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Neolithic agriculture, freshwater resources and rapid environmental changes on the lower Yangtze, China

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ABSTRACT

Analyses of sedimentary evidence in the form of spores, pollen, freshwater algae, dinoflagellate cysts, phytoliths and charcoal from AMS ^{14}C-dated, Holocene-aged sequences provide an excellent opportunity to examine the responses of Neolithic agriculturalists in the lower Yangtze to changing environments. Evidence from two sites close to the southern margin of the Yangtze delta and separated by what is now Hangzhou Bay attests the critical importance to early attempts at food production of access to freshwater resources. More readily, if episodically, available freshwater resources during the early to mid-Holocene on the Hangjiahu plain may have encouraged an early reliance on rice-based agriculture, which in turn facilitated the accumulation of agricultural surpluses and cultural diversification. Cultural change was relatively attenuated and human population pressures possibly lower on the Ningshao plain, seemingly because of much more profound environmental impacts of variations in local hydrological conditions, and because predominantly saline conditions, associated with rising relative sea level, hampered the early development of irrigated agriculture. The evidence, although largely dating to the early and middle parts of the Holocene, provides a timely warning of the complexity of vulnerability to climate change-induced processes of agriculture, and indeed human activities more generally, on megadeltas in Asia.

Introduction

According to the IPCC's latest assessment, the large (mega) deltas of the world are hotspots of vulnerability to climate change-induced impacts (Nicholls et al., 2007). Nowhere is this more so than in Asia, where about 75% of humans residing on deltas are predicted to be affected by future climate change, either directly or indirectly (Ericson et al., 2006). The Yangtze (Changjiang) delta in eastern China is a prime example (Syvitski et al., 2009): almost 100 million people, important economic activities, extensive, human-modified and low-lying landscapes, and extremely dynamic environmental conditions interact to ensure a high level of vulnerability to climate change. Documented impacts of devastating, periodic flooding on the delta over the last 1000 years provide ample evidence of this vulnerability (Jiang et al., 2004).

The Yangtze delta, generally between 3 and 5 m above mean sea level (a.m.s.l.) and extending over 50,000 km^2 (Schneiderman et al., 2003), started to form about 8000 years ago (Hori et al., 2002) and is today divided by the Yangtze River into northern and southern parts. The southern part of the delta, underlain by igneous rocks of Jurassic to Cretaceous age, is dissected by Hangzhou Bay, forming the Hangjiahu (to the north) and Ningshao (to the south) plains (Fig. 1a). Agricultural communities moving east from the middle reaches of the Yangtze River valley and combining foraging with cultivation are believed to have colonised the southern part of the delta soon after it first began to form (Atahan et al., 2008). These early Neolithic people (associated with the Hemudu and Majiabang cultures, on the Ningshao and Hangjiahu plains, respectively) established their settlements of timber houses raised on piles (Bellwood, 2005) close to surface bodies of freshwater (Stanley and Chen, 1996; Chen et al., 2008). Rice, a wetland grass native to the lower Yangtze, may have been domesticated on the delta (Normile, 1997; Wang, 1997; Crawford and Shen, 1998; Zhao, 1998; Liu, 2000; Zhao and Piperno, 2000; Chapman and Wang, 2002; Zheng et al., 2003, Jiang and Liu, 2006; Liu et al., 2007; Zong et al., 2007), with the early importance of rice to food security locally being evident in material remains recovered from several occupation sites, including Hemudu (ca. 7780 cal yr BP) (Zhejiang Institute of Archaeology, 2003)

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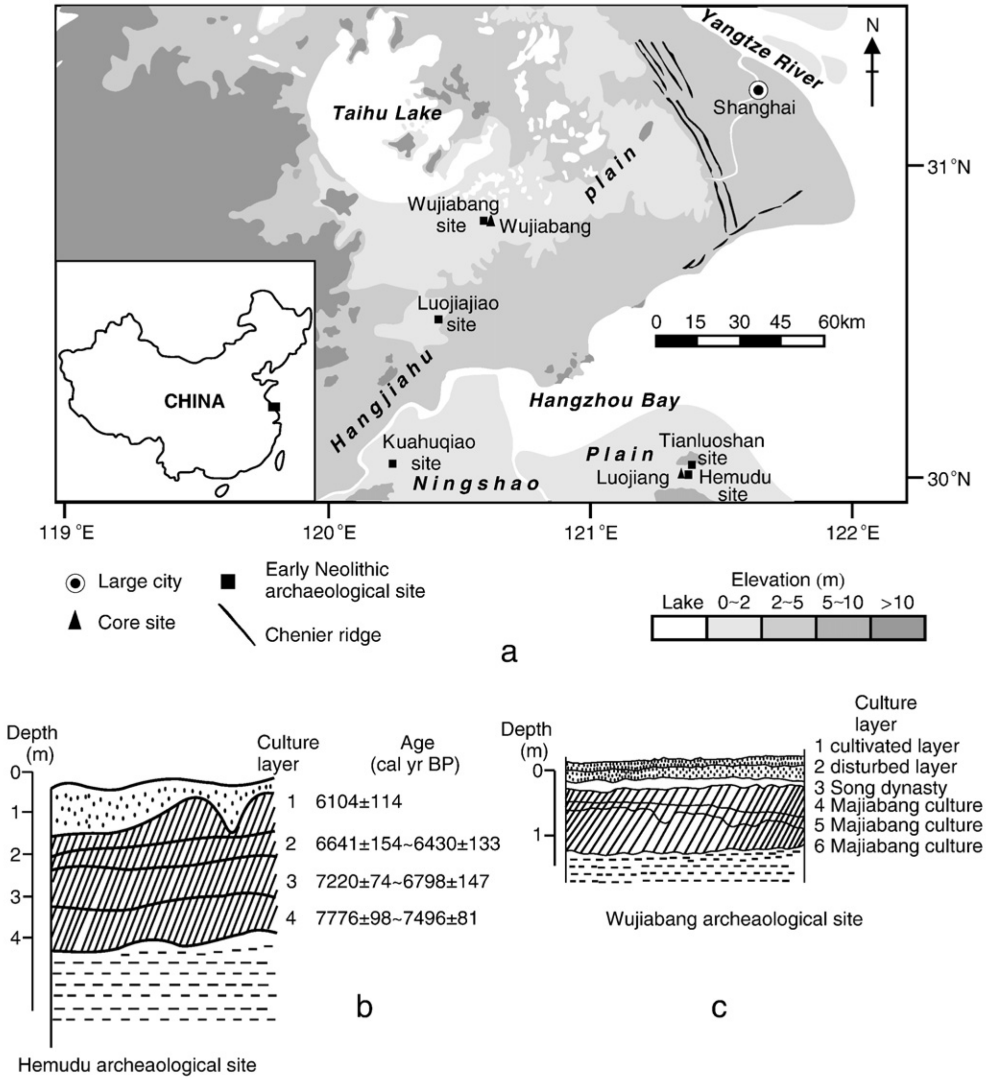

Figure 1. (a) Geographical locations of the Luojiang and Wujiabang cores and important archaeological sites mentioned in the text; (b) Schematic diagram of sediment stratigraphy at Hemudu showing the four cultural layers (reproduced from Wu (1983), approximate ages (Zhejiang Institute of Archaeology (2003)); (c) Schematic diagram of sediment stratigraphy from archaeological site at Wujiabang showing the cultural layers (reproduced from Zhejiang Institute of Cultural Relics and Archaeology and Jiaxing Museum (2005)).

and Kuahuqiao (ca. 8000 cal yr BP) (Jiang and Liu, 2005), and, on the Hangjiahu plain, from the presence of paddy fields dating to at least ca. 5790 cal yr BP (Cao et al., 2006; Li et al., 2007).

Settlement and cultural development on the Yangtze delta both appear to have been highly dynamic and spatially varied processes during the Neolithic period, which terminated locally about 4200 years ago. Some locations on the Hangjiahu plain appear to have been occupied more-or-less continuously throughout the Neolithic (e.g., Caoxieshan (Nanjing Museum, 2004), Chuodun (Changzhou Museum, 2004) and Wujiabu (Zhejiang Institute of Cultural Relics and Archaeology, 2004). More commonly, however, occupation was interrupted (Stanley et al., 1999); often the interruptions are marked in the sedimentary record by archaeologically sterile horizons of fine sand and clay (Yu et al., 2000). The pattern of cultural change during the Neolithic also appears to have varied geographically, according to the material evidence from archaeology (Cai, 2001; Zheng, 2007). For example, Neolithic cultures inhabiting the Hangjiahu plain show greater variability when compared with the Ningshao, forming three distinct cultural phases. The earliest of these was the Majiabang (ca. 7500–6000 cal yr BP). Majiabang occupation sites have yielded abundant evidence of the use of a wide range of aquatic plants in agriculture (Chang, 1986). According to Gu et al. (1998), irrigated agriculture was adopted towards the end of the Majiabang, enabling crops such as rice to be grown beyond the area that flooded naturally.

Social differentiation and sophisticated ceramics, suggestive of relative food security, characterise the succeeding Songze cultural phase (ca. 6000–5200 cal yr BP) (Chang, 1986; Shao, 2005). A trend of increased social stratification, together with improved technologies, including those relating to agriculture, appears to have continued into the late Neolithic (Chalcolithic) Liangzhu cultural phase (ca. 5200–4200 cal yr BP) (Chang, 1986; Shao, 2005). Artifacts recovered from Liangzhu occupation sites provide evidence of advanced agriculture, combining the cultivation of a range of plants with domesticated animals, such as sheep and possibly water buffalo (Chang, 1986; Barnes, 1993; The Cultural Relics and Archaeology Institution of Zhejiang Province and The Cultural Relics Administration Committee of Tongxiang City, 2005; Li et al., 2007; Zhang and Hung, 2008), and pronounced stratification of society (Chang, 1986; You, 1999).

By comparison, the available archaeological evidence indicates a comparatively attenuated process of cultural change to the south of Hangzhou Bay. The archaeological site at Hemudu has yielded abundant artifacts including agricultural tools, utensils and stone, bone, rice, wood and pottery remains (Zhejiang Institute of Archaeology, 2003) and has given its name to the early Neolithic on the Ningshao plain. Two ^{14}C dates on material (acorns (7580 cal yr BP) and wood fragments (7780 cal yr BP)) from the occupation layers, together with additional evidence from a second archaeological site at Tianluoshan, located close-by and from sediment-based data from Kuahuqiao, indicate that agriculture may have been established in this part of the Yangtze delta by about 7500 years ago (Underhill, 1997; Liu, 2000; Zhejiang Institute of Archaeology, 2003; Zhejiang Institute of Archaeology and Xiaoshan Museum, 2004; Zhejiang Institute of Cultural Relics and Archaeology et al., 2007; Zong et al., 2007; Innes et al., 2009). However, there is no equivalent of the Songze—and associated evidence of relative food security during the middle Neolithic—on the Ningshao plain: having initially flourished, the Hemudu culture appears to have stagnated before entering a decline from about 5900 years ago (Liu and Jiang, 1998), eventually being assimilated within the Liangzhu some 5000 years ago (Cai, 2001; Zheng, 2007).

Changes in culture and associated technologies, such as agriculture, are a response to two kinds of factors: those that are internal to society (e.g., invention and innovation) and those that are external (e.g., environmental change) (Richerson et al., 2005). An examination of the relative importance of external, or extrinsic, factors in influencing Neolithic agriculture on the southern part of the Yangtze delta addresses a topic of ongoing scientific debate (e.g., Atahan et al., 2008; Innes et al., 2009) that has recently been brought into sharper focus as a result of current concerns over the vulnerability to climate change-induced impacts on populations inhabiting the world's megadeltas.

The research described in this paper focuses on AMS ^{14}C-dated sequences of Holocene sediments collected from two study sites, located less than 120 km apart and separated today by Hangzhou Bay and close to important occupation sites for the early Neolithic Hemudu and Majiabang cultures. Temporal variability in environmental conditions in the lower Yangtze and the responses of early farmers to these have been the foci of much recent research. A question that has received far less attention is the extent to which environmental changes and their effects varied spatially during the period of early food production. Accumulations of sediments at the two study sites provide an ideal opportunity to investigate the potential for special variability within the context of existing archaeological and palaeoenvironmental data. The results described highlight the importance of hydrological changes driven by variations in relative sea level, and that agricultural impacts of inundation appear to have been much more profound in some locations than in others.

Study area and sites

Climatically the lower Yangtze is currently subtropical in nature and strongly influenced by the East Asian monsoon. Mean annual precipitation is over 1000 mm, and mean January and July temperatures are ca. 4°C and 28°C, respectively (Ningbo Chorography Codification Committee, 1995). Natural vegetation in the study area, although greatly modified by human activity, is characterized by subtropical evergreen broadleaved forests (Wu, 1980) that are now largely restricted to relatively remote, highland areas. Taxa commonly associated with evergreen broadleaved forest to the north of Hangzhou Bay include *Castanopsi carlesii*, *C. eyrei*, *C. sclerophylla*, *Cinnamomum camphora*, *Cyclobalanopsis glauca*, *Lithocarpus glaber*, *Machilus thunbergii*, *Phoebe sheareri* and *Schima superba*, while to the south, on isolated blocks of higher altitude land, *Quercus fabri* and *Liquidambar formosana* are common components of remnants of mixed evergreen-deciduous forest (Fang, 2006). Generally, however, habitats in the lower Yangtze are characterised at lower altitudes by fresh and brackish-water influenced wetlands and by fragments of broadleaved forest on isolated areas of upland.

The coring site at Luojiang village (29°59.064′N, 121°21.754′E) on the Ningshao plain is 4 m above the local (Yellow Sea) datum and about 3 km southeast of the archaeological site at Hemudu (Figs. 1a,b). The coring location at Wujiabang (30°49.060′N, 120°36.928′E) on the Hangjiahu plain is 2.5 m above the local (Yellow Sea) datum and ca. 500 m from the archaeological site of the same name in Lailongqiao village, Zhejiang province (Figs. 1a, c). The archaeological site at Hemudu has already been described: the occupation layer at Wujiabang, the uppermost part of which is 0.6 m above the local datum (Chen et al., 2008), was excavated in 1986 and in 2001–2002. Although no ^{14}C dates are available for artifacts from the archaeological site at Wujiabang, the style of pottery recovered suggests that earliest occupation dates to the early Neolithic (Majiabang) (Zhejiang Institute of Cultural Relics and Archaeology and Jiaxing Museum, 2005).

Methods

Cores of sediment were collected from the coring sites at Luojiang and Wujiabang using a powered corer mounted on a tripod. The sediment cores were transferred in the field to PVC tubes for transportation to Tongji University, Shanghai, where they were described and sampled before being shipped to Ireland for subsequent, detailed laboratory analyses.

Chronological control is provided by ^{14}C AMS dates. Dating was mainly carried out on pollen residues and macrofossils (fragments of wood, macro-charcoal and shell), although a small number of bulk sediment samples were also dated. Preparation of pollen residues for ^{14}C AMS analysis involved sieving through 200-μm and 5-μm meshes to remove material unlikely to be pollen, 10% NaOH to remove humic acids, 15% HCl to remove carbonates and 40% HF to remove silicates. The other samples for ^{14}C AMS dating were pre-treated using 30% HCl and 10% NaOH, except the sample at the depth of 30.37–30.35 m from Luojiang core.

Processing of samples of 5–10 g sediment for pollen, spores, freshwater algae, dinoflagellate cysts and micro-charcoal analyses used standard procedures (Moore et al., 1991). In order to purify the samples further, residues were filtered through a 10-μm mesh in an ultrasonic bath and the larger fraction mounted in glycerine (Sun et al., 1999). Pollen, spores, freshwater algae and dinoflagellate cysts were enumerated using a Lycra optical microscope at 400× magnification. A total of at least 300 pollen grains from terrestrial taxa were counted for each sample. Micro-charcoal was quantified using the point-count method (Clark, 1982). Samples for macro-charcoal analysis were deflocculated in 5% Calgon solution before disaggregation and sieving through a 150-μm mesh. All charcoal particles larger than 150 μm (macro-charcoal) were counted under a stereomicroscope at 20x magnification (note that macro-charcoal counts are only available for material from Wujiabang). For phytolith analysis, 10% HCl was used to remove carbonates and concentrated HNO_3 to remove organic matter. Residues were sieved through a 250-μm mesh to remove large soil particles; sodium polytungstate was used to separate the phytolith fraction from the remaining inorganics. Concentrations of phytoliths in samples from the entire Holocene-aged sequence of sediments from Luojiang and Wujiabang were enumerated using a Lycra optical microscope at 400× magnification.

Identification of pollen and spores was made with reference to Wang et al. (1995). Poaceae pollen was divided into two size categories ($\leq$40 μm and >40 μm): Poaceae grains >40 μm in size in sediments from eastern China have previously been identified as domesticated rice (Wang et al., 1995; Chaturvedi et al., 1998), although the authors acknowledge that the use of a size threshold to separate cereal pollen from other members of the Poaceae is crude, particularly where there is a strong likelihood of encountering material from wild varieties of the same genus (see Maloney, 1990; Tweddle et al., 2005; Atahan et al., 2008). *Quercus* pollen was also separated into two size categories that are thought to have ecological significance: grains with a long axis >30 μm were classified as *Quercus* (deciduous) comp., and grains $\leq$30 μm as *Quercus* (evergreen) comp. (Chang and Wang, 1986). Freshwater algae and dinoflagellate cysts were identified according to Hu and Wei (2006) and Rochon et al.

(1999). Phytolith morphotypes, including those thought likely to be from domesticated rice (*Oryza*), were identified according to Bozarth (1992), Rosen (1992), Wang and Lu (1993), Runge (1999), Lu et al. (2006), Piperno (2006) and Itzstein-Davey et al. (2007a, b), and following nomenclature of the ICPN Working Group et al. (2005).

Results

Stratigraphy

Cores of sediment totaling 45 m and 10 m in length were obtained from Luojiang and Wujiabang, respectively. Basal sediments at both locations were a hard clay deposit, believed to be the "First Hard Clay Layer" of late Pleistocene age and found widely in the lower Yangtze region and other parts of eastern China (Qin et al., 2008). A uniformly dark grey clay, with shells conspicuous in its lower parts, overlay the hard clay. Intercalated within the clay-rich sediment were more organic-rich horizons (peat), most conspicuously between 2.12 and 1.8 m at Luojiang and 4.0 and 3.5 m at Wujiabang. The parts of the sequences above the First Hard Clay Layer at the two sites are the focus for this paper, because of their presumed Holocene age.

Chronology

A total of 18 samples was dated in the current research using the AMS ^{14}C technique (Table 1). Calibrated ages (cal yr BP) were obtained using the CALIB 5.0.2 programme and the INTCAL04 data set of Reimer et al. (2004), although the calibrated age of a single sample of shells was established using the marine dataset of Hughen et al. (2004). Some of the samples dated show age reversals, a commonly encountered problem in the dating of deltaic sequences (e.g., Stanley and Chen, 2000; Stanley and Hait, 2000), presumably because of the mixing of carbon of different ages as a result of the remobilisation and redeposition of sediment. The potential for remobilisation and redeposition exists throughout the sequence of sediments obtained from the two sites, but is perhaps greatest for the clay-rich deposits, which indicate higher energy conditions than accumulations of more organic-rich material (Innes et al., 2009). The lowermost date for the sediments from Luojiang (27,750 ± 240 ^{14}C yr BP) confirms that the First Hard Clay Layer was formed during the last glacial maximum (Zheng et al., 1999). The uppermost First Hard Clay deposits and lowermost Holocene sediments could have conceivably been lost through erosion. However, the minimum age for the uppermost surface of the First Hard Clay Layer is ca. 10,000 cal yr BP, which is supported by the age of 10,104 ± 46 cal yr BP at the depth of 31.57–31.55 m in the sequence of sediments from Luojiang.

Sediments from 30.58–30.56 m, 5.00–4.98 m and 3.02–3.00 m in the core from Luojiang yielded older than expected ages, given their stratigraphic positions, while age for the sediments from 2.22–2.20 m (just below an otherwise well-dated peat deposit) appear too young. Previous research shows that the peat on the Ningshao plain is widespread, largely formed during the period ca. 7000–3600 cal yr BP, and has a minimum ^{14}C age of 3210 cal yr BP (Zhang, 1991). Two anomalous dates were recorded in Wujiabang core: the ages for the material from 4.05–4.03 m and 1.83–1.81 m appear too old. The lowermost of these is a bulk sediment sample, and dating inaccuracies are again likely given the relatively small amount of organic material present and the high possibility that the sediment comprises carbon of different ages.

The above anomalous dates were discounted in the current research, with chronological control, including interpolated and extrapolated dates, based on age–depth relationships formed from the remaining 12 AMS ^{14}C dates (Fig. 2). Note that sequences of Holocene-aged sediments from both coring sites were divided into three, broad stratigraphic units (terrestrial sediment, peat, marine influenced sediment), and that the rate of sediment accumulation over time was assumed, in the age–depth models, to be constant (i.e., the age–depth relationship was assumed to be linear (Webb and Webb, 1988)) within each stratigraphic unit. This approach allows for hiatuses in sedimentation between stratigraphic units (e.g., associated with a transition from a relatively low-energy sedimentary environment to relatively high, denoted in the sediments by an abrupt change in organic matter content). A decline in abundances of dinoflagellate cysts at 2.2 m in the sequence of sediments from Wujiabang indicates a cessation in a strong saline influence at the coring site during the late Holocene. This event is assumed to correspond with a stabilisation in relative sea level, dated locally at ca. 3000 cal yr BP (Zong, 2004). Note also that all ^{14}C-derived ages are referred to in the current research in the calibrated form (cal yr BP) of the mid-point of the 1σ range, resolved to the nearest 10 years. Dates that have been arrived at through interpolation or extrapolation from the relevant age–depth relationship are prefixed with "ca."

Description of macro-and microfossils

Preservation of biological remains was generally good, although a section towards the top of the sedimentary sequence from Wujiabang lacked microfossils. Up-core variations in macro- and microfossil data

Table 1
AMS ^{14}C dates for Luojiang and Wujiabang cores.

Study site	Depth (m)	Laboratory code	Age (^{14}C yr BP)	δ^{13}C	Calibrated date (cal yr BP,1σ)	Central calibrated age (cal yr BP,1σ)	Dated material
Luojiang	1.80–1.82	NZA22890	1050 ± 35	−25.95	928–978	953 ± 25	Pollen residue
	2.00–2.02	NZA22891	4071 ± 30	−26.90	4518–4583	4551 ± 33	Pollen residue
	2.10–2.12	Beta−217556	4350 ± 40	−29.30	4926–4960	4943 ± 17	Plant macrofossil
	2.20–2.22	NZA22892	1940 ± 30	−28.60	1865–1926	1896 ± 31	Pollen residue
	3.00–3.02	Beta-220585	10650 ± 30	not available	12701–12784	12743 ± 42	Pollen residue
	4.98–5.00	NZA23298	10984 ± 55	−24.08	12870–12950	12910 ± 40	Pollen residue
	19.63–19.65	Beta-217551	6050 ± 40	−25.20	6849–6952	6901 ± 52	Charred material
	30.35–30.37	Beta-217555	9010 ± 40	−10.50	9592–9759	9676 ± 84	Shell
	30.56–30.58	NZA23302	10666 ± 75	−24.13	12668–12814	12741 ± 73	Pollen residue
	31.55–31.57	NZA22893	8863 ± 35	−27.20	10058–10149	10104 ± 46	Pollen residue
	36.05–36.07	NZA23303	27750 ± 240	−24.40			Pollen residue
Wujiabang	1.81–1.83	OZL351	9590 ± 60	−21.10	10786–10978	10882 ± 96	Pollen residue
	3.50–3.52	OZL349	6410 ± 60	−26.00	7349–7417	7383 ± 34	Charcoal
	3.50–3.52	OZL350	6250 ± 70	−25.90	7155–7260	7208 ± 53	Pollen residue
	3.74–3.76	OZL374	6600 ± 50	−25.00	7457–7513	7485 ± 28	Peat
	3.74–3.76	OZL375	6630 ± 60	−25.00	7476–7569	7523 ± 47	Peat
	4.03–4.05	OZL376	9010 ± 70	−21.40	10147–10247	10197 ± 50	Clay
	6.00–6.02	OZL377	7350 ± 60	−23.50	8046–8144	8095 ± 49	Clay

NZA = Institute of Geological and Nuclear Sciences, New Zealand; Beta = Beta Analytic Inc., USA; OZL = ANSTO, Australia.

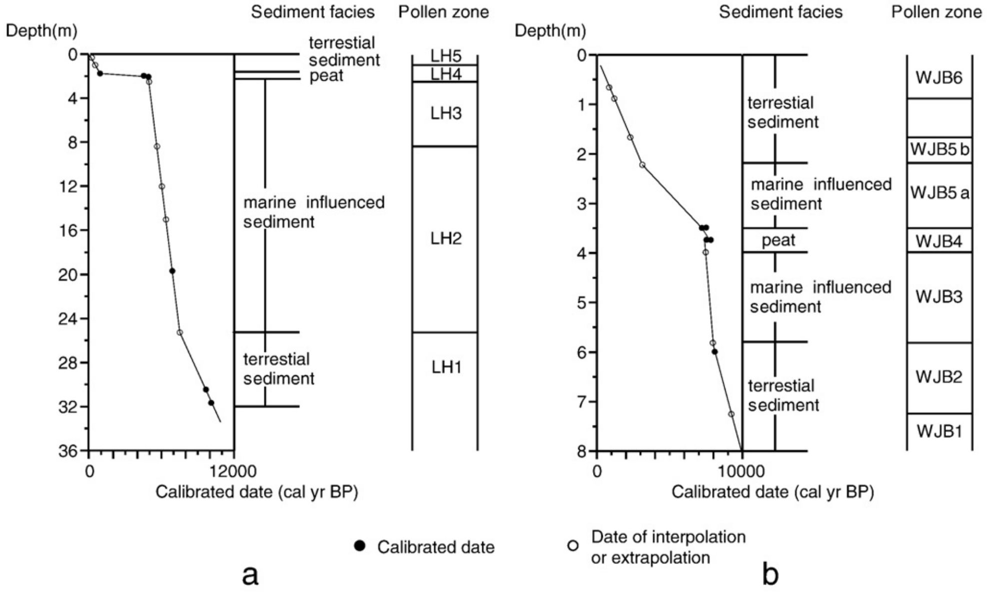

Figure 2. Age–depth relationships for Luojiang (a, 4 m a.m.s.l.) and Wujiabang (b, 2.5 m a.m.s.l.) cores.

are illustrated on Figures 3 and 4. Only the most abundant pollen, spore and phytolith types enumerated are shown on the figures. The remains of freshwater algae and dinoflagellates are grouped separately into two categories on the figures. Many of the remains categorised either as dinoflagellates or freshwater algae were identified to family, genus and even species; up-core variations in abundances of *Concentricystes*, the most abundant freshwater algae encountered, are shown on the figures. Stratigraphical zones were defined numerically according to variations in the remains of pollen and spores using CONISS (Grimm, 1987, 1992). Pollen counts are expressed as percentages of the total pollen sum. The abundances of phytoliths believed to have been produced by members of the Poaceae are presented as percentages of the total phytolith sum, which comprised a minimum of 300 single-celled morphotypes; micro-charcoal data are presented as cm^2 g^{-1} and macro-charcoal as grains g^{-1}. Freshwater algae remains and dinoflagellate cysts are presented as percentages of the total palynomorph sum (comprising spores, pollen, freshwater algae and dinoflagellate cysts).

Luojiang

Up-core variations in macro- and microfossils from Luojiang core are shown in Figure 3 and described below.

Zone LH1 (31.55–25.20 m; early Holocene—ca. 7520 cal yr BP): pollen from arboreal taxa *Quercus* (evergreen) comp. and, to a lesser extent, *Betula*, *Carpinus*, *Juglans*, *Liquidambar*, *Quercus* (deciduous) comp., *Ulmus* and the conifers *Abies*, *Picea*, *Pinus* and *Tsuga* are present throughout this zone. Cyperaceae and Poaceae (≤40 μm) pollen is common among the herb component, while *Typha* pollen is present throughout. Some Poaceae pollen >40 μm is also present. The most common freshwater algae and dinoflagellate cysts encountered are, respectively, *Concentricystes* and *Spiniferites* spp. Phytoliths from both C$_3$ and C$_4$ grasses are common, and remain so throughout the Holocene record. Micro-charcoal concentrations are consistently low.

Zone LH2 (25.20–8.39 m; ca. 7520–5640 cal yr BP): a rise in abundance of pollen from *Liquidambar* characterises the lower boundary of this zone. *Quercus* (evergreen) comp. pollen remains abundant, while the zone also contains pollen from several other arboreal taxa, including *Carpinus*, *Juglans*, *Pterocarya*, *Ulmus* and the conifers *Pinus* and *Tsuga*. Abundances of Cyperaceae and Poaceae (≤40 μm) pollen are lower than in the preceding zone, while large-sized Poaceae (>40 μm) and Chenopodiaceae pollen is more common. *Typha* is consistently present. The remains of the freshwater algae *Concentricystes* are present throughout the zone, although in low abundance, while dinoflagellate cysts are more abundant than in zone LH1 and include *Brigantedinium* spp., *Lingulodinium machaerophorum*, *Operculodinium centrocarpum*, *Protoperidinium nudum*, *Spiniferites* spp. and *Tuberculodinium vancampoae*. Dinoflagellate cysts show a second rise at 15 m (ca. 6380 cal yr BP). Wild rice (*Oryza*)-type phytoliths appear in low abundance. Micro-charcoal concentrations are relatively low, increasing from 12 m (ca. 6050 cal yr BP).

Zone LH3 (8.39–2.55 m; ca. 5640–4990 cal yr BP): abundant *Pinus* pollen characterizes most samples in this zone, while pollen from other conifers, such as *Abies*, *Larix* and *Tsuga*, although present, is less abundant. Evergreen and broadleaved-deciduous arboreal taxa are mainly represented by *Liquidambar*, *Quercus* (deciduous) comp. and *Quercus* (evergreen) comp., with pollen from *Liquidambar* less common than in zone LH2. Pollen from *Pterocarya* and *Ulmus* is also present. Among the herbaceous taxa represented, pollen from Cyperaceae and Chenopodiaceae is more abundant than in zone LH2, Poaceae (≤40 μm) has similar abundances, while Poaceae (>40 μm) is generally less common. *Oryza*-type phytoliths are also rare. *Concentricystes* and Zygaemataceae are the most common representatives of freshwater algae, while highest levels of dinoflagellate cysts (>20% of the total palynomorph sum) for the sequence of sediments as a whole are found in this zone. Concentrations of micro-charcoal, which increased in the upper part of zone LH2, remain high.

Zone LH4 (2.55–1.05 m; ca. 4990–550 cal yr BP): *Quercus* (evergreen) comp. pollen is the most abundant arboreal pollen type represented, accompanied by *Liquidambar*, *Pterocarya* and *Ulmus*. *Pinus* pollen is much reduced in abundance compared with zone LH3, while *Quercus* (deciduous) comp. is absent. *Typha* and both size categories of Poaceae (≤ and >40 μm) pollen are commonly represented. *Concentricystes* remains common, while dinoflagellate cysts are present in lower abundances than in zone LH3. Micro-charcoal concentrations peak in the lower part of this zone.

Zone LH5 (1.05–0.35 m; ca. 550–180 cal yr BP) is characterised by reduced pollen from arboreal sources, increases in Poaceae (particularly *Oryza* comp.) pollen and phytoliths from mainly domesticated *Oryza* sp. and a continuation of low levels of charcoal, compared with Zone LH4.

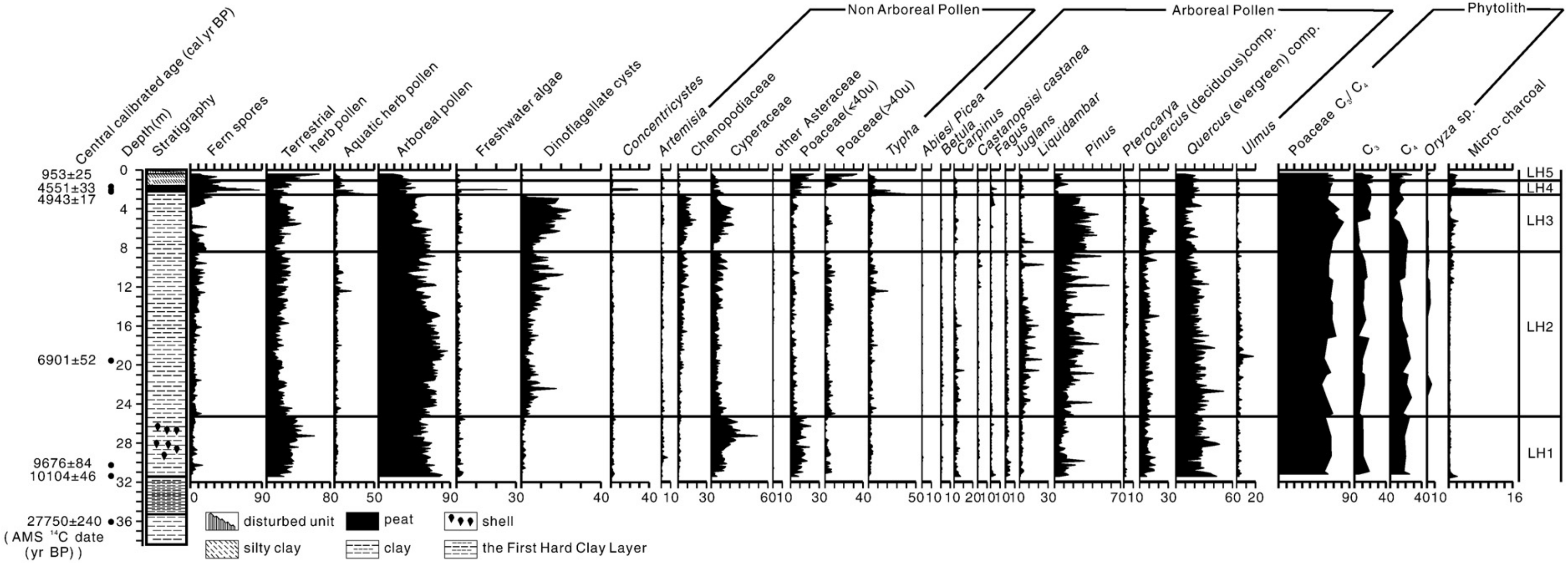

Figure 3. Summary of sediment-based data for the Luojiang core, including pollen (%), phytolith (%) and micro-charcoal ($cm^2\ g^{-1}$) data.

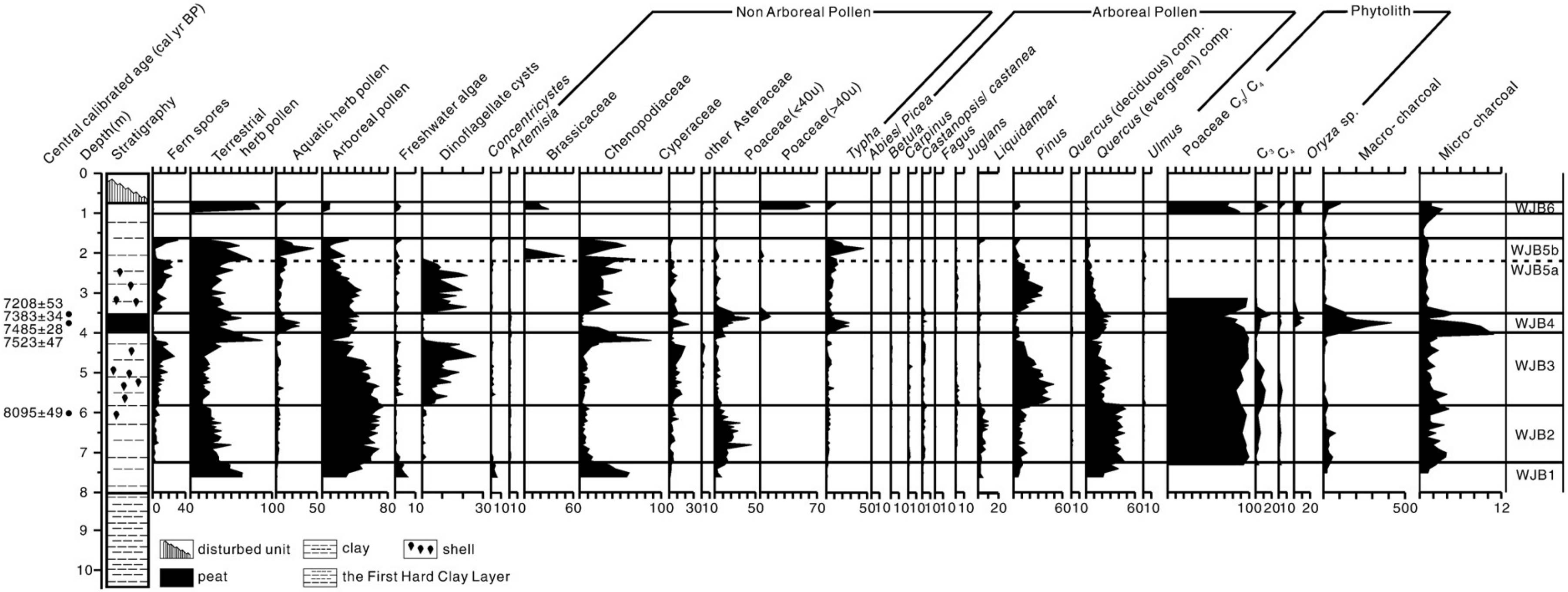

Figure 4. Summary of sediment-based data for Wujiabang core, including pollen (%), phytolith (%), micro-charcoal (cm^2 g^{-1}) and macro-charcoal (grains g^{-1}) data.

Wujiabang

Up-core variations in macro- and microfossils from Wujiabang are shown in Figure 4. The record of microfossil preservation is much more variable when compared with the sequence from Luojiang.

Zone WJB1 (7.61–7.26 m; early Holocene—ca. 9290 cal yr BP) is characterised by high levels of Chenopodiaceae pollen. Cyperaceae, *Pinus*, Poaceae (≤40 µm) and *Quercus* (evergreen) comp. pollen is also present, as are the remains of freshwater algae (*Concentricystes*); dinoflagellate cysts are absent, and abundances of charcoal are low. No phytoliths were recovered from sediments within this zone.

Zone WJB2 (7.26–5.81 m; ca. 9290–8070 cal yr BP): relatively high levels of arboreal pollen (mainly *Liquidambar* and *Quercus* (evergreen) comp.) and markedly reduced abundances of Chenopodiaceae pollen characterise this zone. *Pinus* and Poaceae (≤40 µm) pollen is also common. Phytoliths from both C_3 and C_4 grasses are abundant, as they are in all phytolith-bearing samples from this site. *Concentricystes* remains are rare, and dinoflagellate cysts absent. Concentrations of charcoal remain low.

Zone WJB3 (5.81–4.00 m; ca 8070–7850 cal yr BP): an abrupt fall in abundances of *Quercus* (evergreen) comp. and Poaceae (≤40 µm) pollen and a concomitant rise in *Pinus* characterise this zone. Dinoflagellate cysts are relatively common, rising to peak levels in the uppermost part of the zone, while abundances of freshwater algae remains and charcoal are low.

Zone WJB4 (4.00–3.50 m; ca. 7850–7210 cal yr BP): an abrupt fall in abundances of dinoflagellate cysts together with relatively low levels of arboreal, particularly *Pinus*, pollen and high levels of Poaceae (≤40 µm) and *Typha* pollen, characterise this zone. Poaceae (>40 µm) is also present, as are phytoliths believed to be from domesticated forms of *Oryza*. Charcoal (both macro- and micro-) concentrations reach peak values for the core in this zone.

Concentrations of macro- and micro-charcoal are sharply reduced throughout Zone WJB5 (3.50–1.68 m; ca. 7210–2290 cal yr BP) compared with zone WJB4. Two sub-zones are apparent within zone WJB5, according to up-core variations in microfossils. Sub-zone WJB5a (3.50–2.20 m; ca. 7210–3000 cal yr BP) is characterised by abundant Chenopodiaceae and *Pinus* pollen. Cyperaceae, Poaceae (≤40 um) and *Typha* pollen is present, as is *Quercus* (evergreen) comp., but generally at lower levels than in zone WJB4. Notably, Poaceae (>40 µm) pollen is less abundant, as are phytoliths from domesticated forms of *Oryza* (although no phytoliths are present in this zone from above 3.43 m). Dinoflagellate cysts are abundant. By comparison, sub-zone WJB5b (2.20–1.68 m; ca. 3000–2290 cal yr BP) is characterised by an increased abundance of *Typha* and a short-lived decline in Chenopodiaceae pollen, reduced amounts of dinoflagellate cysts, and low levels of arboreal and Poaceaea (>40 µm) pollen.

With the exception of charcoal, the levels of which remain relatively low, macro- and microfossils are absent from sediments from 1.68–0.9 m (ca. 2290–1230 cal yr BP) in the core from Wujiabang.

Zone WJB6 (0.90–0.67 m; ca. 1230–910 cal yr BP), the uppermost zone recognized at this site, is characterised by abundant, large-sized Poaceae (>40 µm) and Brassicaceae pollen, together with phytoliths from domesticated forms of *Oryza*. The remains of freshwater algae (Zygaemataceae) are present. Concentrations of macro- and micro-charcoal are also higher than zone WJB5.

Discussion

Holocene environmental changes in the lower Yangtze

Data from the Luojiang and Wujiabang cores provide evidence of Holocene climatic instability in the lower Yangtze that is supported by previously published work in the region (e.g., Wang and Zhang, 1985; Liu et al., 1992; Liu and Chang, 1996; Chen et al., 2005; Shu et al., 2007). The influence on local environmental conditions of spatially and temporally varying hydrological processes is also clearly apparent. Evidence from the two study sites of Holocene environmental changes provides a context for the discussions that follow on apparent differences in vulnerability of Neolithic activity on the Yangtze delta.

An early Holocene presence of subtropical deciduous and evergreen broadleaved forests in the lower Yangtze (Liu and Chang, 1996; Shu et al., 2007) is supported by the records from Luojiang and Wujiabang, and reflects climatic amelioration following the ending of the last glacial in the form of warmer temperatures and increased activity of the East Asian monsoon (Yi and Saito, 2004). An initial abundance of pollen from cool-temperate taxa, such as *Abies*, *Picea* and *Pinus*, indicates temperatures somewhat cooler than present, however, and is again in keeping with existing data (Liu et al., 1992; Liu and Chang, 1996).

Post-glacial climatic amelioration continued into the mid-Holocene (the mid-Holocene climatic optimum of warm temperatures and abundant monsoon precipitation of An et al. (2000)), and led to vegetation at the two coring sites being characterised by a subtropical flora, including evergreen *Quercus*, *Juglans*, *Liquidambar*, *Magnolia* and *Pterocarya*. Warm, humid conditions also explain the abundant Lauraceae plant remains recovered from the Hemudu archaeological site (Yu and Xu, 2000).

Two abrupt increases in *Pinus* pollen at ca. 8070 cal yr BP and ca. 7210 cal yr BP in the Wujiabang core are less evident in the core from Luojiang. Similar increases in conifer pollen elsewhere in the lower Yangtze during the early to mid-Holocene have been attributed to climatic cooling and reduced monsoonal activity (e.g., Cai et al., 2001). However, the relative complacency of well-dated pollen and phytoliths records from Luojiang and Kuahuqiao (Innes et al., 2009), both less than 120 km away, would appear to discount climate change as the main driver. Instead, a much more locally specific cause is indicated. *Pinus* pollen is generally widely dispersed (Heusser, 1988), and variations in the abundances of *Pinus* pollen are therefore expected to be consistent over large areas, particularly if being driven by climate change. The decline in abundance of *Pinus* pollen between the two peaks in the core from Wujiabang is associated with changes in the sedimentary environment, and in particular an oscillation between brackish-water and peat-accumulating (i.e., saline and freshwater) conditions. Increased abundance of *Pinus* pollen, coincident with other sediment-based evidence of salinisation, could therefore represent a change in primary source area, and in particular a greater input of regionally sourced pollen as opposed to locally derived material commonly associated with peat-forming environments, or reworking and redeposition of sediment associated with marine transgression. According to Sun et al. (1999) and Sun and Luo (2001), *Pinus* pollen accounts for more than 80% of total pollen in surface sediments in the South China Sea, having been transported long distances from its source areas by the northeast (northern hemisphere winter) monsoon.

As with abrupt changes in *Pinus* pollen, two stepped declines in *Quercus* (evergreen) comp. at Wujiabang, dated to ca. 8070 cal yr BP and ca. 7210 cal yr BP, are unrecorded at Luojiang, which is again suggestive of local rather than region-wide causal factors. According to Fuller et al. (2007), declines in *Quercus* pollen at about 7700 and 7000 years ago in a core of sediment from a site to the east of Lake Taihu, described by Tao et al. (2006), may reflect over-exploitation by people for whom acorns were an important food resource. Reduced availability of acorns could, however, have motivated increased interest in other available food sources, including rice.

In addition to climate changes, variations in relative sea level have also been a major factor influencing environmental conditions on the lower Yangtze during the Holocene (Stanley and Chen, 1993; Zong, 2004; Chen et al., 2008). Inundation by brackish water at the coring sites at Luojiang appears to have been a factor throughout much of the Holocene to ca. 4990 cal yr BP, as is attested by the presence of sedimentary indicators such as shells, the remains of dinoflagellate cysts and pollen from salt marsh taxa, notably members of the Chenopodiaceae. Conditions were therefore similar to those at the nearby archaeological site at Hemudu, where shallow, saline conditions are thought to have existed prior to its occupation (Zhu et al., 2003). The situation at the Wujiabang coring site during the early to mid-Holocene was somewhat different, however, with greater variation in hydrological conditions evident. Thus, inundation of the site at Wujiabang with brackish water from ca. 8070 cal yr BP was interrupted at least twice by less saline conditions during the early to mid-Holocene, ca. 7850–7210 cal yr BP and ca. 3000–2290 cal yr BP. Evidence of relatively dynamic hydrological conditions is available from other locations on the Hangjiahu plain (Yan and Huang, 1987) and is in keeping with model simulations (Xin and Xie, 2006). Such dynamism could also explain the poorer preservation of plant material at Wujiabang when compared with Luojiang. One possible reason for a greater vulnerability to inundation is the high density of channels on the Hangjiahu plain to the south of Lake Taihu (Yan and Huang, 1987), providing conduits for fresh and saline water, and facilitating sediment supply and removal.

Responses of Neolithic farmers on the Ningshao and Hangjiahu plains to varying environmental conditions

Early Neolithic populations in the lower Yangtze are likely to have relied upon a broad range of sources of nutrition, including rice (Cai, 2001; Chen and Zheng, 2005; Qin et al., 2006; Fuller et al., 2007, 2009; Zheng, 2007). Hemudu people are thought to have had access to abundant food resources from the wild (Ikehashi, 2007); the large quantities of animal, acorn and other plant remains found at Hemudu (Zhejiang Institute of Archaeology, 2003) and Tianluoshan (Zhejiang Institute of Cultural Relics and Archaeology et al., 2007) suggest that the collection and hunting of food were major activities (Chen and Zheng, 2005; Qin et al., 2006; Fuller et al., 2007; Zheng, 2007; Chen et al., 2008). Acorn, a bulk carbohydrate-provider, is potentially storable for long periods (Mason, 2000), and likely to have been a particularly important food resource (Qin et al., 2006). Rice remains from the site at Hemudu were predominantly empty husks, mixed with stalks, leaves and carbonised grains (Zhejiang Institute of Archaeology, 2003), and are believed to represent a mixture of wild and domesticated varieties (Liu et al., 2007). Domesticated rice-type morphophytes were, however, largely absent from the sedimentary record from Luojiang and the cultivation of domesticated rice may therefore have been highly localised, or even absent, until the late Holocene. By comparison, evidence from Wujiabang, in the form of pollen and phytoliths from rice, including domesticated varieties, together with abundant charcoal, firmly dated to ca. 7850–7210 cal yr BP, suggest the presence of domesticated rice-based agriculture during the early Neolithic. Evidence from Wujiabang indicates one or more, possibly brief, reoccupations of the site by rice-growing farmers following the onset of less saline conditions from ca. 3000 cal yr BP.

Persistently high soil salinity is also thought to have been a factor at Tianluoshan throughout its occupation during the early Neolithic period (Li et al., 2009), and maintaining the productivity of rice-based agriculture as conditions there became progressively more saline may have required a similar level of environmental manipulation to that reported for the site at Kuahuqiao (Zong et al., 2007; Innes et al., 2009). Inundation by brackish water could also have hampered the cultivation of domesticated rice at Luojiang during the same period, as is reported for the site at Qingpu on the Hangjiahu plain as recently as 2500–2000 years ago (Itzstein-Davey et al., 2007a). The cultivation of domesticated rice—a glycophyte—is hampered by high soil salinity, while wild relatives of rice are able to thrive in brackish water and estuarine habitats (Zeng and Shannon, 2000; Latha et al., 2004).

Lower population levels overall, and a relatively attenuated development of Neolithic culture on the Ningshao plain when compared with the Hangjiahu plain, may have been caused by much more limited supplies of freshwater on the former during the transgressive stages of early to mid-Holocene sea level change, limiting rice-based agriculture and preventing the accumulation of large agricultural surpluses and increasing food insecurity. Hemudu-aged sites on the Ningshao plain were geographically restricted to what is now the Yuyao River (Wang and Liu, 2005). Wooden wells, used to store freshwater, have been uncovered at Hemudu (Wang and Huang, 2002). However, these appear to have been used to store water for drinking: no evidence of irrigated rice fields dating to the early Neolithic has yet to be found on the Ningshao plain (Cao et al., 2006). Limited development of irrigated agriculture would explain why relatively sedentary populations retained fishing, gathering and hunting as important sources of nutrition, as is evident from the material remains recovered from archaeological sites on the Ningshao plain. Such a situation could have persisted until reduced salinity from ca. 4990 cal yr BP eventually led to the development and spread of rice-based agriculture and associated food surpluses, providing the basis for an albeit relatively delayed diversification of society.

By comparison, the long-term availability of freshwater to irrigate paddy fields on the Hangjiahu plain (Cao et al., 2006), innovations in agricultural implements, such as the introduction of a stone plough (Administration of Cultural Heritage of Shanghai, 1985), and the additional productivity that came with these developments could have facilitated population growth, the accumulation of agricultural wealth and the diversification of society evident in the archaeological record. A reliance on freshwater resources could also, however, have enhanced vulnerability to environmental vicissitudes, and variations in local hydrological conditions (Zhang et al., 2005). A consequence of this could have been the frequent abandonment of settlements, as rising levels of salinity forced farmers to seek out new sources of freshwater for irrigation and became an important motivator of changes in settlement pattern on the Hangjiahu plain (Chen et al., 2008).

Conclusion

Multi-proxy evidence from two cores on the Ningshao and Hangjiahu plains, together with existing archaeological and palaeoecological records, highlight the complexity of vulnerability of Neolithic farmers on the lower Yangtze to hydrological changes driven by variations in relative sea level. Moreover, local environmental conditions appear to have been much more variable on the Hangjiahu plain to the south of Lake Taihu during the early to mid-Holocene when compared with the Ningshao plain. Development of rice-based agriculture and the associated Neolithic culture and relatively high population densities on the Hangjiahu plain may have been facilitated by more readily, if episodically, available freshwater resources; while on the Ningshao plain, the cultivation of rice, population growth and cultural change could all have been curtailed by persistently high soil salinity from the early Neolithic.

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References

Administration of Cultural Heritage of Shanghai, 1985. Tangmiaocun site in Songjiang county of Shanghai. Archaeology 584–594 (in Chinese).

An, Z.S., Porter, S.C., Kutzbach, J.E., Wu, X.H., Wang, S.M., Liu, X.D., Li, X.Q., Zhou, W.J., 2000. Asynchronous Holocene optimum of the East Asian monsoon. Quaternary Science Reviews 19, 743–762.

Atahan, P., Itzstein-Davey, F., Taylor, D., Dodson, D., Qin, J., Zheng, H., Brooks, A., 2008. Holocene-aged sedimentary records of environmental changes and early agriculture in the lower Yangtze, China. Quaternary Science Reviews 27, 556–570.

Barnes, G.L., 1993. China, Korea and Japan: The Rise of Civilization in East Asia. Thames and Hudson, London.

Bellwood, P., 2005. First Farmers: the Origins of Agricultural Societies. Blackwell Publishing, UK.

Bozarth, S.R., 1992. Classification of opal phytoliths formed in selected dicotyledons native to the Great Plains. In: Rapp, G.J., Mulholland, S.C. (Eds.), Phytolith Systematics. Plenum Press, New York, pp. 193–214.

Cai, B.Q., 2001. Culture and environment across the Hangzhou Bay in the Neolithic age. Journal of Xiamen University (Arts & Social Sciences) 126–133 (in Chinese, with English abstract).

Cai, Y.L., Chen, Z.Y., Zhang, W., Guo, Z.Y., Chen, Y., 2001. Climate fluctuation of the western Shanghai district by correspondence analysis since 8.5 ka BP. Journal of Lake Sciences 13, 118–126 (in Chinese, with English abstract).

Cao, Z.H., Ding, J.L., Hu, Z.Y., Knicker, H., Kögel-Knabner, I., Yang, L.Z., Yin, R., Lin, X.G., Dong, Y.H., 2006. Ancient paddy soils from the Neolithic age in China's Yangtze River delta. Die Naturwissenschaften 93, 232–236.

Chang, K.C., 1986. The Archaeology of Ancient China. Yale University Press, New Haven, USA.

Chang, K.T., Wang, P.L., 1986. Pollen morphology of *Quercus* L. in China. Acta Phytotaxonomica Sinica 24, 362–369 (in Chinese, with English abstract).

Changzhou Museum, 2004. The excavation report of Chuodun site in Changzhou, Jiangsu province in 1985. In: Jiaxing Culture Bureau (Ed.), Majiabang Culture. Zhengjiang photograph press, Hangzhou, pp. 134–153 (in Chinese).

Chapman, G.P., Wang, Y.Z., 2002. The Plant Life of China. Springer, Berlin.

Chaturvedi, M., Datta, K., Nair, P.K.K., 1998. Pollen morphology of *Oryza* (Poaceae). Grana 37, 79–86.

Chen, C., Zheng, J.M., 2005. An archaeological exploration of the origin of paddy agriculture. Fudan Journal (Social Sciences) 126–131 (in Chinese, with English abstract).

Chen, Z.Y., Wang, Z.H., Schneiderman, J., Tao, J., Cai, Y.L., 2005. Holocene climate fluctuations in the Yangtze delta of eastern China and the Neolithic response. Holocene 15, 915–924.

Chen, Z.Y., Zong, Y.Q., Wang, Z.H., Wang, H., Chen, J., 2008. Migration patterns of Neolithic settlements on the abandoned Yellow and Yangtze River deltas of China. Quaternary Research 70, 301–314.

Clark, R.L., 1982. Point count estimation of charcoal in pollen preparations and thin sections of sediments. Pollen et Spores 24, 523–535.

Crawford, G.W., Shen, C., 1998. The origins of rice agriculture: recent progress in East Asia. Antiquity 72, 858–867.

Ericson, J.P., Vörösmarty, C.J., Dingman, S.L., Ward, L.G., Meybeck, M., 2006. Effective sea level rise and deltas: causes of change and human dimension implications. Global and Planetary Change 50, 63–82.

Fang, X.F., 2006. Researching in the Species Diversity Character of Vegetation within Ningbo. Master thesis, East China Normal University, Shanghai (in Chinese, with English abstract).

Fuller, D.Q., Harvey, E., Qin, L., 2007. Presumed domestication? Evidence for wild rice cultivation and domestication in the 5th millennium BC of the Lower Yangtze region. Antiquity 81, 316–331.

Fuller, D.Q., Qin, L., Zheng, Y., Zhao, Z., Chen, X., Hosoya, L.A., Sun, G.P., 2009. The domestication process and domestication rate in rice: spikelet bases from the lower Yangtze. Science 323, 1607–1610.

Grimm, E.C., 1987. CONISS: a Fortran 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. Computers and Geosciences 13, 13–35.

Grimm, E.C., 1992. Tilia Software. Illinois State Museum, Chicago.

Gu, J.X., Zou, H.B., Li, M.C., Tang, L.H., Ding, J.L., 1998. A primary study on rice cultivation of Majiabang culture at Caoxieshan site. Southeast Culture 15–24 (in Chinese).

Heusser, L.E., 1988. Pollen distribution in marine sediments on the continental margin off northern California. Marine Geology 80, 131–147.

Hori, K., Saito, Y., Zhao, Q.H., Wang, P.X., 2002. Architecture and evolution of the tide-dominated Changjiang (Yangtze) River delta, China. Sedimentary Geology 146, 249–264.

Hu, H.J., Wei, Y.X., 2006. The Freshwater Algae of China—Systematics, Taxonomy and Ecology. Science Press, Beijing. (in Chinese).

Hughen, K.A., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C., Blackwell, P.G., Buck, C.E., Burr, G., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Kromer, B., McCormac, F.G., Manning, S., Bronk Ramsey, C., Reimer, P.J., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. MARINE04 marine radiocarbon age calibration, 26–0 ka BP. Radiocarbon 46, 1059–1086.

ICPN Working Group, Madella, M., Alexandre, A., Ball, T., 2005. International code for phytolith nomenclature 1.0. Annals of Botany 96, 253–260.

Ikehashi, H., 2007. The origin of flooded rice cultivation. Rice Science 14, 161–171.

Innes, J.B., Zong, Y.Q., Chen, Z.Y., Chen, C., Wang, Z.H., Wang, H., 2009. Environmental history, palaeoecology and human activity at the early Neolithic forager/cultivator site at Kuahuqiao, Hangzhou, eastern China. Quaternary Science Reviews 28, 2277–2294.

Itzstein-Davey, F., Atahan, P., Dodson, J., Taylor, D., Zheng, H.B., 2007a. Environmental and cultural changes during the terminal Neolithic: Qingpu, Yangtze delta, eastern China. Holocene 17, 875–887.

Itzstein-Davey, F., Taylor, D., Dodson, J., Atahan, P., Zheng, H.B., 2007b. Wild and domesticated forms of rice (*Oryza* sp.) in early agriculture at Qingpu, lower Yangtze, China: evidence from phytoliths. Journal of Archaeological Science 34, 2101–2108.

Jiang, L.P., Liu, L., 2005. The discovery of an 8000-year-old dugout canoe at Kuahuqiao in the Lower Yangzi River, China. Antiquity 79, 305.

Jiang, L.P., Liu, L., 2006. New evidence for the origin of sedentism and rice domestication in the lower Yangzi River, China. Antiquity 80, 355–361.

Jiang, T., Zhang, Q., Wang, S.M., 2004. The relationship between droughts, floods and climatic changes in the middle and lower reaches of the Changjiang River since last 1000 years. Quaternary Sciences 24, 518–524 (in Chinese, with English abstract).

Latha, R., Rao, C.S., Subramaniam, H.M.S.R., Eganathan, P., Swaminathan, M.S., 2004. Approaches to breeding for salinity tolerance — a case study on *Porteresia coarctata*. The Annals of Applied Biology 144, 177–184.

Li, C.H., Zhang, G.Y., Yang, L.Z., Lin, X.G., Hu, Z.Y., Dong, Y.H., Cao, Z.H., Zheng, Y.F., Ding, J.L., 2007a. Pollen and phytolith analyses of ancient paddy fields at Chuodun site, the Yangtze River delta. Pedosphere 17, 209–218.

Li, L., Xu, X.M., Tian, M., Lu, M.X., 2007b. Protection and restoration of the stone plow unearthed on the Pinghu Zhuangqiaofen relic site. Sciences of Conservation and Archaeology 19, 53–57 (in Chinese, with English abstract).

Li, M.L., Mo, D.W., Sun, G.P., Zhou, K.S., Mao, L.J., 2009. Paleosalinity in Tianluoshan site and the relation between Hemudu culture and its environmental background. Acta Geographica Sinica 64, 807–816 (in Chinese, with English abstract).

Liu, Z.Y., 2000. Thoughts about the domestication of rice. Agricultural Archaeology 122–128 (in Chinese).

Liu, J.L., Chang, W.Y.B., 1996. Uses of pollen profiles to show the last 12,000 years of environmental changes in the Yangtze River delta. Acta Palaeontologica Sinica 35, 136–154 (in Chinese, with English abstract).

Liu, J., Jiang, L.P., 1998. Study on several problems about Neolithic culture in Ningshao region. In: Zhejiang Provincial Bureau of Culture Relics (Ed.), Researches on Hemudu Culture. Hangzhou University Press, Hangzhou, pp.84–99 (in Chinese).

Liu, K.B., Sun, S.C., Jiang, X.H., 1992. Environmental change in the Yangtze River delta since 12, 000 years BP. Quaternary Research 38, 32–45.

Liu, L., Lee, G.A., Jiang, L.P., Zhang, J.Z., 2007. Evidence for the early beginning (c. 9000 cal. BP) of rice domestication in China: a response. Holocene 17, 1059–1068.

Lu, H.Y., Wu, N.Q., Yang, X.D., Jiang, H., Liu, K.B., Liu, T.S., 2006. Phytoliths as quantitative indicators for the reconstruction of past environmental conditions in China I: Phytolith-based transfer functions. Quaternary Science Reviews 25, 945–959.

Maloney, B.K., 1990. Grass pollen and the origins of rice agriculture in north Sumatra. Modern Quaternary Research in Southeast Asia 11, 135–160.

Mason, S.L.R., 2000. Fire and Mesolithic subsistence-managing oaks for acorns in northwest Europe? Palaeogeography, Palaeoclimatology, Palaeoecology 164, 139–150.

Moore, P.D., Webb, J.A., Collinson, M.E., 1991. Pollen Analysis. Blackwell Scientific Publications, Oxford, UK.

Nanjing Museum, 2004. Caoxieshan site in Wuxian, Jiangsu province. In: Jiaxing Culture Bureau (Ed.), Majiabang Culture. Zhengjiang photograph press, Hangzhou, pp. 126–133 (in Chinese).

Nicholls, R.J., Wong, P.P., Burkett, V.R., Codignotto, J.O., Hay, J.E., McLean, R.F., Ragoonaden, S., Woodroffe, C.D., 2007. Coastal systems and low-lying areas. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., Hanson, C.E., van der Linden, P.J. (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the IPCC. Cambridge University Press, Cambridge, pp. 315–356.

Ningbo Chorography Codification Committee, 1995. Ningbo Chorography. Zhonghua Book Company, Beijing. (in Chinese).

Normile, D., 1997. Yangtze seen as earliest rice site. Science 275, 309.

Piperno, D.R., 2006. Phytoliths: a Comprehensive Guide for Archaeologists and Paleoecologists. AltaMira Press, USA.

Qin, L., Fuller, D.Q., Harvey, E., 2006. Subsistence of Hemudu site, and reconsideration of issues in the study of early rice from Lower Yangtze. Oriental Archaeology 3, 307–350 (in Chinese).

Qin, J.G., Wu, G.X., Zheng, H.B., Zhou, Q., 2008. The palynology of the First Hard Clay Layer (late Pleistocene) from the Yangtze delta, China. Review of Palaeobotany and Palynology 149, 63–72.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Freidrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Dromer, B., McCormac, G., Manning, S., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plitch, J., Weyhenmeyer, C.E., 2004. IntCal04 terrestrial radiocarbon age calibration, 0–26 cal kyr BP. Radiocarbon 46, 1029–1058.

Richerson, P.J., Bettinger, R.L., Boyd, R., 2005. Evolution on a restless planet: were environmental variability and environmental change major drivers of human evolution? In: Wuketits, F.M., Ayala, F.J. (Eds.), Handbook of Evolution Volume 2: The Evolution of Living Systems (Including Hominids). Weiley-VCH, Weinheim, pp. 223–240.

Rochon, A., de Vernal, A., Turon, J.L., Mathiessen, J., Head, M.J., 1999. Distribution of Recent Dinoflagellate Cysts in Surface Sediments from the North Atlantic Ocean and Adjacent Seas in Relation to Sea-Surface Parameters. The American Association of Stratigraphic Palynologists Foundation, America.

Rosen, A.M., 1992. Preliminary identification of silica skeletons from Near Eastern archaeological sites: an anatomical approach. In: Rapp, G.J., Mulholland, S.C. (Eds.), Phytolith Systematics. Plenum Press, New York, pp. 129–147.

Runge, F., 1999. The opal phytolith inventory of soils in central Africa—quantities, shapes, classification, and spectra. Review of Palaeobotany and Palynology 107, 23–53.

Schneiderman, J.S., Chen, Z.Y., Eckert, J.O., 2003. Heavy minerals and river channel migration in the Yangtze delta plain, eastern China. Journal of Coastal Research 19, 326–335.

Shao, W., 2005. The formation of civilization: the interaction sphere of the Longshan period. In: Chang, K.C., Xu, P.F., Allen, S., Lu, L.C. (Eds.), The Formation of Chinese Civilization: An Archaeological Perspective. Yale University and New World Press, New Haven, USA, pp. 85–124.

Shu, J.W., Wang, W.M., Chen, W., 2007. Holocene vegetation and environment changes in the NW Taihu plain, Jiangsu province, East China. Acta Micropalaeontologica Simica 24, 210–221 (in Chinese, with English Abstract).

Stanley, D.J., Chen, Z.Y., 1993. Yangtze delta, eastern China: 1. Geometry and subsidence of Holocene depocenter. Marine Geology 112, 1–11.

Stanley, D.J., Chen, Z.Y., 1996. Neolithic settlement distributions as a function of sea level-controlled topography in the Yangtze delta, China. Geology 24, 1083–1086.

Stanley, D.J., Chen, Z.Y., 2000. Radiocarbon dates in China's Holocene Yangtze delta: record of sediment storage and reworking, not timing of deposition. Journal of Coastal Research 16, 1126–1132.

Stanley, D.J., Hait, A.K., 2000. Deltas, radiocarbon dating and measurements of sediment storage and subsidence. Geology 28, 295–298.

Stanley, D.J., Chen, Z.Y., Song, J., 1999. Inundation, sea-level rise and transition from Neolithic to Bronze Age cultures, Yangtze delta, China. Geoarchaeology 14, 15–26.

Sun, X.J., Luo, Y.L., 2001. Pollen record of the last 280 ka from deep sea sediments of the South China Sea. Science in China. Series D: Earth Sciences 44, 879–888.

Sun, X.J., Li, X., Beug, H.J., 1999. Pollen distribution in hemipelagic surface sediments of the northern South China Sea and its relation to modern vegetation distribution. Marine Geology 156, 211–226.

Syvitski, J.P.M., Kettner, A.J., Overeem, I., Hutton, E.W.H., Hannon, M.T., Brakenridge, G.R., Day, J., Vörösmarty, C., Saito, Y., Giosan, L., Nicholls, R.J., 2009. Sinking deltas due to human activities. Nature Geoscience 2, 681–686. doi:10.1038/NGEO629.

Tao, J., Chen, M.T., Xu, S.Y., 2006. A Holocene environmental record from the southern Yangtze River delta, eastern China. Palaeogeography, Palaeoclimatology, Palaeoecology 230, 204–229.

The Cultural Relics and Archaeology Institution of Zhejiang Province, The Cultural Relics Administration Committee of Tongxiang City, 2005. Brief excavation report of Xindili site, Tongxiang City, Zhejiang province. Cultural Relics 4–31 (in Chinese, with English abstract).

Tweddle, J.C., Edwards, K.J., Fieller, N.R.J., 2005. Multivariate statistical and other approaches for the separation of cereal from wild Poaceae pollen using a large Holocene dataset. Vegetation History and Archaeobotany 14, 15–30.

Underhill, A.P., 1997. Current issues in Chinese Neolithic archaeology. Journal of World Prehistory 11, 103–160.

Wang, J.G., 1997. Population pressure and growth of Chinese primitive agriculture. Agricultural Archaeology 58–73 (in Chinese).

Wang, L.H., Huang, W.J., 2002. The well of Hemudu site and the origin of Chinese well. Agricultural Archaeology 195–205 (in Chinese).

Wang, H.M., Liu, S.H., 2005. The spreading and propagation for Hemudu culture. Relics from South 114–118 (in Chinese).

Wang, Y., Lu, H., 1993. The Study of Phytolith and its Application. China Ocean Press, Beijing. (in Chinese).

Wang, K.F., Zhang, Y.L., 1985. The spore–pollen algal assemblages and its paleogeography in the late Quaternary sediment in the Ningbo plain. Scientia Geographica Sinica 5, 145–152 (in Chinese, with English abstract).

Wang, F., Qian, N., Zhang, Y., Yang, H., 1995. Pollen Flora of China (second edition). Science Press, Beijing. (in Chinese).

Webb, R.S., Webb III, T., 1988. Rates of sediment accumulation in pollen cores from small lakes and mires of eastern North America. Quaternary Research 30, 284–297.

Wu, Z.Y. (Ed.), 1980. The Vegetation of China. Science Press, Beijing (in Chinese).

Wu, W.T., 1983. Evolution of the Yaojiang plain in last 7000 years. Scienta Geographica Sinica 3, 269–275 (in Chinese, with English abstract).

Xin, Z.B., Xie, Z.R., 2006. Construction of the simulating model for geomorphic evolution on the Yangtze delta, China. Acta Geographica Sinica 61, 549–560 (in Chinese, with English abstract).

Yan, Q.S., Huang, S., 1987. Evolution of Holocene sedimentary environment in the Hangzhou-Jiaxing-Huzhou plain. Acta Geographica Sinica 42, 1–15 (in Chinese, with English abstract).

Yi, S., Saito, Y., 2004. Latest Pleistocene climate variation of the East Asian monsoon from pollen records of two east China regions. Quaternary International 121, 75–87.

You, X., 1999. Liangzhu culture and rice production. Collected Studies of Agricultural History 1, 1–8 (in Chinese).

Yu, W.J., Xu, X.L., 2000. Study of the foliage relics from Hemudu archaeological site. Culture of Southeast China 7, 24–32 (in Chinese).

Yu, S., Zhu, C., Song, J., Qu, W., 2000. Role of climate in the rise and fall of Neolithic cultures on the Yangtze delta. Boreas 29, 157–165.

Zeng, L., Shannon, M.C., 2000. Salinity effects on seedling growth and yield components of rice. Crop Science 40, 996–1003.

Zhang, S.F., 1991. The peat in Ningshao plain of the Zhengjiang province and its reflection on the sea-level changes. Journal of Nanjing Normal University (Natural Science Edition) 14, 78–86 (in Chinese, with English abstract).

Zhang, C., Hung, H.C., 2008. The Neolithic of southern China: origin, development, and dispersal. Asian Perspectives 47, 299–329.

Zhang, Q., Zhu, C., Liu, C.L., Jiang, T., 2005. Environmental change and its impacts on human settlement in the Yangtze delta, P.R. China. Catena 60, 267–277.

Zhao, Z.J., 1998. The Middle Yangtze region in China is one place where rice was domesticated: phytolith evidence from the Diaotonghuan cave, northern Jiangxi. Antiquity 72, 885–897.

Zhao, Z.J., Piperno, D.R., 2000. Late Pleistocene/Holocene environments in the middle Yangtze River valley, China and rice (*Oryza sativa* L.) domestication: the phytolith evidence. Geoarchaeology 15, 203–222.

Zhejiang Institute of Archaeology, 2003. Hemudu: Excavation Report of the Neolithic Archaeological Site. Wenwu Press, Beijing. (in Chinese).

Zhejiang Institute of Archaeology, Xiaoshan Museum, 2004. Kuahuqiao. Wenwu Press, Beijing. (in Chinese).

Zhejiang Institute of Cultural Relics and Archaeology, Jiaxing Museum, 2005. A preliminary report of excavation at the Wujiabang site, Jiaxing, Zhejiang province. Cultural Relics 34–42 (in Chinese).

Zhejiang Institute of Cultural Relics and Archaeology, Yuyao Municipal Office of the Preservation of Cultural Relics, Hemudu Site Museum, 2007. Brief report of the excavation on a Neolithic site at Tianluoshan hill in Yuyao city, Zhejiang. Cultural relics 4–24 (in Chinese, with English abstract).

Zhejiang Institute of Cultural Relics and Archaeology, 2004. Wujiabu Neolithic site in Yuhang. In: Jiaxing Culture Bureau (Ed.), Majiabang Culture. Zhengjiang photograph press, Hangzhou, pp. 94–111 (in Chinese).

Zheng, J.M., 2007. A Research on the different neolithic culture trajectories around Taihu Lake area and Ningshao plain. Ph.D. thesis, Fudan University, Shanghai (in Chinese, with English abstract).

Zheng, X.M., Peng, J.L., Zhang, W.G., Fan, W.Y., 1999. Aeolian Loess Depositions and Environment in Yangtze Delta and Adjacent Continental Shelf. East China Normal University Press, Shanghai. (in Chinese, with English abstract).

Zheng, Y.F., Matsui, A., Fujiwara, H., 2003. Phytoliths of rice detected in the Neolithic sites in the valley of the Taihu Lake in China. Environmental Archaeology 8, 177–184.

Zhu, C., Zheng, C.G., Ma, C.M., Yang, X.X., Gao, X.Z., Wang, H.M., Shao, J.H., 2003. On the Holocene sea-level highstand along the Yangtze delta and Ningshao plain, east China. Chinese Science Bulletin 48, 2672–2683.

Zong, Y.Q., 2004. Mid-Holocene sea-level highstand along the Southeast Coast of China. Quaternary International 117, 55–67.

Zong, Y., Chen, Z., Innes, J.B., Chen, C., Wang, Z., Wang, H., 2007. Fire and flood management of coastal swamp enabled first rice paddy cultivation in east China. Nature 449, 459–463.