature Oryza sativa</i>	4.32	1.89	<i>Immature Panicum miliaceum</i>	1.11	0.91	<i>Galium tricoratum</i>	1.73	1.5
<i>Immature Oryza sativa</i>	4.28	1.88	<i>Immature Panicum miliaceum</i>	1.16	1.04	<i>Physalis angulate</i>	1.4	1.12
<i>Immature Oryza sativa</i>	4.26	1.89	<i>Immature Panicum miliaceum</i>	1.29	1.15	<i>Plantago asiatica</i>	1.7	1.1
<i>Immature Oryza sativa</i>	4.57	1.67	average value of immature <i>P. miliaceum</i>	1.18	1.07	<i>Plantago asiatica</i>	1.52	0.8
<i>Immature Oryza sativa</i>	4.5	1.9	standard deviation of immature <i>P. miliaceum</i>	0.09	0.10	<i>Abutilon theophrasti</i>	2.9	2.3
<i>Immature Oryza sativa</i>	3.8	1.7				<i>Hibiscus trionum</i>	2.7	2.3

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<i>Immature Oryza sativa</i>	3.9	1.3				<i>Malva cathayensis</i>	2	2
<i>Immature Oryza sativa</i>	3.6	1.4						
<i>Immature Oryza sativa</i>	4.1	1.9						
<i>Immature Oryza sativa</i>	3.8	1.5						
<i>Immature Oryza sativa</i>	3.9	1.5						
<i>Immature Oryza sativa</i>	3.6	1.9						
<i>Immature Oryza sativa</i>	3.1	1.4						
<i>Immature Oryza sativa</i>	3.3	1.9						
<i>Immature Oryza sativa</i>	3.4	1.8						
<i>Immature Oryza sativa</i>	3.9	1.5						
<i>Immature Oryza sativa</i>	3.9	1.6						
<i>Immature Oryza sativa</i>	4.3	1.9						
<i>Immature Oryza sativa</i>	2.77	1.21						
<i>Immature Oryza sativa</i>	4.09	1.87						
<i>Immature Oryza sativa</i>	4.29	2.67						
<i>Immature Oryza sativa</i>	4.17	2.43						
<i>Immature Oryza sativa</i>	4.22	2.11						
<i>Immature Oryza sativa</i>	3.87	1.46						
<i>Immature Oryza sativa</i>	3.94	2.04						
average value of immature <i>O. sativa</i>	4.1	1.8						
standard deviation of immature <i>O. sativa</i>	0.5	0.3						

**Najas marina* is not a typical rice field weed but it grows on the edge of rice field, therefore can be easily mixed with rice grains while harvesting.

Appendix

Table II. 5 Measurement data of soybean seeds and wild soybean seeds (mm)

Serial No.	Soybean from the Xinzhai site		Modern soybeans*		Wild soybean from the Xinzhai site	
	Length	Width	Length	Width	Length	Width
1	2.6	1.9	6.92	6.01	2.49	1.7
2	4.2	3.3	7.17	5.93	2.42	1.55
3	4.5	2.5	7.99	6.21	2.99	2.4
4	4.6	2.8	8.56	6.14	2.69	1.96
5	3.3	2.4	6.91	6.08	3.05	2.6
6	2.2	1.8	7.48	6.61	2.99	2.2
7	3.5	2.5	7.46	6.32	2.52	1.61
8	5.1	2.8	7.33	6.56	3.33	2.78
9	3.8	2.4	7.25	5.7	3.12	2.56
10	2.6	2.1	8.15	5.93	2.56	1.88
11	2.8	1.8	7.14	6.03	2.97	1.9
12	4.7	2.9	6.86	6.01		
13	2.5	1.9	7.79	6.69		
14	3.6	2.4	7.45	5.62		
15	5.2	2.8	7.54	5.07		
16	3.4	1.7	7.21	6.6		
17	3.4	2.0	8.42	6.57		
18	3.2	1.9	6.75	5.99		
19	2.7	1.7	7.22	5.89		
20	2.2	1.5	7.92	5.96		
21	2.5	1.8	7.35	6.45		
22	5.1	2.6	7.89	6.16		
23	3.3	2.3	7.11	6.66		
24	5.0	2.3	6.75	5.67		
25	3.8	2.3	8.44	6.34		
26	3.6	2.6	7.27	5.93		
27	5.1	2.3	7.14	5.77		
28	3.8	2.3	7.17	6.43		
29	4.0	2.1	7.82	6.54		
30	4.6	2.8	6.55	6.11		
31	4.1	2.6	6.34	5.83		
32	3.6	2.4	7.94	6.32		
33	3.4	1.9	7.74	6.6		
34	3.6	2.2	7.88	6.53		
35	4.4	2.9	5.66	5.23		
36	5.1	3.0	6.55	5.96		
37	5.3	2.8	7.22	6.03		
38	4.6	3.2	7.93	6.37		
39	4.2	3.3	8.17	6.08		
40	2.8	2.0	7.74	6.74		
41	2.6	1.9	8.16	6.06		
42	2.8	1.9	7.45	6.16		
43	2.7	2.1	6.84	6.74		
44	2.9	2.1	6.97	6.01		
45	2.9	1.7	7.48	6.71		
46	6.1	4.1	7.43	6.11		
47	5.7	3.6	7.24	5.88		
48	5.4	3.3	8.31	6.59		
49	4.8	3.2	7.61	6.45		
50	5.5	3.2	7.01	6.2		
51	5.2	2.7	7.89	6.48		
52	5.2	3.4	7.72	6.3		
53	5.9	3.1	7.22	6.56		
54	5.9	3.3	8.14	6.61		
55	5.0	3.1	7.61	6.17		

Appendix

56	4.9	3.2	7.43	6.42		
57	5.4	3.4	6.83	6.09		
58	5.2	3.4	8.16	5.69		
59	4.5	3.2	7.14	5.86		
60	5.2	2.9	7.51	6.47		
61	5.3	3.0	8.43	5.62		
62	3.6	2.4	7.52	6.04		
63	3.2	2.3	7.4	6.34		
64	3.9	2.1	7.47	6.61		
65	3.0	2.2	7.78	6.35		
66	3.3	2.5	7.59	6.16		
67	3.5	1.9	8.17	5.39		
68	2.5	1.9	6.99	6.52		
69	3.5	2.9	6.24	5.44		
70	3.9	2.4	6.88	6.19		
71	3.8	2.2	7.32	5.75		
72	3.3	1.9	7.52	6.45		
73	3.4	2.1	7.22	6.3		
74	4.3	3.3	6.19	5.24		
75	5.0	3.3	7.66	5.02		
76	5.9	4.0	6.74	5.67		
77	3.7	2.7	7.62	5.78		
78	3.8	2.7	7.94	6.65		
79	5.1	2.7	8.91	6.06		
80	5.7	3.3	7.69	6.07		
81	4.4	3.1	7.76	5.85		
82	4.7	3.2	7.53	6.5		
83	4.2	3.2	8.23	5.82		
84	4.6	2.7	7.35	6.35		
85	4.4	2.4	7.38	6.35		
86	4.8	3.4	7.27	6.2		
87	5.8	3.9	7.42	6.04		
88	4.7	3.2	7.05	6.61		
89	3.1	1.9	7.08	6.17		
90	5.6	3.4	7.48	6.2		
91	5.5	3.3	7.25	6.16		
92	4.9	2.8	7.58	6.35		
93	5.7	3.1	6.82	5.9		
94	5.0	3.7	8.38	5.76		
95	4.4	2.8	6.84	6.04		
96	3.7	2.1	6.71	6.09		
97	2.9	1.9	7.27	5.88		
98	3.8	1.9	7.31	5.9		
99	4.1	2.8	6.96	5.93		
100	2.7	1.7	6.85	5.77		
average value	4.1	2.6	7.42	6.13	2.8	2.1
standard deviation	1.1	0.6	0.56	0.37	0.3	0.4

* Modern soybean measurement data from Zhao and Yang (2007).

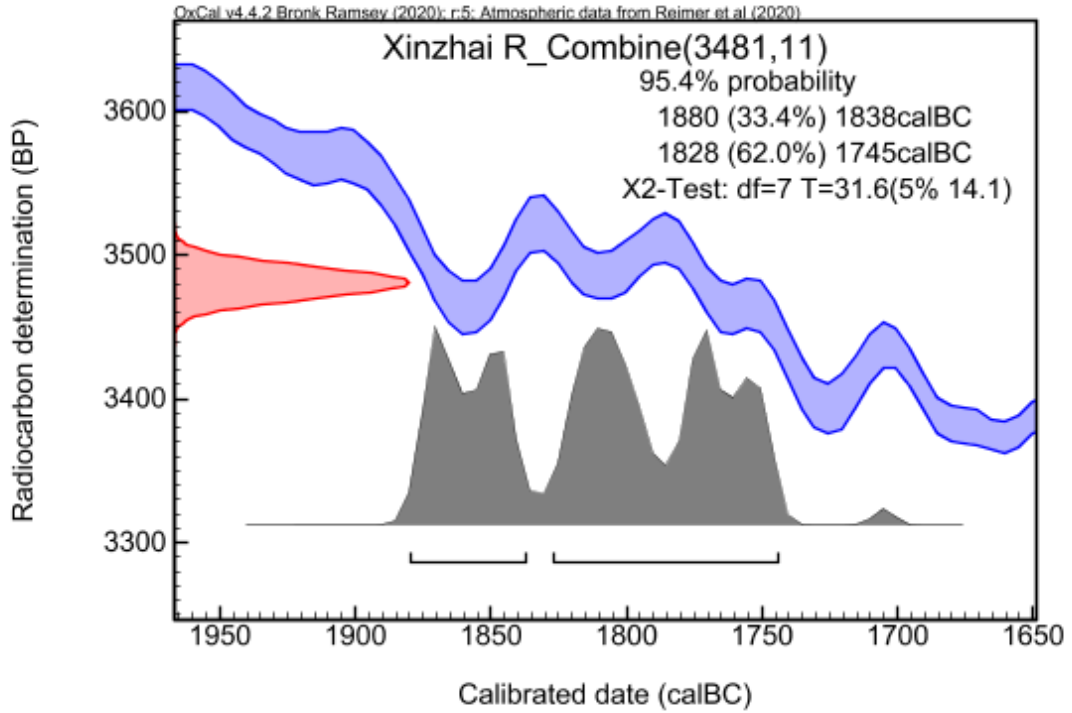
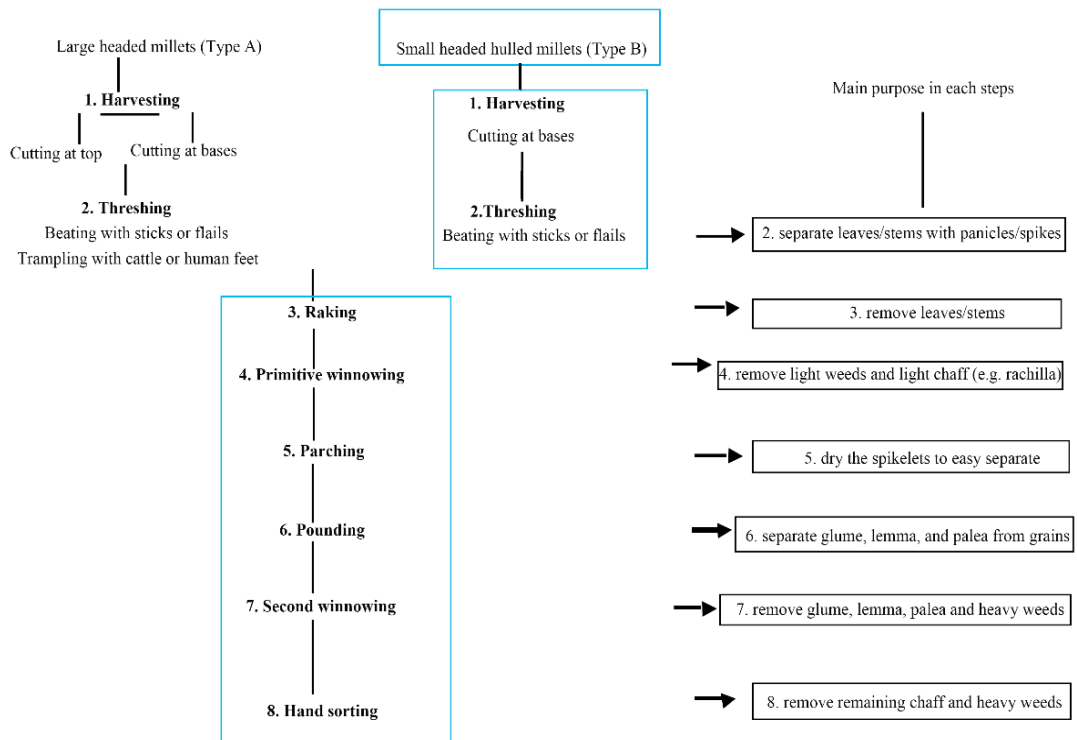
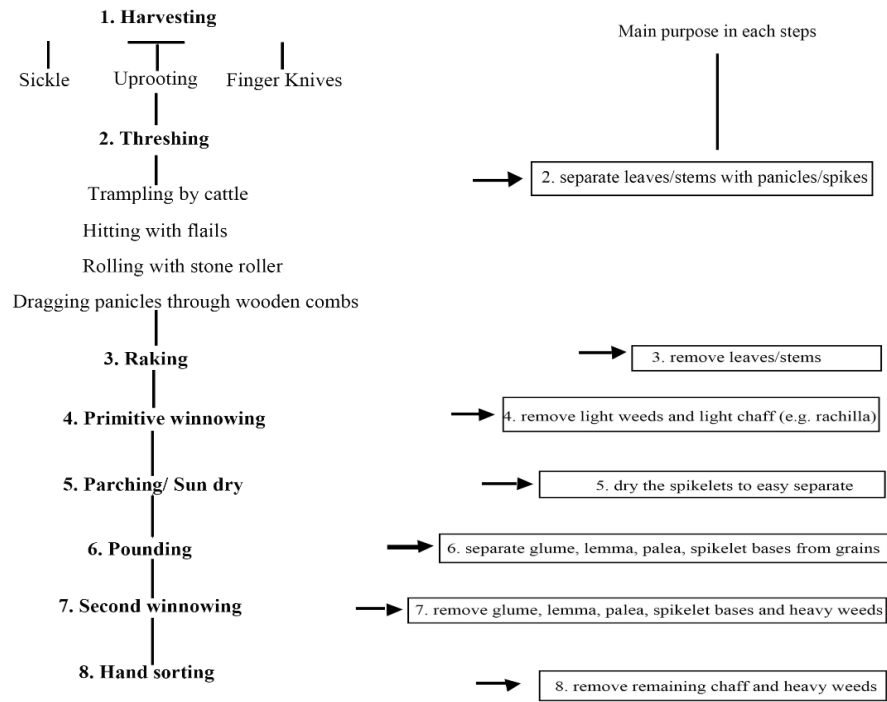


Figure II. 1 Oxcal plot of the combined AMS dating results of the Xinzhai site

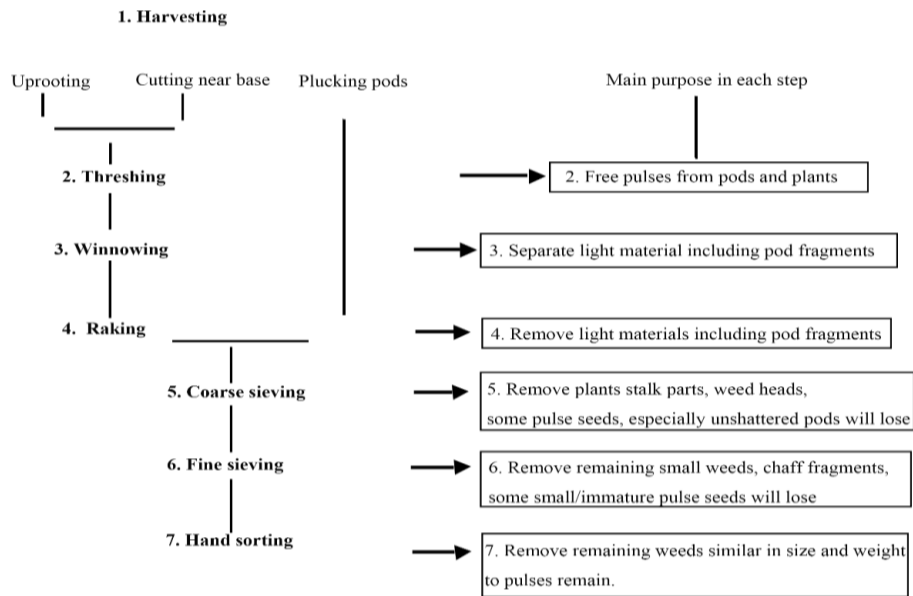


a

Appendix



b



c

Figure II. 2 General models for crop-processing of **a.** millet (follows Reddy 1994, Song et al. 2013, 2014); **b.** rice (follows Thompson 1992,1996, Harvey and Fuller 2005, Weisskopf 2010); **c.** soybean (follows Fuller and Weber 2005, Fuller and Harvey 2006); the point of storage is not fixed and occurs at any point during the processing, as such, storage is not present in any model

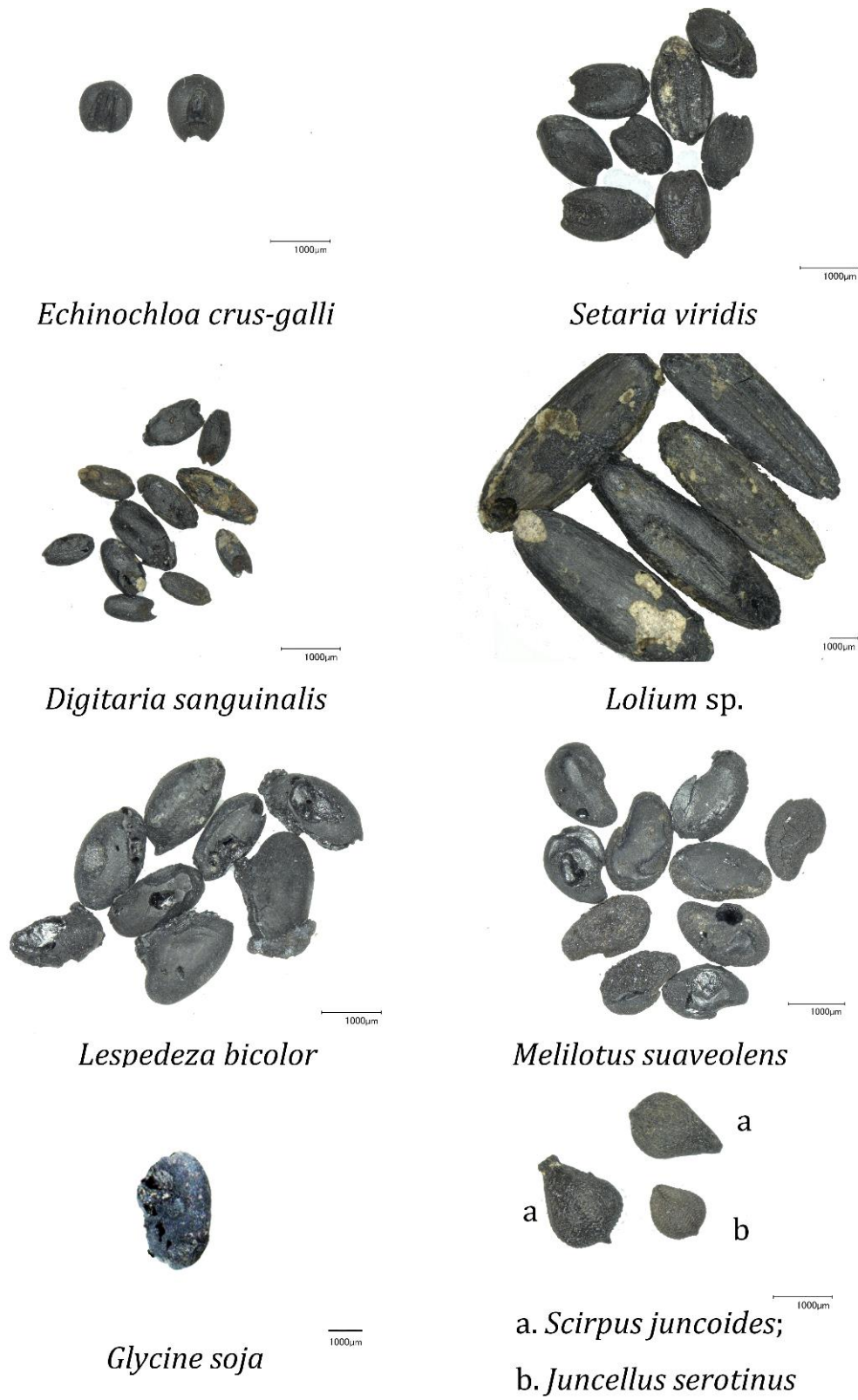


Figure II. 3 Macro-botanical remains-1 (photographed by JP An with Keyence microscope VHX-2000D)

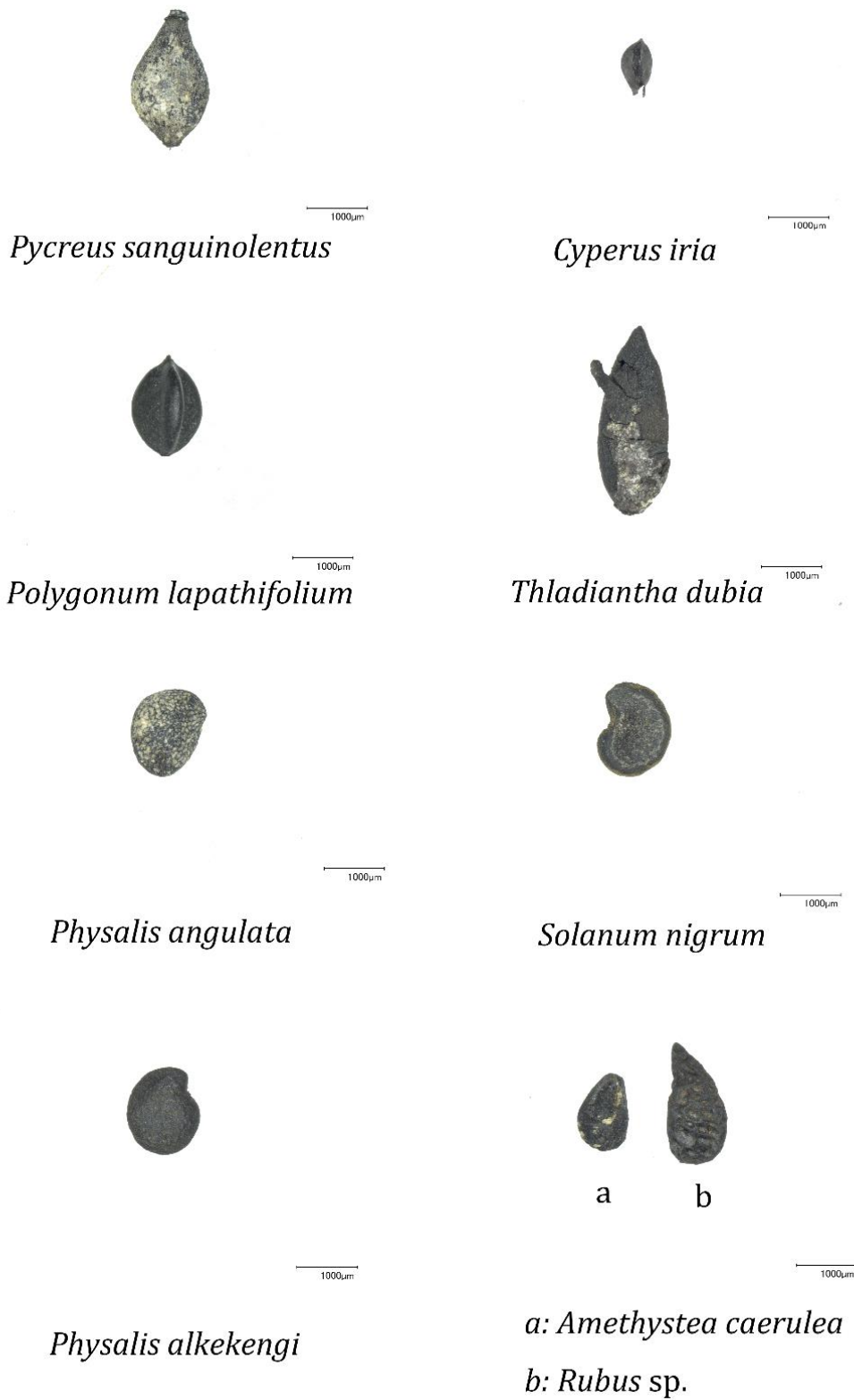


Figure II. 4 Macro-botanical remains-2 (photographed by JP An with Keyence microscope VHX-2000D)



1000µm

Viola verecunda



100µm

Oxalis corniculata



1000µm

Najas marina



1000µm

Galium tricornutum



1000µm

Chenopodium album



1000µm

Suaeda glauca



1000µm

Perilla frutescens

Figure II. 5 Macro-botanical remains-3 (photographed by JP An with Keyence microscope VHX-2000D)

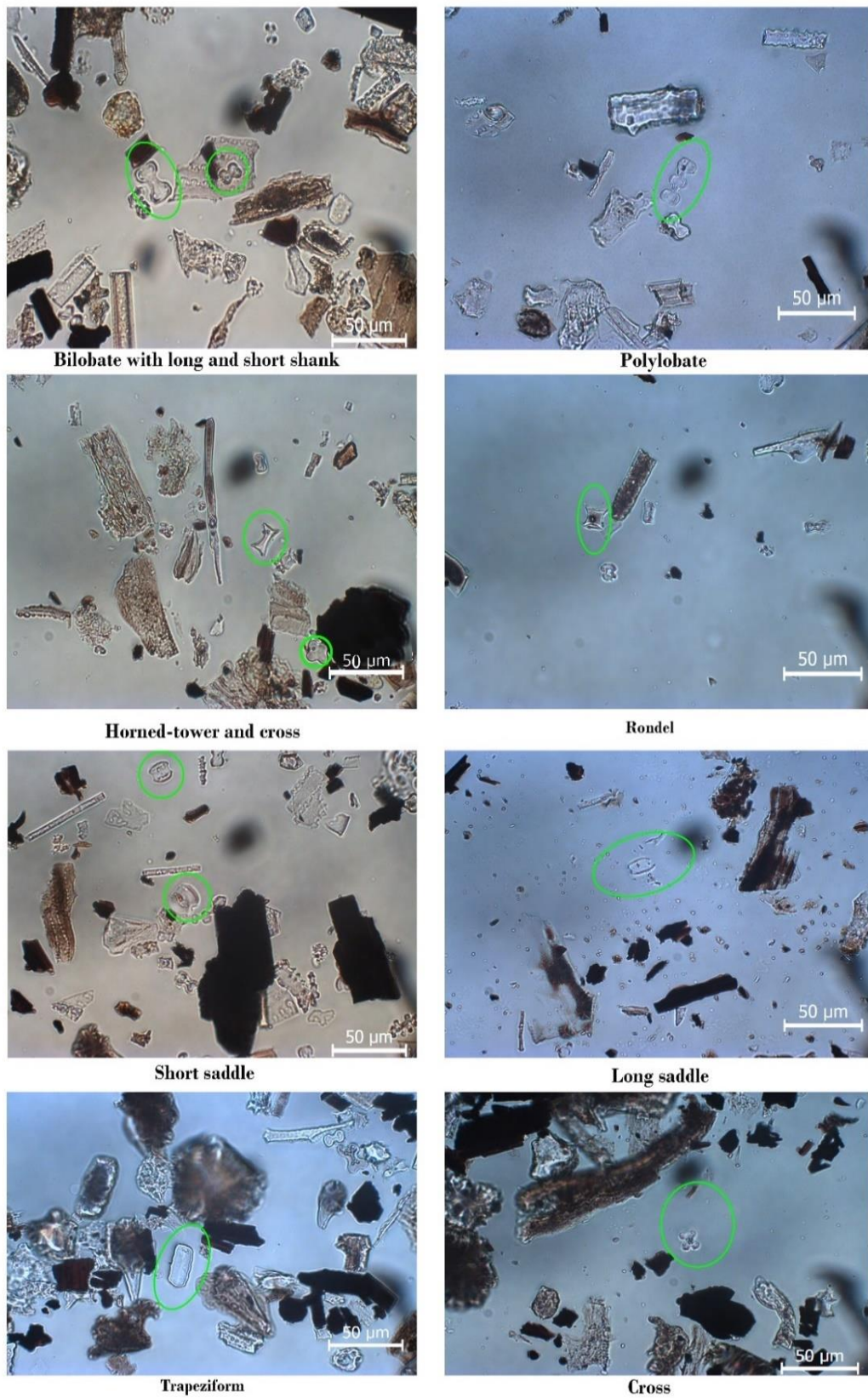


Figure II. 6 Phytolith morphotypes-1 (photographed by JP An)

Appendix

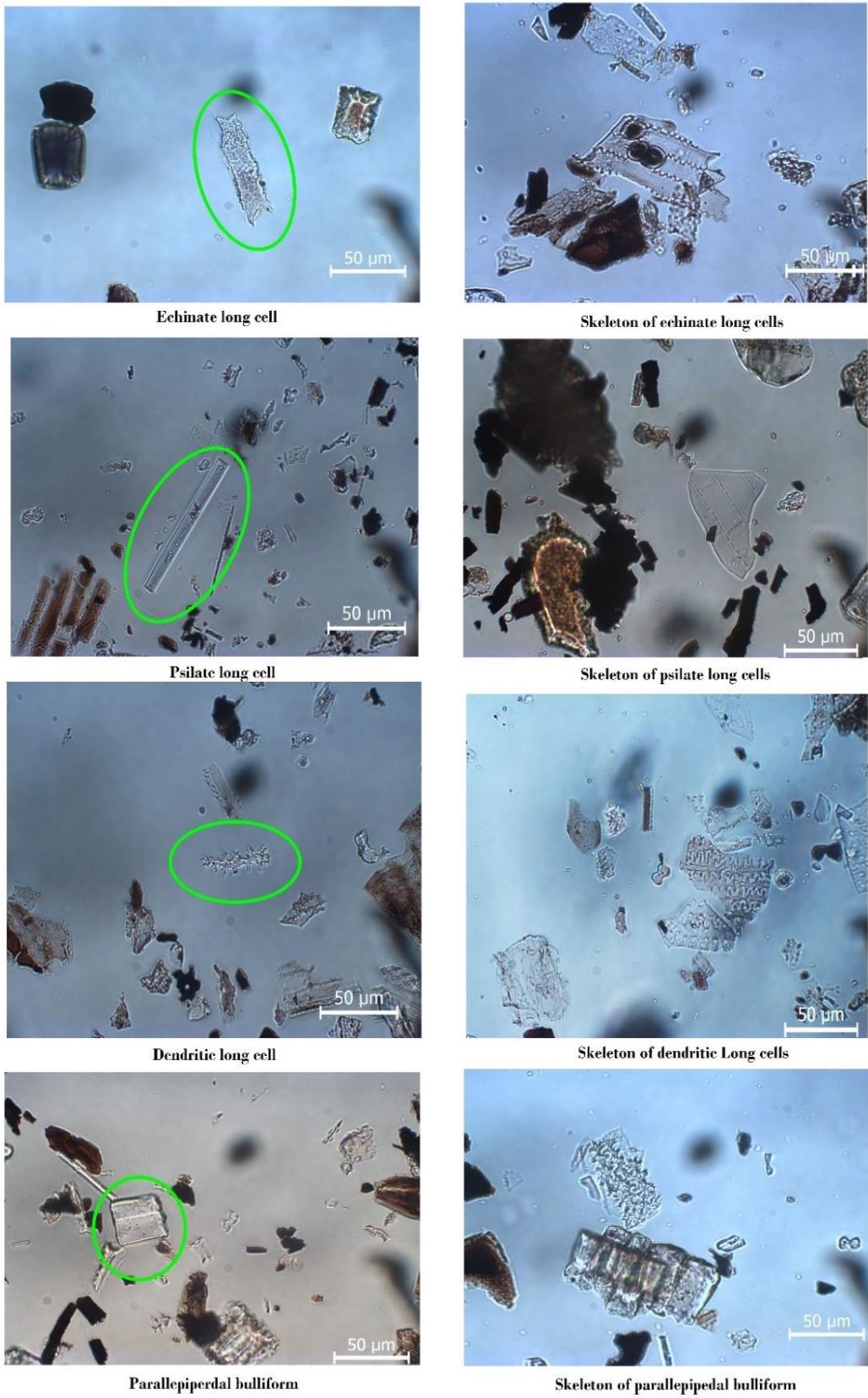


Figure II. 7 Phytolith morphotypes-2 (photographed by JP An)

Appendix

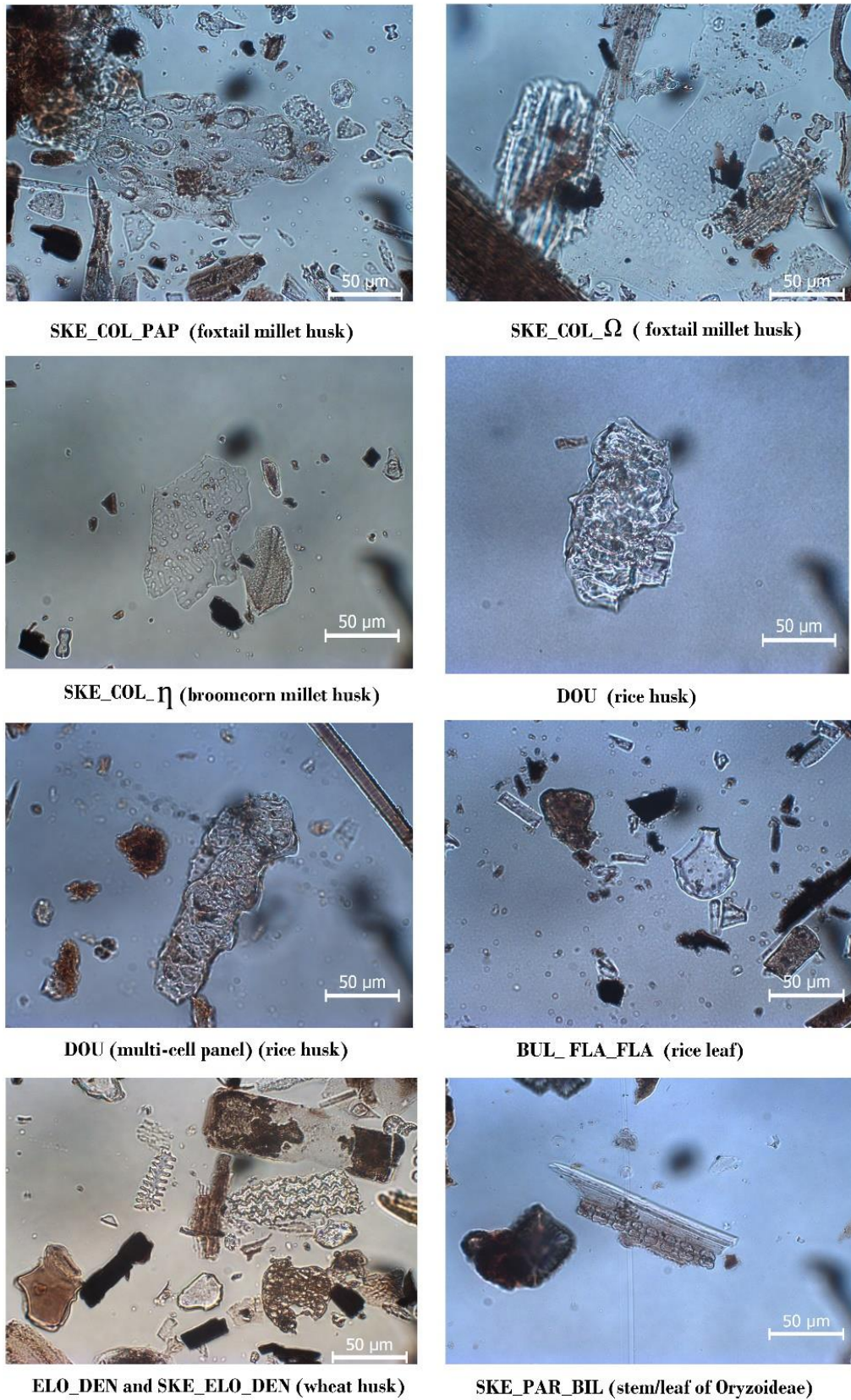


Figure II. 8 Phytolith morphotypes-3 (photographed by JP An)

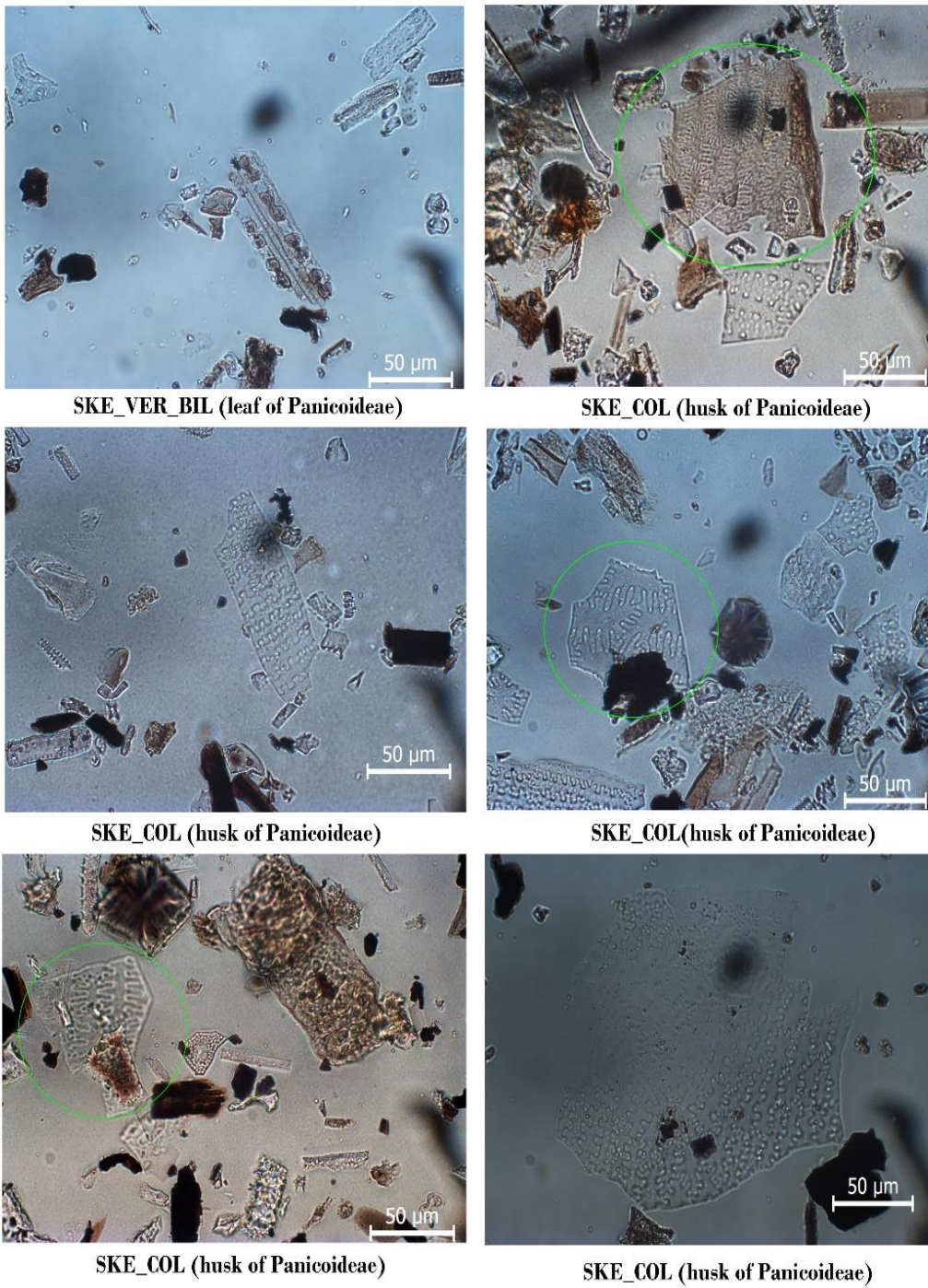


Figure II. 9 Phytolith morphotypes-4 (photographed by JP An)

Appendix III

Table III. 1 Absolute counts, ubiquities and RI values of cereal crops and oilseeds in each site in the Central Plain

Period [#]	Sites	Total seeds/fruits	Sample volumes	Information	Cereal crops				Oilseeds		
					<i>Setaria italica</i>	<i>Panicum miliaceum</i>	<i>Oryza sativa</i>	<i>Triticum aestivum</i>	<i>Glycine max</i>	<i>Glycine soja</i>	<i>Perilla frutescens</i>
Longshan	Wangchenggang	2601	59	Count	1442	124	17		153		3
				Ubiquity	72.2%	44.4%	16.7%		38.9%		5.08%
				RI value	112	32	16		56		4
Longshan	Guchengzhai	282	20	Count	241	18					
				Ubiquity	100%	36.4%					
				RI value	40	8					
Longshan	Wadian-1*	12190	255	Count	5253	1110	1231	22	905	24	604
				Ubiquity	63.1%	47.5%	45.5%	6.7%	40.8%	5.9%	12.9%
				RI value	150	50	140	20	70	10	30
Longshan	Wadian-2*	11537	139	Count	2253	385	1144	8	573	14	557
				Ubiquity	67%	49%	63%	5%	45%	10.1%	45%
				RI value	100	50	140	20	60	18	60
Longshan	Zhengzhou Shang City	1588	14	Count	268	52	1				
				Ubiquity	35.70%	14.30%	7.10%				
				RI value	14	6	1				
Longshan	Dalaidian	6734	88	Count	3341	216	1	2	44		
				Ubiquity	87%	51%	1.50%	1.50%	11%		
				RI value	140	80	4	8	28		
Longshan	Xijincheng	2162	37	Count	740	5	82	1	8		3
				Ubiquity	93.30%	10%	36.70%	3.30%	13.3%		8.1%
				RI value	70	4	4	24	7		1
Longshan	Chengyao	1345	19	Count	724	168	10	10	32		94
				Ubiquity	100%	25%	31.3%	6.3%	31.3%		25%
				RI value	35	12	3	4	4		14
Longshan	Xinzhai 1999	231	18	Count	62	/	134				
				Ubiquity	72.2%	11.1%	72.2%				
				RI value	3		16				
Xinzhai	Xinzhai 2014	8737	109	Count	5887	1035	381	1	150		49
				Ubiquity	99.1%	83.5%	43.6%	1%	35%		45%
				RI value	175	125	60	10	70		20

Xinzhai	Xinzhai 1999	789	13	Count	256	98	429				
				Ubiquity	38.5%	15.4%	84.6%				
				RI value	8	4	20				
Xinzhai	Dongzhao	3582	37	Count	2325	175				25	
				Ubiquity	54.5%	54.5%				/	
				RI value	56	32				15	
Xinzhai	Huadizui	1898	30	Count	1228	179	397		23		
				Ubiquity	73.3%	53.3%	66.7%		20%		
				RI value	60	32	56		14		
Xinzhai	Zhengzhou Shang City	225	4	Count	125	35					
				Ubiquity	100%	50%					
				RI value	20	12					
Erlitou	Erlitou phase I	322	1	Count	113	31	15				
				Ubiquity	100%	100%	100%				
				RI value	20	15	20				
Erlitou	Erlitou phase II	11983	62	Count	5653	977	3234		23		
				Ubiquity	80%	60%	78%		20%		
				RI value	100	100	140		28		
Erlitou	Erlitou phase III	1060	16	Count	599	24	58		39		
				Ubiquity	100%	50%	100%		30%		
				RI value	35	12	30		14		
Erlitou	Erlitou phase IV	7930	58	Count	3659	342	2358		38		1
				Ubiquity	100%	55%	70%		56%		4%
				RI value	100	80	112	12	112		4
Erlitou	Nanwa (Erlitou I)	1837	6	Count	587	35			1		
				Ubiquity	100%	83%			17%		
				RI value	35	15			7		
Erlitou	Nanwa (Erlitou II)	21165	63	Count	7667	623	3	6	74	17	
				Ubiquity	80%	42%	2%	7%	26%	19%	
				RI value	140	40	8	16	56	8	
Erlitou	Nanwa (Erlitou III)	2090	11	Count	1166	107	6		19		
				Ubiquity	100%	72%	9%		46%		
				RI value	35	16	2		7		
Erlitou	Nanwa (Erlitou IV)	3090	2	Count	1470	113	1				
				Ubiquity	100%	100%	50%		100%		
				RI value	35	20	4		14		
Erlitou	Guchengzhai (Erlitou III)	63	6	Count	52	3		1			

				Ubiquity	83%	16.7%		16.7%		
				RI value	15	1		2		
Erlitou	Guchengzhai (Erlitou IV)	778	2	Count	60	10			2	
				Ubiquity	100%	100%			50%	
				RI value	15	10			4	
Erlitou	Huizui	4549	87	Count	1246	133	34	24		
				Ubiquity	93.1%	46%	16%	<25%		
				RI value	70	16	8	8		
Erlitou	Dongzhao	16391	164	Count	10303	1798	31	7	176	
				Ubiquity	95.1%	65.9%	14.6%	8.5%	53.7%	
				RI value	175	120	20	20	140	
Erlitou	Wangchenggang	21	26	Count		1		2	2	
				Ubiquity		3.8%		7.7%	7.7%	
				RI value		4		8	2	
Erlitou	Zhengzhou Shang City	9	3	Count	6	2	1			
				Ubiquity	66.7%	66.7%	33.3%			
				RI value	4	4	4			
E-Erligang	Erlitou	4	1	Count	1	1				
				Ubiquity	100%	100%				
				RI value	5	5				
L-Erligang	Erlitou	102242	19	Count	1034	167	22	5	26	
				Ubiquity	/	/	/	/	/	
				RI value	7	4	4	3	7	
L-Erligang	Guchengzhai	155	4	Count	124	1		1		
				Ubiquity	100%	25%		25%		
				RI value	20	2		4		
Yinxu	Guchengzhai	551	1	Count	463	21		2		
				Ubiquity	100%	50%		13%		
				RI value	20	12		2		
L-Erligang	Guchengzhai	289	15	Count	204	15		5		
				Ubiquity	100%	53%		27%		
				RI value	20	8		6		
L-Erligang	Zhenzhou Shang City	543	3	Count	449	23	15			
				Ubiquity	100%	100%	100%			
				RI value	20	15	20			
L-Erligang	Zhengzhouhoubian	881	7	Count	657	13	95	39		
				Ubiquity	100%	29%	86%	57.1%		

				RI value	20	4	20	16			
L-Erligang	Hengligongyu	168	7	Count	137	4	9	4			
				Ubiquity	100%	28.6%	71.4%	57.1%			
				RI value	20	4	12	12			
L-Erligang	Hanghezongyue	226	1	Count	143	2	27	25			
				Ubiquity	100%	100%	100%	100%			
				RI value	20	5	10	10			
L-Erligang	Zhongyixueyuan	255	2	Count	168	2	43	21			
				Ubiquity	100%	50%	100%	100%			
				RI value	20	4	20	20			
Erligang	Wangchenggang	3582	14	Count	1534	160	30	191	12		
				Ubiquity	100%	90.9%	72.7%	100%	36.4%		
				RI value	30	20	16	35	14		
Yinxu	Wangchenggang	236	2	Count	108	13	1	60			
				Ubiquity	100%	100%	50%	100%			
				RI value	20	10	4	20			
Erligang	Dongzhao	2625	37	Count	1543	239	3	103	158		
				Ubiquity	100%	77.3%	13.6%	59%	54.5%		
				RI value	60	50	4	48	56		
Yinxu	Nanwa	1479	12	Count	847	39		16	28		
				Ubiquity	83%	58%		33%	17%		
				RI value	35	12		4	7		

*Wadian-1 from Liu et al. (2018) and Wadian-2 from Liu and Fang (2010).

#E-Erligang: Early Erligang; L-Erligang: Late Erligang.

Table III. 2 Information of arable weeds in the Central Plain (absolute counts)

Periods ¹	Sites	Juncaceae	Portulacaceae	Poaceae					Cyperaceae			
		<i>Arenaria serpyllifolia</i>	<i>Portulaca oleracea</i>	<i>Poa annua</i>	<i>Setaria viridis</i>	<i>Paspalum Thunbergii</i>	<i>Eriochloa villosa</i>	<i>Digitaria sanguinalis</i>	<i>Carex Diandra</i>	<i>Carex rigescens</i> <i>Carex duriuscula</i>	<i>Scirpus juncoides</i> <i>Schoenoplectus juncoides</i>	<i>Pycnus Sanguinolentus</i>
Species name after Li, 1998*												
Species name after iPlant [#]												
Height ²		Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
Longshan	Guchengzhai				12							
Longshan	Wadian-1	2			442			823		7	44	
Longshan	Wadian-2		5		2817			509				
Longshan	Dalaidian				157			430				
Longshan	Xijincheng			3								
Xinzhai	Xinzhai 2014				292	1		94	3		4	2
Xinzhai	Dongzhao				457		24	48				
Xinzhai	Huadizui				62			1				
Erlitou I	Erlitou				163							
Erlitou II	Erlitou				1977			17				
Erlitou III	Erlitou				299			1				
Erlitou III	Guchengzhai				3							
Erlitou IV	Erlitou				947			260				
Erlitou IV	Guchengzhai				7							
Erlitou	Dongzhao				2871		48	265				
E-Erligang	Guchengzhai				23							
L-Erligang	Erlitou				688			516				
L-Erligang	Guchengzhai				29							
Erligang	Dongzhao				471		5	15				
Yinxu	Guchengzhai				45							

Periods	Sites	Cyperaceae	Geraniaceae	Potamogetonaceae	Violaceae	Polygonaceae		Poaceae			Malvaceae	Cyperaceae
Species name after Li, 1998		<i>Fimbristylis Dichotoma</i>	<i>Erodium stephanianum</i>	<i>Potamogeton distinctus</i>	<i>Viola verecunda</i>	<i>Polygonum lapathifolium</i>	<i>Rumex acetosa</i>	<i>Eleusine indica</i>	<i>Digitaria chrysoblephara</i>	<i>Agrostis matsumurae</i>	<i>Hibiscus trionum</i>	<i>Salsola Collina</i>
Species name after iPlant					<i>Viola arcuata</i>				<i>Digitaria ciliaris</i>	<i>Agrostis clavata</i>		
Height		Low	Low	Low	Low	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Longshan	Wadian-1	1	2	5	4	2			4	5		1
Longshan	Wadian-2	1						3				
Xinzhai	Xinzhai 2014		1	1	1		2					
Xinzhai	Zhengzhou Shang City										1	
Erlitou IV	Erlitou											2
Erlitou	Dongzhao							1				
L-Erligang	Erlitou											2
Yinxu	Guchengzhai							1				

Periods	Sites	Lamiaceae	Lamiaceae	Cyperaceae			Verbenaceae	Amaranthaceae	Euphorbiaceae	Solanaceae
Species name after Li, 1998		<i>Amethystea caerulea</i>	<i>Amethystea caerulea</i>	<i>Scirpus triangulatus</i>	<i>Juncellus serotinus</i>	<i>Scirpus triquetar</i>	<i>Verbena officinalis</i>	<i>Amaranthus retroflexus</i>	<i>Acalypha australis</i>	<i>Physalis angulate</i>
Species name after iPlant				<i>Schoenoplectus mucronatus</i>	<i>Cyperus serotinus</i>	<i>Schoenoplectus triquetar</i>				
Height		Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Longshan	Wangchenggang	15	15							15
Longshan	Wadian-1	16	16			8	1			37
Longshan	Wadian-2	10	10						23	36
Longshan	Dalaidian	3	3						3	6
Xinzhai	Xinzhai 2014	1	1		39				8	2
Xinzhai	Dongzhao								2	
Xinzhai	Huadizui			1						
Erlitou II	Erlitou	1	1							
Erlitou III	Erlitou	1	1							
Erlitou IV	Erlitou	22	22							
Erlitou	Dongzhao							9	31	
L-Erligang	Erlitou	44	44							
Erligang	Dongzhao							3	3	

Periods	Sites	Poaceae	Gramineae	Gramineae	Cyperaceae	Lamiaceae	Asteraceae	Malvaceae	Cucurbitaceae	Cannabaceae	Rubiaceae
Species name after Li, 1998		<i>Avena fatua</i>	<i>Echinochloa crus-galli</i>	<i>Echinochloa</i> sp.	<i>Chenopodium album</i>	<i>Lycopus lucidus</i>	<i>Xanthium sibiricum</i>	<i>Abutilon theophrasti</i>	<i>Thladiantha dubia</i>	<i>Humulus scandens</i>	<i>Galium tricornae</i>
Species name after iPlant							<i>Xanthium strumarium</i>				<i>Galium tricornutum</i>
Height		High	High	/	High	High	High	High	Climbing	Climbing	Climbing
Longshan	Wangchenggang				10						
Longshan	Guchengzhai		2		7						
Longshan	Wadian-1	9	116		653		9	1	9	1	
Longshan	Wadian-2			77	337		1		11		
Longshan	Dalaidian				1096				13		1
Longshan	Xijincheng				21						
Xinzhai	Xinzhai 2014		1		314	1		2	5		
Xinzhai	Dongzhao			12							
Erlitou I	Nanwa				5						
Erlitou II	Erlitou				37						
Erlitou II	Nanwa				2525						
Erlitou III	Erlitou				4				4		
Erlitou III	Guchengzhai				3						
Erlitou III	Nanwa				27						
Erlitou IV	Erlitou				161				1		
Erlitou IV	Nanwa				5						
Erlitou	Dongzhao			142	1						
E-Erligang	Guchengzhai				2						
E-Erligang	Hengligongyu				1						
E-Erligang	Zhongyixueyuan						2				
L-Erligang	Erlitou								5		
L-Erligang	Guchengzhai		2		13						
Erligang	Dongzhao			18							
Yinxu	Guchengzhai		3		6						

*In this research, plant nomenclature follows the *Chinese weed flora* (Li, 1998) and cf. species are included in the database as well.

the scientific name of some species are updated. New scientific names can be found in the *Plant Plus of China* (see www.iPlant.cn) that hosted by the State Key Laboratory of Systematic and Evolutionary Botany Institute of Botany, the Chinese Academy of Sciences (LSEB, IB, CAS).

1. E-Erligang: Early-Erligang; L-Erligang: Late Erligang.

2. The height of each plant species is the mean value = (the maximum height + the minimum height)/2; Height- H(high): above 80 cm, M(middle): 40-80 cm, L(low): below 40 cm.

Appendix IV

Table IV. 1 Information of samples dates and archaeological contexts

Sites	Period*	References	Waste pits	Pots	Houses	Cultural layers	Hearths	Kiln	Waste ditches	Post-holes	Burials	Wells	Activity surfaces	Wall foundations
Ningjiabu	Early Longshan	Luan 2016	12											
Huangnsangyuan	Longshan	Zhang F et al. 2018	2				1							
Pengjiazhuang	Longshan	Wu et al. 2010	2											
Dinggong	Longshan	Luan 2016;Wu et al. 2018	68		16	12				2				
Fangjia	Early Longshan	Luan 2016	20						2					
Tonglin	Longshan	Luan 2016	70	5	1	2			6				1	
Shilipubei	Middle and Late Longshan	Luan 2016	83		2									
Zhuanglixi	Middle and Late Longshan	Kong et al. 1999	13											
Haojiatai	Longshan	Peking University et al. 2017	66		3	2		2	11					
Pingliangcheng	Middle and Late Longshan from 4355±175 to 4130 BP	Wu 2011	50						5		3	1		
Beitaishang	Longshan	Wang 2018	240		6				16		6			
Wangjiacun	Early Longshan	Ma et al. 2015	*											
Wutai	Early Longshan	Luan 2016; Chen et al. 2019	83+28(post-pits)		2	24	1			28	18			
Xuejiazhuang	Early Longshan	Jin et al. 2010	8											
Zhaojiazhuang	Phase 1-Phase 3 4400-4100 cal. BP	Jin et al. 2011	*								*			
Liangchengzhen	Longshan	Crawford et al. 2005	222	49	19	43			3	8	12		15	

	4600-3900 cal. BP													
Liujiashuang	Early Longshan	Luan 2016	29						1	5				
Dongpan	Early Longshan	Luan 2016	132		1	1			2	11	6			
Houyangguanzhuang	Early Longshan	Luan 2016	5											
Yangpu	Longshan	Cheng et al. 2016	4			1								
Luchengzi	Longshan	Wang et al. 2016	*											
Yuchisi	Longshan	AICASS 2001; Luan 2016	9						1					
Gongzhuang	Early Longshan 4630-4030 cal. BP	Cheng et al. 2019	2		1	3								
Yuhuicun	Late Longshan	Yin 2013	29+3(sacrifice pit)	1	4	15			13(sacrifice ditches)		1		1	
Diaoyutai	Late Longshan	Zhang J et al. 2018	8		1	4			3	1				1

*There are different cultural divisions of the Longshan culture (see Luan 2016): 1. early Longshan (2400-2200 cal. BCE), middle Longshan (2200-2000 cal. BCE), late Longshan (2000-1800 cal. BCE); 2. Phase 1: 2400-2300 cal. BCE, phase 2: 2300-2200 cal. BCE, phase 3: 2200-2100 cal. BCE, phase 4: 2100-2000 cal. BCE, phase 5: 2000-1900 cal. BCE, phase 6: 1900-1800 cal. BCE; 3. early Longshan 2400-2100/2000 cal. BCE, late Longshan 2100/2000-1800 cal. BCE. In this research, we choose the third one and put all the sites into early and late Longshan two phases.

Table IV. 2 Absolute counts, ubiquities and RI values of cereals and oil plants in each site

Sites	Total seeds/fruits	Sample volumes	Information	Cultivated cereals					Cultivated oily seeds		Wild oily seeds		
				Cereals	Cereals	Cereals	Cereals	Cereals	Pulses	Oilseeds	Pulses	Oilseeds	Oilseeds
				<i>Setaria italica</i>	<i>Panicum miliaceum</i>	<i>Oryza sativa</i>	<i>Triticum aestivum</i>	<i>Hordeum vulgare</i>	<i>Glycine max</i>	<i>Cannabis sativa</i>	<i>Glycine soja</i>	<i>Perilla frutescens</i>	<i>Sesamum indicum</i>
Ningjiabu	82	12	Count	37	6				6				
			Ubiquity	60-70%	<10%				25%				
			RI	8	2				2				
Huangsangyuan	10	3	Count	7	3								
			Ubiquity	100%	67%								
			RI	5	4								
Pengjiazhuang	50	2	Count	2					2				
			Ubiquity	100%					8.3%				
			RI	5					1				
Dinggong	21586	98	Count	10021	1374	270	35		514	2		106	
			Ubiquity	98.9%	92.9%	82%	16.3%		60%	2%		22%	
			RI	140	100	100	20		112	4		16	
Fangjia	460	22	Count	116	111	4			8		7		
			Ubiquity	59%	36%	18%			13%		31%		
			RI	32	16	4			2		4		
Tonglin	25450	85	Count	7020	5658	3423			99				
			Ubiquity	89%	64%	66%			19%				
			RI	100	96	112			28				
Shilipubei	2526	85	Count	1566	327	345	13		197		14	2	
			Ubiquity	87.1%	62.4%	22%	2.4%		29%		<25%	<25%	
			RI	120	80	28	16		56		8	4	
Zhuanglixu	<1000	13	Count		2	280					10		
			Ubiquity		7.7%	38%						7.7%	
			RI		1	8					2		
Wangjiacun	10824	/	Count	334	191	5	7				21	6	
			Ubiquity	35-40%	40-45%	<10%	<10%				/	/	
			RI	24	24	4	8				7	1	
Haojiatai	>1000	15	Count	2362	152	1			73				
			Ubiquity	86.7%	66.7%	6.7%			40%				
			RI	35	16	1			14				
Pingliangtai 1*	1399	17	Count	737	137	6	1				25		

			Ubiquity	76.5%	76.5%	18%	5.9%					41%	
			RI	35	30	2	2		28			4	
Pingliangtai 2*	4384	59	Count	2876	310	2	2		80				
			Ubiquity	78%	30.5%	3.4%	3.4%		24%				
			RI	140	40	8	8		14				
Beitaishang	33122	113	Count	27454	595	113	17	1	2	6		2	1
			Ubiquity	79.7%	31.9%	18%	6.2%	1%	/	3%			1%
			RI	175	50	25	20	10	35	5		5	5
Wutai	2283	184	Count	120	52	25	3				3	40	
			Ubiquity	18.5%	15.2%	4.9%	3%				0.5%	/	
			RI	20	20	30	15				5	35	
Xuejiazhuang	190	8	Count	17	6	4			2			5	
			Ubiquity	65%	40%	13%			25%			/	
			RI	8	2	1			2			2	
Zhaojiazhuang	1008	44	Count	232	75	425	10	1			11	22	
			Ubiquity	70%	36%	61%	16%	1.4%			7%	/	
			RI	64	32	112	16	8			24	28	
Liangchengzhen	4189	122	Count	98	6	454	2				30		
			Ubiquity	100%	4.9%	32%	1.6%				24.6%		
			RI	75	10	70	10				35		
Liujiashuang	32	68	Count	4		16						2	
			Ubiquity	5.9%		23.5%						/	
			RI	4		16						4	
Dongpan	1038	153	Count	37	6	359	6	2			131	3	
			Ubiquity	23.5%	8.8%	87%	4.4%	1.5%			5.9%	2.2%	
			RI	10	10	175	20	10			35	5	
Houyangguanzhuang	97	5	Count	9	1	3					2	7	
			Ubiquity	100%	100%	100%					50%	50%	
			RI	5	5	10							
Yangpu	7	5	Count			2							
			Ubiquity			20-40%							
			RI			4							
Luchengzi	421	15	Count	49	5	190							
			Ubiquity	60%	12%	67%							
			RI	8	2	16							
Yuchisi	139	10	Count	57	5	70						1	
			Ubiquity	60%	10%	60%							

			RI	12	2	16						1	
Yuhuicun	568	66	Count	2		33	18	2					
			Ubiquity	<5%		10-15%	10-15%	<5%					
			RI	4		16	16	8					
Diaoyutai	166	18	Count	17		71			11				
			Ubiquity	22%		39%			11%				
			RI	2		8			1				
Gongzhuang	150	6	Count			147	2						
			Ubiquity			83%	33%						
			RI			20	2						

* Archaeobotanical data of Pingliangtai 1 from Deng and Qin (2017) and Pingliangtai 2 from Zhao et al. (2019).

Table IV. 3 The collection of direct AMS dating results of Longshan wheat grains in Haidai

	Sites	Lab-no.	Conventional ¹⁴ C age BP (±1σ)	Calibrated 95% range (cal. BCE/CE) *	References
West-Haidai	Shilipubei	Poz-82365	2980±30 ^a	1375-1059 BCE	Long et al. 2018
	Shilipubei	Poz-82367	2510±30 ^a	786-541 BCE	Long et al. 2018
	Dinggong	Poz-82358	3705±35 ^b	2202-1978 BCE	Long et al. 2018
	Dinggong	Poz-82362	3680±35 ^b	2195-1952 BCE	Long et al. 2018
	Wangjiacun	Poz-82368	Modern ^a	Modern	Long et al. 2018
	Jiaochangpu	QAS1320	2710±20 ^a	902-812 BCE	Liu et al. 2017
	Jiaochangpu	QAS1321	2210±25 ^a	373-180 BCE	Liu et al. 2017
East-Haidai	Zhaojiazhuang	Poz-82349	2420±30 ^a	748-402 BCE	Long et al. 2018
	Zhaojiazhuang	Poz-82352	3840±30 ^b	2455-2201 BCE	Long et al. 2018
	Zhaojiazhuang	BA-061052	3905±50 ^b	2563-2206 BCE	Jin et al. 2011
	Liujiiazhuang	Beta-432552	/ ^a	1665CE- Post1950	Archaeology Institute 2016
	Dongpan	Poz-82348	1360±30 ^a	607-774 CE	Long et al. 2018
	Wutai	Poz-82354	125±30 ^a	1675-1942 CE	Long et al. 2018
	Wutai	Poz-82356	395±30 ^a	1440-1628 CE	Long et al. 2018

*except for Liujiiazhuang, which the conventional age is not available in the report, all these radiocarbon data were collated with Bayesian statistical software OxCal ver. 4.4, working with the IntCal 20 by author; ^a Garins intrusive; ^b Cultural period based on stratigraphy matches the radiocarbon age.

Table IV. 4 Classification of arable weeds in the West- and East-Haidai (absolute counts)

Family	Species*	Life span	Related crop [#]	Ecology [#]	West-Haidai			East-Haidai			
					Early	Late	Undivided	Early	Late	Undivided	
Poaceae	<i>Alopecurus aequalis</i>	Annual/perennial	Wheat				2				
	<i>Eleusine indica</i>	Annual	Dry rice	Upland rice field			818	788	2	1	
	<i>Poa annua</i>	Perennial	Dry rice	/			7	2			
	<i>Digitaria sanguinalis</i>	Annual			13	765	1760	8	2	33	
	<i>Digitaria ischaemum</i>	Annual					2				
	<i>Chloris virgata</i>	Annual					5				
	<i>Arthraxon hispidus</i>	Annual					1				
	<i>Setaria viridis</i>	Annual				3	56	687	49	25	36
	<i>Echinochloa crus-galli</i>	Annual	Wet rice	Lowland irrigated, rainfed, tidal rice field			52	32	22	1	
	<i>Echinochloa</i> sp.		Dry/wet rice	/			581			8	
	<i>Setaria pumila</i>	Annual					8				
<i>Avena fatua</i>	Annual/perennial	Wheat				12	9				
<i>Leersia japonica</i>	Perennial	Dry rice	/			34					
Cyperaceae	<i>Schoenoplectus triquetar</i>	Annual	Wet rice	Lowland irrigated, tidal rice field		1	3				
	<i>Cyperus iria</i>	Annual	Dry rice	All kinds of rice fields				6			
	<i>Schoenoplectus juncooides</i>	Annual	Wet rice	Lowland irrigated and tidal rice fields		38	4				
	<i>Cyperus difformis</i>	Annual	Wet rice	Lowland irrigated and rainfed rice fields		1					
	<i>Pycnus sanguinolentus</i>	Annual	Wet rice	Lowland irrigated, rainfed and tidal rice fields			17				
Vitaceae	<i>Euphorbia humifusa</i> ^a	Annual					2				
Portulacaceae	<i>Portulaca oleracea</i> ^a	Annual	Dry rice	Upland rice fields			61	38	1	7	
Oxalidaceae	<i>Oxalis corniculata</i>	Annual								1	
Chenopodiaceae	<i>Suaeda glauca</i>	Annual					3				
	<i>Chenopodium album</i> ^a	Annual			19	2	791	715	8	5	
	<i>Kochia scoparia</i>	Annual			20	1	43	2			
	<i>Salsola collina</i>	Annual					9				
Fabaceae	<i>Kummerowia stipulacea</i>	Annual				3					
	<i>Glycine soja</i>	Annual			21	16	21	149	30		
Asteraceae	<i>Cirsium arvense</i>	Perennial	Wheat					1			
	<i>Xanthium strumarium</i>	Annual			36		5	1	2		
Rubiaceae	<i>Galium aparine</i>	Annual/perennial	Wheat		9				1		
Convolvulaceae	<i>Cuscuta chinensis</i>	Annual					9				

Euphorbiaceae	<i>Acalypha australis</i> ^a	Annual				3	1			
Malvaceae	<i>Hibiscus trionum</i> ^a	Annual			6		4			
	<i>Malva pusilla</i>	Perennial	/			3				
	<i>Abutilon theophrasti</i> ^a	Annual			18	3				
Papaveraceae	<i>Corydalis bungeana</i>	Annual/perennial	Wheat			5				
Polygonaceae	<i>Polygonum amphibium</i>	Perennial	Dry rice	/			1			
	<i>Polygonum lapathifolium</i>	Annual					2			
	<i>Polygonum aviculare</i>	Annual				4	2	17		
Lamiaceae	<i>Amethystea caerulea</i>	Annual					3			
	<i>Mosla dianthera</i>	Annual						1		
Solanaceae	<i>Solanum nigrum</i>	Annual					1			
Total					145	899	4957	1814	63	122

a. These species are fertile soil indicators.

* The nomenclature of species is updated according to *Plant Plus of China* (see www.iPlant.cn) that hosted by the State Key Laboratory of Systematic and Evolutionary Botany Institute of Botany, the Chinese Academy of Sciences (LSEB, IB, CAS).

Information of weeds from “wet rice” and “dry rice” is based on Fuller and Qin (2009); Ecological information of rice field weeds is based on Soerjani et al. (1987).

Table IV. 5 Classification of non-arable weeds in the West- and East-Haidai (absolute counts)

Family	Species ¹	Life span	Categories	Related crop	West-Haidai			East-Haidai		
					Early	Late	Undivided	Early	Late	Undivided
Lamiaceae	<i>Perilla frutescens</i> [#]	Annual	Undifferentiated		6	29	110	79	1	
	<i>Lycopus lucidus</i>	Perennial	Riverbank/lakeshore				3			
	<i>Leonurus japonicus</i>	annual/perennial	Ruderal		22					
	<i>Ajuga ciliata</i>	Perennial	Hillside grassland			1				
Commelinaceae	<i>Commelina communis</i>	Annual	Ruderal		20					
Crassulaceae	<i>Phedimus aizoon</i>	Perennial	Hillside grassland				4			
Fabaceae	<i>Senna tora</i>	Annual	Woodland				11			
	<i>Vigna vexillata</i>	Perennial	Undifferentiated		1					
	<i>Medicago sativa</i>	Perennial	Hillside grassland				5			
	<i>Vicia sepium</i>	Perennial	Undifferentiated					1		
	<i>Astragalus laxmannii</i>	Perennial	Woodland				30			
	<i>Astragalus mongholicus</i>	Perennial	Hillside grassland				17			
	<i>Lespedeza bicolor</i>	Perennial	Hillside grassland /woodland		2	4	666			
	<i>Senna nomame</i>	Annual	Hillside grassland					32		
Cannabaceae	<i>Melilotus officinalis</i>	Annual/perennial	Ruderal		4	9	874			
Cannabaceae	<i>Humulus scandens</i>	Perennial	Undifferentiated					2		
Thymelaeaceae	<i>Diarthron linifolium</i>	Annual	Hillside grassland				1			
Poaceae	<i>Phalaris arundinacea</i>	Perennial	Ruderal				3			
	<i>Arundo donax</i>	Annual/perennial	Riverbank/lakeshore				4			
	<i>Panicum bisulcatum</i>	Annual	Undifferentiated			3	33			
	<i>Tragus berteronianus</i>	Annual	Ruderal					193		
	<i>Paspalum thunbergia</i>	Perennial	Ruderal				35			
	<i>Setaria faberi</i>	Annual	Hillside grassland				98			
	<i>Phragmites australis</i> [*]	Perennial	Riverbank/lakeshore	Rice field ridge			6			
Cucurbitaceae	<i>Thladiantha dubia</i>	Perennial	Undifferentiated			6	21	1		7
Rosaceae	<i>Potentilla chinensis</i>	Perennial	Undifferentiated				1			
Violaceae	<i>Viola arcuate</i>	Perennial	Undifferentiated				2			
Nymphaeaceae	<i>Euryale ferox</i>	Annual	Riverbank/lakeshore				3			
Typhaceae	<i>Typha orientalis</i>	Perennial	Riverbank/lakeshore					8		
Vitaceae	<i>Vitis bryoniifolia</i>	Perennial	Undifferentiated		1	12	5	16		1
	<i>Cayratia japonica</i>	Perennial	Woodland				2			

Solanaceae	<i>Physalis alkekengi</i>	Perennial	Undifferentiated		1		2	1		
Phytolaccaceae	<i>Phytolacca acinose</i>	Perennial	Undifferentiated					6		
Polygonaceae	<i>Rumex acetosa</i>	Perennial	Undifferentiated		232	1	30			
Caprifoliaceae	<i>Patrinia scabiosifolia</i> *	Perennial	Riverbank/lakeshore	Rice/wheat field ridge			18			
Haloragaceae	<i>Myriophyllum spicatum</i> *	Perennial	Riverbank/lakeshore	Rice field ridge		19	1			
Cyperaceae	<i>Schoenoplectus tabernaemontani</i> *	Perennial	Riverbank/lakeshore	Rice field ridge		1				
Alismataceae	<i>Alisma plantago-aquatica</i> *	Perennial	Riverbank/lakeshore	Rice field ridge			1			
Total					289	85	1986	339	1	8

*Those species are common at riverbank or lakeshore but also have high possibilities to grow at the ridges of rice field. Therefore, although they are not typical arable weeds but still included in the rice field weeds.

Species that are exploitable and their seeds also contain a high amount of oil content.

1. The nomenclature of species is updated according to *Plant Plus of China* (see www.iPlant.cn) that hosted by the State Key Laboratory of Systematic and Evolutionary Botany Institute of Botany, the Chinese Academy of Sciences (LSEB, IB, CAS).

Appendix VI

Table VI. 1 Absolute counts, ubiquities and RI values of cereals in each Yueshi and Shang site in the Haidai Region

Period	Sites	Total seeds/fruits	Sample volumes	Information	<i>Setaria italica</i>	<i>Panicum miliaceum</i>	<i>Oryza sativa</i>	<i>Triticum aestivum</i>	<i>Hordeum vulgare</i>
Yueshi	Shilipubei	1711	63	Count	1180	116	12	6	
				Ubiquity	95.2%	60.3%	9.5%	6.4%	
				RI value	140	64	12	16	
	Yinjia	694	19	Count	101	40	10		
				Ubiquity	63.2%	47.4%	31.6%		
				RI value	16	6	6		
	Miaohou	206	9	Count	66	9			
				Ubiquity	88.9%	44.5%			
				RI value	15	4			
	Maan	1221	10	Count	693	23		5	
				Ubiquity	100%	60%		10%	
				RI value	35	12		3	
	Yangpu	198	6	Count	24	8	53	48	
				Ubiquity	100%	38%	90%	60%	
				RI value	10	4	20	16	
	Liujiazhuang (六甲庄)	7	17	Count	1		1	1	
				Ubiquity	/		/	/	
				RI value	1		1	2	
	Tonglin	3758	37	Count	1751	305	184		
				Ubiquity	94.6%	75.7%	51.4%		
				RI value	60	50	48		
Zhaogezhuang 2008	1128	34	Count	344	47				
			Ubiquity	64.7%	41.1%				
			RI value	56	16				
Zhaogezhuang 2007	14524	93	Count	7505	421	4	16	1	
			Ubiquity	83.8%	32.5%	5%	7.5%	1.25%	
			RI value	140	120	8	16	8	
Pengjiazhuang	85575	49	Count	67169	2710				
			Ubiquity	45.3%	13.2%				
			RI value	56	20				
Shang	Daxinzhuang 2003	7008	175	Count	5602	70	44	22	

			Ubiquity	69.7%	18.2%	11.5%	3.6%	
			RI value	140	20	20	20	
Daxinzhuang 2015	17377	165	Count	14115	1128	1161	22	
			Ubiquity	99.4%	69.1%	40%	8.5%	
			RI value	175	100	60	20	
Liujiuzhuang (刘家庄)	8544	128	Count	4829	126		9	
			Ubiquity	99.2%	32.8%		5.5%	
			RI value	175	40		20	
Shilipubei	3015	93	Count	1975	163	14	10	
			Ubiquity	91%	57%	8.6%	7.5%	
			RI value	140	64	16	16	
Tonglin	185	4	Count	80	14	16		
			Ubiquity	75%	50%	50%		
			RI value	15	8	8		