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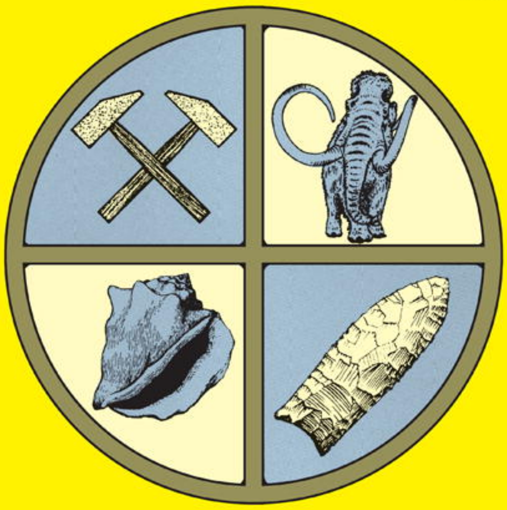

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Holocene-aged sedimentary records of environmental changes and early agriculture in the lower Yangtze, China

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Abstract

Sedimentary evidence from a total of 21 AMS ^{14}C dates and 192 pollen and charcoal and 181 phytolith samples from three study sites in the archaeologically rich lower Yangtze in China provides an indication of interactions between early agriculturalists and generally highly dynamic environmental conditions. Results suggest that environmental changes influenced agricultural development, and attest the localised environmental impacts of incipient agriculture. Evidence of human activity, in the form of indicators of deforestation and possibly food production, is apparent by ca 7000 BP (early Neolithic or Majiabang). Clearer evidence of human activity dates to ca 4700 BP (late Neolithic or Liangzhu). Extensive, profound and apparently widespread human impacts do not appear until the Eastern Zhou (Iron Age, ca 2800–2200 BP), however, which in the lower Yangtze was a period associated with technological advances in agriculture, increased urbanisation and relatively stable hydro-geomorphological conditions.

1. Introduction

The agriculturally fertile middle and lower reaches of the Yangtze and Yellow rivers in central and eastern China are regarded as one of several regions globally where agriculture developed more-or-less independently (Bellwood, 2005). The region is at present associated with several domesticated summer cereals, most notably rice (*Oryza sativa* L.). Environmental changes at the end of the Pleistocene and during the early part of the Holocene may have facilitated the initiation and development of agriculture (Yasuda, 2002; Bellwood, 2005), as has been suggested for other parts of the world (e.g., Wright, 1993). Archaeological investigations have yielded numerous cereal grain assemblages dating to the late Pleistocene/early Holocene, a period of rapid climate change, with 'firmly identified cultivated rice' present in the middle Yangtze by 'no later than' 8500 BP (Lu, 1999, p. 67). Domestication followed and the subsequent accumulation and concentration of wealth among agriculturalists, and their colonisation of previously unfarmed areas, are thought to have underpinned the formation of civilisation by facilitating the emergence and unification of states, cultural assimilation and the appearance of a dynastic system in which economic, political and religious authority became closely integrated (Lu and Yan, 2005).

Archaeological and palaeoenvironmental data for the period of emergence of food production in China are relatively scarce (Chang, 1986; Elston et al., 1997; Lu et al., 2006; Fuller et al., in press), while incontrovertible evidence of the domestication of plants does not occur until much later in the archaeological record (Fuller et al., 2007). Several important questions naturally arise from this, including: what sequence of events led to the emergence of agriculture characterised by domestication; to what extent did the sequence vary geographically; and was the sequence influenced by varying environmental conditions?

These questions guide the current research focusing on the lower Yangtze, the results of which are synthesised and reported in this paper. The lower Yangtze is associated with a large number of archaeological sites, some of

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which — notably the sites at Hemudu and Shangshan and the evidence for rice consumption during the early Holocene that they have yielded — are well known, and characterised by conditions conducive to the accumulation of relatively continuous sediment-based archives. The lower Yangtze is also highly dynamic, environmentally and socio-economically. Thus, in addition to abundant opportunities to integrate archaeological with sediment-based records of human activity, the lower Yangtze also provides an almost ideal location for examining the influence of environmental changes on incipient food production, and in particular early rice-based agriculture.

1.1. The emergence of rice as a food source

Currently there are about 20 species of wild-growing rice (*Oryza*) and two cultigens: *O. sativa* L., domesticated in Asia, and *O. glaberrima* Steud., grown in west Africa (Chang, 1989; Morishima, 2001). Recent genetic evidence suggests that perennial populations of wild red rice, *O. rufipogon* Griff, were the ancestor of *O. sativa* and that at least two, independent domestication events led to the two main subspecies of domesticated rice: *O. sativa indica* and *O. sativa japonica* (Londo et al., 2006; Li et al., 2006b). Ancestral populations of wild rice may also have included annual wild rice (*O. nivara* S.D. Sharma et Shastry) as part of the same gene pool (Londo et al., 2006) and references to wild rice here do not differentiate between them.

Wild rice grows well in shallow (<1 m deep) permanent water bodies, is intolerant of low temperatures (Khush, 1997), and is largely perennial and therefore mainly reliant on vegetative reproduction. The relatively few seeds produced ripen over a prolonged period of time and, once ripened, are dispersed by shattering. In China and aside from a few isolated stands in the middle and lower Yangtze, wild rice is currently restricted to swampy land in the southern part of the country. Existing archaeobotanical and palaeoecological evidence suggests, however, that wild rice was more extensive during a brief interlude in the lateglacial and during the early-to-mid Holocene, during which warm temperatures together with increased monsoonal rainfall and rising sea and river levels led to an expansion of suitable habitat, with wild rice abundant over a large part of southern and central China as far north as the Yellow River (Crawford and Shen, 1998; Crawford et al., 2005).

The Yangtze is thought to have featured prominently in the domestication of rice (Normile, 1997; Wang, 1997; Crawford and Shen, 1998; Zhao, 1998; Liu, 2000; Zhao and Piperno, 2000; Chapman and Wang, 2002; Jiang and Liu, 2006). The common occurrence of wild rice, particularly during relatively warm, humid phases in the past, in combination with the high nutritional value of its seeds, would have ensured its high value among hunter-gatherer communities. Evidence suggests that wild rice was being exploited as early as ca 12,000 BP (Crawford and Shen, 1998; Zhang and Wang, 1998; Liu, 2000; Zheng et al., 2003). Less controvertible evidence of the use of rice — dating to the early-to-mid Holocene — comes from sites that appear to have been occupied more or less permanently: Bashidang, Chengbeixi and Pengtoushan (ca 8500 BP) in the middle Yangtze; Hemudu (ca 7000 BP), Kuahuqiao (possibly ca 7700 BP) and Shangshan (ca 10,000 BP) in the lower Yangtze (Lu, 1999; Jiang and Liu, 2006; Zong et al., 2007). However, how this rice was obtained is debatable: was the rice collected from the wild or was it cultivated — perhaps closer to home, and do at least some rice remains dating to the early-to-mid Holocene represent the product of domestication?

Recognising the *domestication syndrome* (the number of traits associated with domesticated plants but not with their wild relatives) in rice is problematic, owing to difficulties in determining distinguishing features that are incontrovertible (Fuller et al., 2007, in press). Many of the domestication syndrome traits in rice relate to dispersal of seeds, and in immature wild rice features such as the awn and spikelet base may be more similar to mature domesticated rice than to mature wild rice (Fuller et al., 2007). This is important because wild rice may have been harvested before the bulk of the grains were fully mature, and therefore before the gains had been dispersed by shattering, which does not occur in domesticated rice. Such difficulties in identification are compounded by the degree of morphological overlap between domesticated and extant wild rice, by the incomplete nature of archaeological and palaeoecological records, and by the fact that the original wild progenitor of domesticated rice could be now extinct. As a result, although a period of pre-domestication cultivation of rice is expected, the actual onset and length of this period are unknown.

2. Study area and sites

The current research is based on sedimentary evidence from three sites in the lower Yangtze, to the south of the main river channel (Fig. 1). According to existing data, the mouth of the palaeo-Yangtze was located some hundreds of kilometres east of the present coast at the Last Glacial Maximum (LGM) (Chen and Stanley, 1995; Chen et al., 1997; Elvin and Su, 1998). Rising sea-level during the lateglacial brought the coastline closer to its present location, although the coastline was still over 100 km farther east by ca 12,000 BP (Chen et al., 2000; Liu et al., 2000) and what is now the delta was part of a wide coastal plain drained by a network of incised river channels (Stanley and Chen, 1996). Relative sea level (RSL) rose rapidly during the early Holocene in areas bordering what is now the Yangtze delta (Zong, 2004), while the delta plain and an enlarged Lake Taihu may date to as recently as 3000–4000 BP (Chen and Zong, 1998; Hori et al., 2001) and to relatively stable RSL and, particularly since ca 2000 BP, rapid progradation as a result of deforestation and associated soil erosion in the catchment for the Yangtze river (Wang et al., 2001).

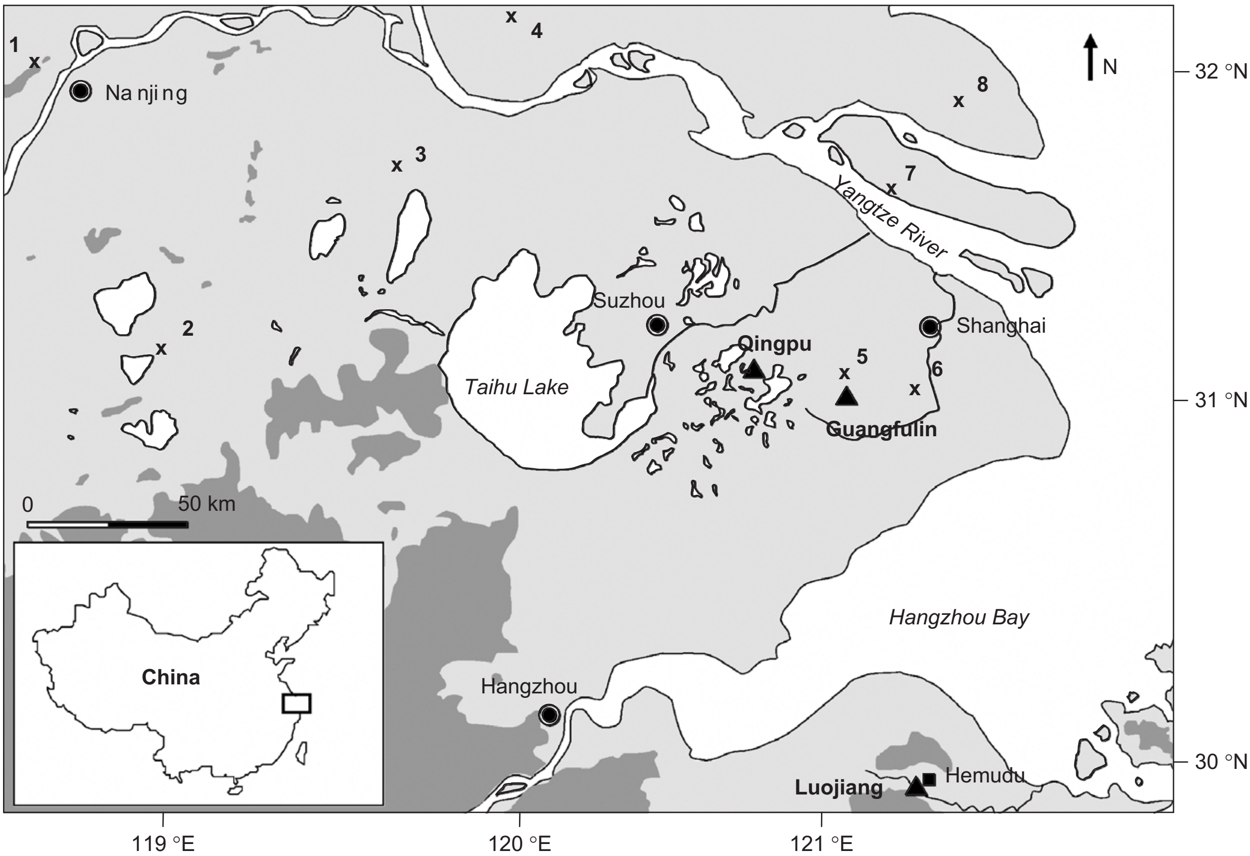

Fig. 1. Location of well-dated Holocene sediment records in the Yangtze delta region (crosses), in addition to sites of the present study (triangles): (1) Linfengqiao (Yu et al., 2003; Zhang et al., 2005); (2) Cauduntou (Okuda et al., 2003); (3) Zk01 (Shu et al., 2007); (4) HQ98 (Yi et al., 2003, 2006); (5) ZX-1 (Chen et al., 2005; Tao et al., 2006); (6) Maqiao (Yu et al., 2000); (7) CM97 (Yi et al., 2003, 2006); (8) Qidong (Liu et al., 1992). The area shaded darker grey represents land of higher elevation.

A trench was excavated at Qingpu, located about 40 km southwest of Shanghai, at 31°07.728′N and 120°54.656′E, to a depth of 260 cm. A total of 100 samples was collected from 260 to 60 cm for subsequent laboratory analyses. Analyses were carried out on a further 60 samples of sediment from 191 to 40 cm in a second trench, excavated at Guangfulin (31°3.870′N and 121°11.500′E). The ground altitudes of the sample sites at Qingpu and Guangfulin were estimated using an altimeter and GPS at 4.3 m a.m.s.l., or about 6 m above the local (Wusong) datum. The sample sites at Qingpu and Guangfulin are located in a part of the Yangtze delta that is particularly rich in archaeological sites, some of which date to the early Neolithic. Moreover, the site at Guangfulin is only ca 200 m from a major archaeological site of the same name, relics from which are thought to date from the late Neolithic to the Iron Age.

The third site, Luojiang (29°59.062′N and 121°21.752′E), is located on a floodplain draining into the southern part of Hangzhou Bay. The ground altitude at the sample site was estimated at 4 m a.m.s.l. (4 m above the local (Yellow Sea) datum), but the site is bounded by land of higher elevation (ca 40–50 m a.m.s.l.). A 45 m-long core of sediment was obtained from Luojiang: this paper refers to abundances of pollen and charcoal (32 samples) and phytoliths (21 samples) extracted from sediment samples from the uppermost 5 m of the core. Luojiang is situated ca 3 km to the southwest of the archaeological site at Hemudu (ca 1.1 m a.m.s.l.). The lowermost occupation layer at Hemudu (layer 4, ca 7100–6500 BP) contains abundant rice remains and evidence of sedentary settlement. Artifacts recovered from this layer include bone tools and cooking vessels.

3. Materials and methods

Pollen residues formed the majority (17) of the 21 samples collected from the three study sites submitted for AMS ^{14}C dating. Preparation of pollen residues for dating involved 10% NaOH to remove humic colloids; 15% HCl to remove carbonates; 40% HF to remove silicates and sieving through a 5 μm mesh to remove the fine fraction. The other four AMS ^{14}C dates were obtained on fragments of wood and macro-charcoal and were pre-treated using 30% HCl and 10% NaOH.

Processing of samples for pollen and micro-charcoal analyses followed standard preparation techniques, as outlined in Moore et al. (1991). *Lycopodium* spores were added as markers prior to processing in order to estimate pollen and micro-charcoal concentrations. Pollen and micro-charcoal residues were mounted in silicon oil and scanned under an Olympus Nikon microscope at 400 × magnification.

Pollen identification was made with reference to Wang et al. (1995). Pollen produced by grasses (Poaceae) was divided into two size categories (⩽40 μm and >40 μm). Poaceae grains >40 μm have previously been identified as domesticated rice (see Wang et al., 1995; Chatuvedi et al., 1998, but also see Shu et al., 2007, who suggest that pollen from domesticated rice in the lower Yangtze may predominantly fall in the 35–45 μm size range) and are here referred to as Poaceae (*Oryza* comp.). Although the use of a size threshold to distinguish Poaceae pollen produced by cereals such as rice is crude, particularly where there is a strong likelihood of encountering wild varieties of the same genus (see Maloney, 1990; Tweddle et al., 2005), in the current context size criteria are used in this way along with other forms of supporting evidence, notably other pollen types, charcoal and phytolith remains. *Quercus* pollen was also separated into two size categories: grains with a long axis >30 μm were classified as *Quercus* (deciduous comp.), and grains ⩽30 μm as *Quercus* (evergreen comp.) (Chang and Wang, 1986). Micro-charcoal (5–150 μm) was quantified using the point-count method (Clark, 1982). Samples of 1 cm^3 were prepared for analysis of macro-charcoal (>150 μm) through gentle disaggregation in 5% Calgon solution and sieving through a sieve of 150 μm mesh. All charcoal particles larger than 150 μm were counted under a stereomicroscope at 20 × magnification.

Phytoliths were extracted from 1 g crushed air-dried sediment samples using HCl to remove carbonates, agitation followed by settling to separate clays, firing in a muffle furnace to remove organics, and density (heavy liquid, sodium polytungstate) separation. Phytolith counts were conducted using a Meiji Techno Co. Ltd. ML5000 series laboratory microscope at 400 × magnification. Phytolith morphotypes were identified according to Bozarth (1992), Rosen (1992), Wang and Lu (1993), Runge (1999), Lu et al. (2006) and Piperno (2006), and following the nomenclature of ICPN Working Group et al. (2005). A list of phytolith types identified in this research, and their botanical affinities, is provided in Itzstein-Davey et al. (2007a). Rice phytoliths in the form of four single-cell morphotypes (cuneiform (fan-shaped) bulliforms; bilobate (dumbbell) short cells, bumpy long cells and double-peaked glumes) and one multi-cell morphotype (Jiang, 1995; Lu et al., 1997; Itzstein-Davey et al., 2007a, b) were studied in detail. At one site (Qingpu), single-celled, double-peaked *Oryza* glume phytoliths were sufficiently numerous to permit their separation into likely wild and likely domesticated morphotypes (Itzstein-Davey et al., 2007b). Samples were selected from regular intervals down the profile sampled at Qingpu. Up to a total of 25 double-peaked rice glume phytoliths per sample were measured (Pearsall et al., 1995; Zhao et al., 1998).

Because of uncertainties associated with both the precision and accuracy of empirical evidence of variations in RSL during the Holocene for the East China Sea bordering what is now the Yangtze delta (see Zong, 2004), changes in RSL from ca 10,000 BP to the present were simulated at 1000 yr intervals using a geophysical model. Generally, such models consist of three key components: an ice loading model, an earth model, and an algorithm to compute sea level change. The global ice model incorporated in the geophysical model used here follows the analyses of Bassett et al. (2005), which provide a close fit with far-field observations of RSL dating from the time of the LGM to ca 9000 BP. The Holocene component of the ice model is consistent with the findings of Nakada and Lambeck (1989), who suggest a late Holocene eustatic melt water contribution of ca 2 m between 6000 and 2000 BP. The response to loading episodes is computed using a spherically symmetric, Maxwell visco-elastic Earth model that is self-gravitating and compressible (e.g., Wu and Peltier, 1982). Sea level predictions were computed in a gravitationally self-consistent manner by solving the most recent, generalised, form of the sea level equation (see Mitrovica and Milne, 2003; Kendall et al., 2005), which takes into account such effects as perturbations in the Earth's rotation (e.g., Milne, 2002).

4. Results

Information on the 21 samples dated using the AMS ^{14}C technique is provided in Table 1. Generally dates obtained have low counting errors and are stratigraphically consistent. However, some anomalous dates were returned, presumably because of the nature of the local sedimentary environment and the sedimentary matrix from which the samples were originally taken. Problems with the ^{14}C dating of deltaic sediments are common, in part because of the numerous opportunities for carbon to be stored and reworked prior to final deposition (Stanley and Chen, 2000; Stanley and Hait, 2000).

Diagrams summarising sediment-based data from each site (Figs. 2–4) were constructed using C2 version 1.4.2 (Juggins, 2003) and zoned according to variations in the remains of pollen, phytoliths and charcoal using CONISS (Grimm, 1987, 1992). Pollen counts are expressed as percentages of the total pollen sum, which generally comprised 300 grains in total; phytolith results are presented as percentages of the total phytolith sum, which comprised a minimum of 400 single-celled morphotypes; charcoal data are presented in concentration form ($cm^2\,cm^{-3}$). Pollen, phytoliths and macro-charcoal remains are likely to be largely local in origin, as the terrestrial or semi-terrestrial nature of the three sample sites does not favour the accumulation of material transported long distances (Andersen, 1986). Moreover, phytoliths tend to be relatively poorly dispersed in general (Piperno, 2006),

Table 1
AMS ^{14}C dates for sediment samples taken from trenches at Qingpu and Guangfulin, and the core at Luojiang

Study site	Depth (cm)	Laboratory code	Age (^{14}C yrs BP)	Calibrated date (95.4% prob.)	Dated material
Guangfulin	62–64	NZA 26016	945±30	AD 1025–1158	Wood
	70–72	NZA 26011	2057±30	170 BC–AD 16	Pollen residue
	88–90	NZA 26017	2453±30	753–411 BC	Charcoal
	124–126	NZA 26012	6209±30	5295–5056 BC	Pollen residue
	138–140	NZA 26013	6375±30	5468–5306 BC	Pollen residue
	154–156	NZA 26014	12218±45	12,256–12,000 BC	Pollen residue
	174–176	NZA 26264	5517±55	4461–4259 BC	Charcoal
	179–181	NZA 26015	12366±55	12,796–12,133 BC	Pollen residue
Luojiang	180–182	NZA 22890	1050±35	AD 895–1030	Pollen residue
	200–202	NZA 22891	4071±30	2854–2491 BC	Pollen residue
	210–212	NZA 22897	4350±40	3090–2894 BC	Plant macrofossil
	300–302	Beta-220585	10,650±30	10,857–10,710 BC	Pollen residue
	498–500	NZA 23298	10,984±55	11,096–10.901 BC	Pollen residue
Qingpu	62–64	NZA 21231	1827±35	AD 85–315	Pollen residue
	120–122	NZA 21213	2152±35	359–58 BC	Pollen residue
	182–184	NZA 20038	2386±35	732–392 BC	Pollen residue
	210–212	NZA 21230	3853±40	2462–2205 BC	Pollen residue
	238–240	NZA 22222	5780±30	4708–4549 BC	Pollen residue
	242–244	NZA 20037	5600±40	4491–4359 BC	Pollen residue
	250–252	NZA 22221	5114±35	3979–3800 BC	Pollen residue
	258–260	NZA 21212	4920±35	3770–3645 BC	Pollen residue

Calibrated dates are determined from the calibration curve IntCal04 (Reimer et al., 2004) using the program OxCal v4.0.1 (Bronk Ramsey, 1995, 2001).

while work on modern pollen assemblages from the lower Yangtze has shown the main sources to be vegetation growing on the delta plain, or in adjacent uplands (Wang et al., 1982).

4.1. Guangfulin

4.1.1. Sediment stratigraphy and AMS ^{14}C chronology

According to the AMS ^{14}C chronology, sediment samples from Guangfulin range in age from ca 12,400 to 400 BP. An age reversal occurs in the lower sediments: the sample at 174 cm is younger than three overlying dates and has been rejected as a result. The age-depth curve based on the remaining seven AMS ^{14}C dates correlates well with the chronology from the archaeological excavation at Guangfulin (Chen, 2002; Li et al., 2006a) and indicates two main accumulation phases, separated by either a period of slow sediment accumulation or, perhaps most likely given the sedimentary setting, a hiatus accounting for the lateglacial-Holocene transition and much of the early Holocene to ca 7400 BP.

4.1.2. Charcoal, phytoliths and pollen analyses

Sediment data for Guangfulin are summarised in Fig. 2 and were divided into four zones. GFL 1 (191–140 cm, ca 12,400–11,400 BP) is characterised by pollen from arboreal taxa, in particular *Pinus* and *Quercus*, and by phytoliths mainly assignable to C_3 Poaceae. A few C_4 Poaceae phytoliths were also recorded. Pollen from *Betula*, *Castanopsis*/*Castanea*-type, *Juglans*, *Salix* and *Tsuga* is also present. The vast majority of *Quercus* pollen on the basis of size appears to be from evergreen taxa. Chenopodiaceae, Cyperaceae, Poaceae and *Typha* are prominent among non-arboreal pollen types, while fern spores are also relatively abundant. Very low numbers of phytoliths from *Oryza* sp. were present in three samples from this zone (189, 169 and 164 cm). The upper boundary of the zone is marked by a rapid reduction in *Pinus* pollen and, to a lesser extent, Chenopodiaceae and *Quercus*, and an increase in Poaceae and *Typha* pollen. Micro- and macro-charcoal abundances are very low. The lower boundary of GFL 2 (140–110 cm, ca 7400–4700 BP) appears to coincide with a break in sedimentation. The zone is characterised by high percentages of pollen from herbs (*Artemisia*, Cyperaceae, Poaceae and *Typha*) and greatly reduced levels of *Pinus* when compared with Zone GFL 1. Reduced percentages of *Juglans*, *Quercus* (deciduous-comp.) and *Tsuga* pollen were noted. Arboreal pollen present includes *Carpinus*, *Castanopsis*/*Castanea*-type, *Quercus* (evergreen-comp.) and *Salix*. Phytoliths from *Oryza* sp. are present in low numbers, and a *Setaria*-type morphotype was recorded. Abundances of macro- and micro-charcoal are higher when compared with the earlier zone. Sediments comprising GFL 3 (110–80 cm, ca 4700–2400 BP) include a pottery-rich layer. Their microfossil content is distinguished primarily by increases in phytoliths from *Oryza*, particularly multi-celled forms, and in Poaceae (*Oryza* comp.) pollen. High abundances of charcoal (micro- and macro) remains when

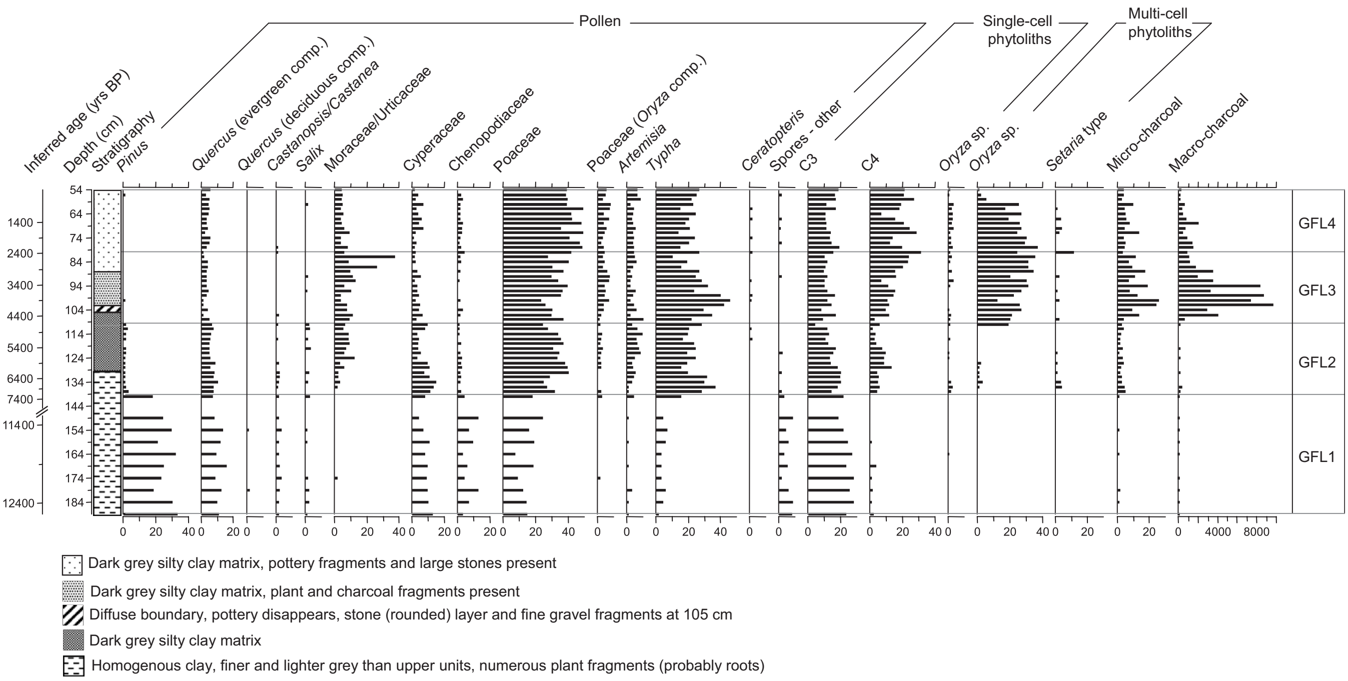

Fig. 2. Summary of sediment-based data from the Guangfulin site, comprising pollen (%), phytolith (%) and micro-charcoal ($cm^2\,cm^{-3}$) data.

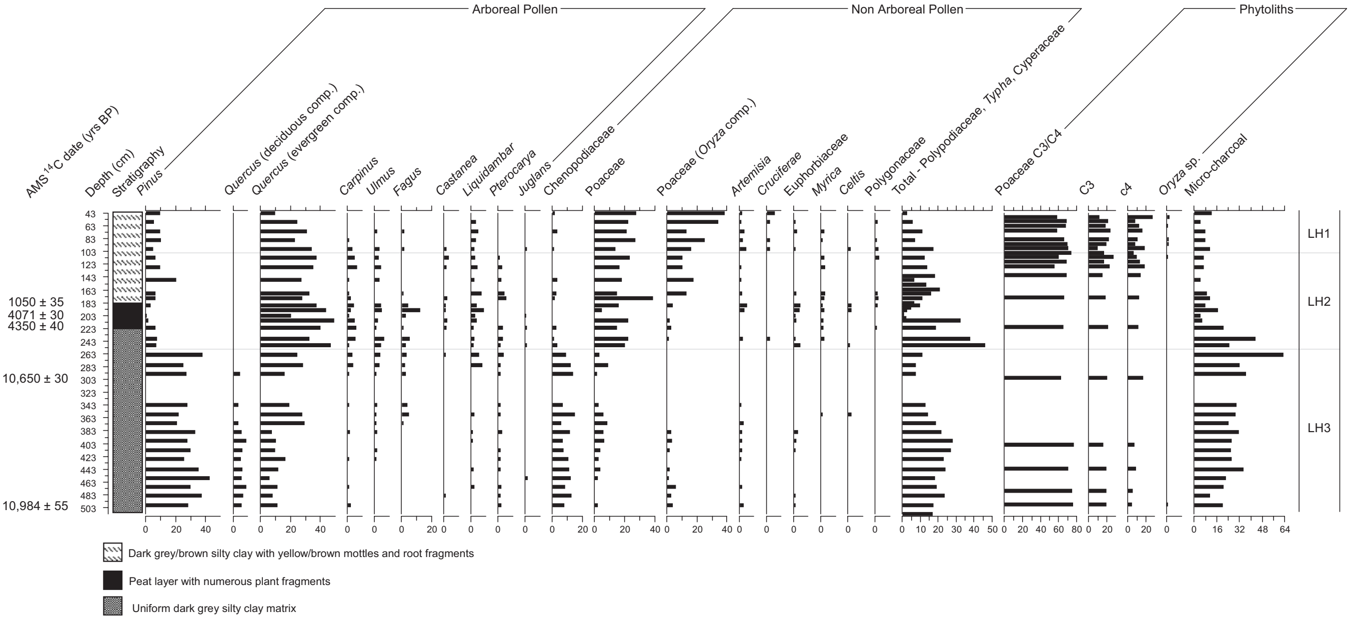

Fig. 3. Summary of sediment-based data for the Luojiang core, including pollen (%), phytolith (%) and micro-charcoal ($cm^2 cm^{-3}$) data. *Oryza* sp. (phytolith) counts are shown as 5 × exaggeration.

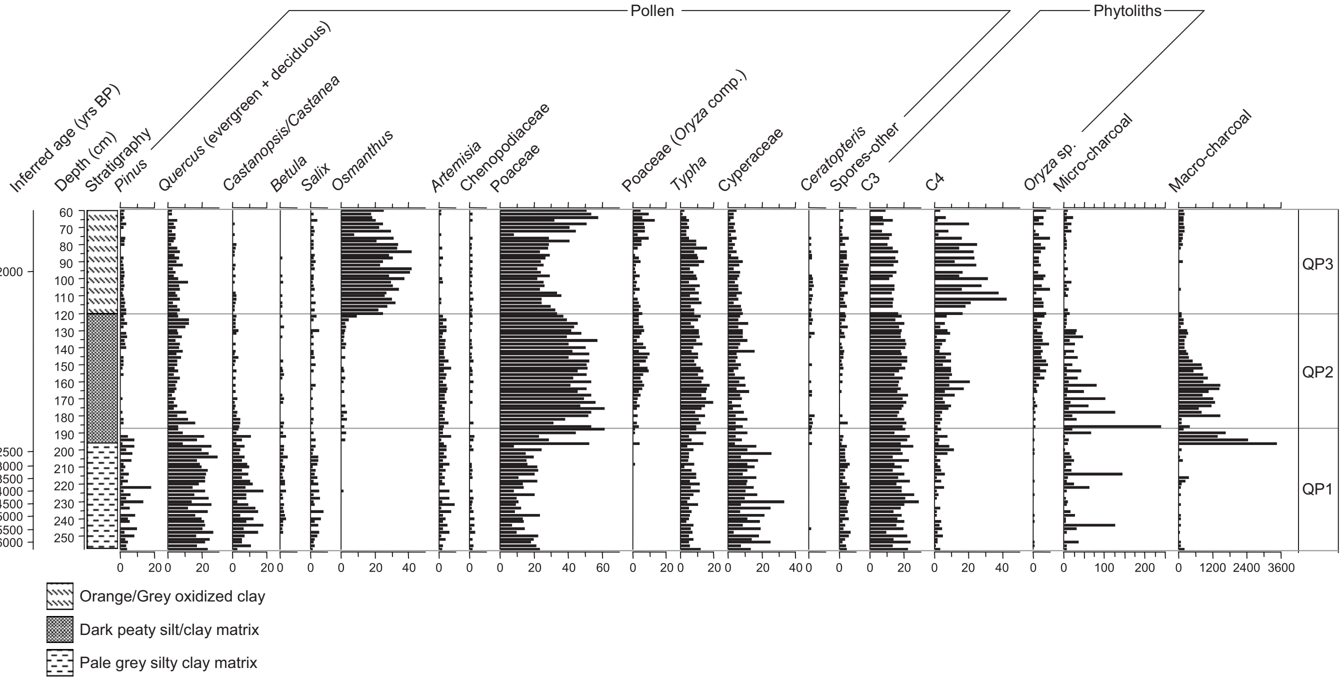

Fig. 4. Summary of sediment-based data for Qingpu trench, including pollen (%), phytolith (%), micro-charcoal ($cm^2\,cm^{-3}$) and macro-charcoal ($grains\,cm^{-3}$) data.

compared with GFL 2 also characterise GFL 3. Pollen from *Artemisia*, Poaceae and *Typha* remains common, and there are two distinct peaks in Moraceae/Urticaceae-type pollen. GFL 4 (80–54 cm, ca 2400–400 BP) is characterised by increased abundances of Poaceae pollen, although numbers of *Oryza* comp. grains remain largely unchanged when compared with GFL 3. Multi-celled *Oryza* sp. glume phytoliths remain common and several *Setaria*-type phytoliths were also recorded. Pollen from *Typha* is abundant, with *Artemisia* and Cyperaceae pollen also present but in lower abundances when compared with GFL 3, as are levels of micro- and macro-charcoal.

4.2. Luojiang

4.2.1. Sediment stratigraphy and AMS ^{14}C chronology

AMS ^{14}C dating of macrofossils and pollen residues extracted from core sediments from Luojiang has proven particularly problematic: several age reversals are apparent over the total length of the core. Furthermore, the early Holocene record appears to be missing, as is part of the late Holocene, unless the most recent date obtained (1050 ± 35 BP) is erroneous, which appears likely based on age-depth relationships for sediment sequences from other sites in the lower Yangtze.

4.2.2. Charcoal, phytoliths and pollen analyses

Microfossil data, summarised in Fig. 3, were classified into three zones. L1 (500–255 cm, from ca 11,000 to pre 4350 ± 40 BP) is characterised by high levels of *Pinus* and *Quercus* pollen and relatively low levels of other types of arboreal pollen. Pollen from wetland taxa is also relatively abundant, as is pollen associated with open habitats, including Poaceae and Chenopodiaceae. Poaceae phytoliths are common, particularly those from C_3 taxa, although *Oryza* sp. phytoliths are absent. Charcoal is relatively abundant throughout this zone. Abrupt changes in pollen and charcoal abundances distinguish the lower boundary of L2 (255–105 cm, from pre-4350 ± 40 BP to post-4071 ± 20 BP, and possibly post-1050 ± 35 BP). It seems highly likely that the boundary coincides with a break in sedimentation. *Pinus* pollen declines in abundance, while pollen from Poaceae and evergreen forms of *Quercus* increases. *Oryza* sp. phytoliths are present also. L3 (105–35 cm, post-4071 ± 20 BP, and possibly post-1050 ± 35 BP) is characterised by reduced pollen from arboreal sources, increases in Poaceae (particularly *Oryza* comp.) pollen and phytoliths from *Oryza* sp. and a continuation of low levels of charcoal.

4.3. Qingpu

4.3.1. Sediment stratigraphy and AMS ^{14}C chronology

The AMS ^{14}C chronology indicates that sediment samples obtained from this site range in age from ca 6000 to 1800 yr BP. According to the age-depth profile, a change in sediment accumulation rate is apparent at about 202 cm depth, although this change is more likely to be at 196 cm and to correspond to an abrupt break in stratigraphy.

4.3.2. Pollen, phytolith and charcoal analysis

Microfossil data, summarised in Fig. 4, were classified into three zones. QP1 (260–186 cm, ca 6000–2400 BP) is characterised by high abundances of pollen from arboreal sources and, particularly in the upper part of the zone, charcoal. *Castanopsis*/*Castanea*-type, *Pinus* and *Quercus* are common among arboreal taxa. Other forest taxa present include *Betula, Diospyros, Juglans* and *Salix*. Poaceae makes a large contribution to non-arboreal pollen, as do to a lesser extent *Artemisia*, Brassicaceae and Chenopodiaceae. A range of wetland pollen and spore types is present, of which Cyperaceae and *Typha* are the most abundant. Poaceae morphotypes are also abundant among the phytoliths encountered, and include both C_3 and C_4 forms. Low numbers of *Oryza* sp. phytoliths are also present. The lower boundary of QP2 (186–120 cm, ca 2400–2100 BP) is marked by a major decline in arboreal pollen and a large increase in Poaceae. Poaceae (*Oryza* comp.) is also relatively abundant, as is *Artemisia*. Of pollen from wetland taxa, Cyperaceae is present throughout this zone, but in reduced amounts, while *Ceratopteris* and *Typha* are more abundant when compared with QP1. Phytolith counts show an increase in C_4 types, although C_3 types remain most common. Morphotypes indicative of *Oryza* sp. are present, particularly in the upper section of this zone, from 160 to 120 cm. A large peak in microcharcoal concentrations marks the boundary between QP1 and QP2, and charcoal abundances are generally higher and more variable in the latter than the former. QP3 (120–60 cm, ca 2100–1800 BP) is marked by large amounts of *Osmanthus* pollen and consistently low levels of charcoal. Poaceae pollen, both $\leqslant 40\,\mu m$ and $>40\,\mu m$, is also abundant. Pollen from wetland taxa (Cyperaceae and *Typha*) and fern spores persist with proportions similar to QP2, while pollen from arboreal taxa is in relatively low abundance. Common phytoliths in this zone include both C_3 and C_4 Poaceae morphotypes, and several *Oryza* sp. morphotypes.

Of the 26 samples from Qingpu investigated to determine whether rice glume phytoliths recovered from sediment samples were from domesticated or wild forms, measurements indicate that the majority was from wild *Oryza* species, although glume phytoliths from domesticated forms were present from ca 2400 BP and abundant from ca 2100 BP (Itzstein-Davey et al., 2007b).

4.4. Estimated relative sea level, ca 10,000 BP-present

When compared with existing empirical data for the delta area as a whole (Zong, 2004), results from the geophysical RSL model employed in the current research simulate accurately both the rate and direction of RSL movement in the period to ca 8000 BP. Thereafter, the model output suggests that RSL exceeded present level by ca 7000 BP, although such a scenario is at odds with existing empirical data, which suggest a slowing of RSL rise from ca 8000 BP, with the present level not attained until ca 3000 BP, after which date there was little movement of RSL (Zong, 2004). The discrepancy may be related to inaccuracies in the model (the model is poorly constrained for the East China Sea and fails to account for local variations in sedimentary and tectonic conditions), or reflect sediment compaction, which will serve to lower the altitude of sea level reconstructed from empirical evidence. Xin and Xie (2006) recently published preliminary results of a model of Holocene geomorphic evolution of the Yangtze delta. According to these results, the period ca 7000–3000 BP was characterised by repeated transgressions and regressions, during which parts of the delta plain may have been inundated. Frequent inundation of low-lying parts of the delta plain during the mid Holocene is therefore not inconceivable, particularly given the wide tidal range of the lower Yangtze and that seasonal typhoons can result in local rises of sea level of the order of 2–3 m (Wang et al., 2005).

5. Discussion

5.1. Palaeoenvironmental synthesis

Data from the Guangfulin and Luojiang sites indicate that cool temperate forest and open terrestrial and wetland habitats were extensive in the lower Yangtze during the lateglacial, with forest presumably restricted to relatively well-drained sites. Such a pattern of vegetation is in keeping with existing published data from the Yangtze delta (e.g., Liu et al., 1992; Chen and Chen, 1996; Chen et al., 1997; Yi et al., 2003), and the diversity of lateglacial habitats is likely to have proven attractive to hunter-gatherers who had access to fire as a means of manipulating their environment. According to the charcoal data, vegetation fires were far more common during the lateglacial in the southern part of the study area than they were farther north, and this pattern may reflect greater levels of human activity on and around the southernmost part of the delta.

Sediments dated to the early Holocene were not sampled at the three study sites. Evidence from elsewhere in the lower Yangtze suggests that post-glacial warming led to a mid-Holocene climatic optimum, when temperatures were 2–4 °C warmer (Wang and Gong, 2000; Yi et al., 2003; Chen et al., 2005) and levels of precipitation were substantially higher than present — the latter due to an enhanced East Asia summer monsoon (Yu et al., 2005; Steinke et al., 2006), and to the replacement of cool temperate forests by more thermophilous taxa (e.g., Liu et al., 1992; Chen and Chen, 1996; Chen et al., 1997; Yi et al., 2003). This replacement is in accordance with data from Guangfulin and Qingpu, although human activity could have been a factor, given a concomitant increase in charcoal, along with hydrological change: at Guangfulin, pollen from forest taxa, notably conifers and several temperate evergreen and deciduous taxa, is far lower in abundance than during the lateglacial, while pollen from more open types of vegetation (e.g., Poaceae) and fresh-water wetland habitats (Cyperaceae and *Typha*) is much more common.

The lower Yangtze is thought to have been first settled by humans ca 7000 BP (Lu, 1999; Yu et al., 2000), possibly earlier, and the occurrence around that time of *Oryza* sp. phytoliths, *Oryza* comp. pollen and evidence of increased burning at the Guangfulin site may represent the onset of incipient agriculture during the early Neolithic. Occasional occurrences of *Setaria* sp. phytoliths in the sediments from Guangfulin may also represent early agriculture. *Setaria italica* (L.) P. Beauv., or foxtail millet, is thought to have been one of the first domesticated cereals in Asia, and has been recorded at Chengtoushan on the middle Yangtze in deposits dating from ca 5600 BP, where it appears to have been cultivated along with rice (Nasu et al., 2007). However, the wild progenitor of foxtail millet is widely distributed across Asia and could conceivably have been the source of *Setaria* sp. phytoliths recovered from the Guangfulin site.

Major increases at Guangfulin in both micro- and macro-charcoal from ca 4700 BP suggest an important shift in burning regime, and the occurrence of vegetation fires close-by. The date roughly coincides with the onset of occupation of the nearby archaeological site, and with the beginning of a pottery-rich layer in the sampled sediment profile. Moreover, an increased abundance of rice phytoliths and *Oryza* comp. pollen from around the same time would appear to indicate an increased importance of rice-based agriculture locally. Raised levels of Moraceae/Urticaceae-type pollen from ca 3000 BP may represent the cultivation of *Morus,* and the production of silk close to the study site (particularly as this pollen type is not common in sediments at the other two study sites). Sericulture in China is believed to date to the Neolithic (Gu and Hu, 2003), with the earliest evidence in the lower Yangtze dating to ca 4850–4650 BP (Kuhn, 1988; Yan, 1992).

Human impact during the mid Holocene is much less evident in the sediments from Qingpu, and pollen and phytoliths indicate the persistence of thermophilous forest, presumably on relatively well-drained sites, to ca 2400 BP. Trace amounts of *Oryza* sp. phytoliths, relatively few *Oryza* comp. pollen and fluctuating but generally low levels of charcoal suggest a much lower level of agricultural activity than at Guangfulin. A similar picture emerges from the relatively few data relating to the mid Holocene extracted from the Luojiang core, although a greater extent of forest than around Qingpu is evident. As with Qingpu, however, low abundances of charcoal, *Oryza* sp. phytoliths and *Oryza* comp. pollen suggest relatively low levels of rice-based agricultural activity locally.

None of the three sites studied in the current research have yielded evidence of climatic cooling and drying dated ca 4000 BP, which reportedly caused a re-colonisation of the lower Yangtze by cool temperate vegetation (Sun and Chen, 1991; Yi et al., 2003). Human activity is, however, apparent in the late Holocene records from all sites, with local variability again evident. Environments continued to be human-influenced post-ca 2400 BP at Guangfulin. Rice continued to feature, while a reduced abundance of Moraceae/Urticaceae-type pollen may reflect a decline in the importance of sericulture around Guangfulin. A change in fire regime, indicated by reduced levels of charcoal, may reflect changes in farming techniques, such as reduced burning of stubble (Cao et al., 2006), a more general decline in human activity, possibly brought about by increased inundation (concomitant changes in sediment composition — in the form of the occurrence of pebble-sized stones in a dark silty clay and increased abundances of *Typha* pollen and the remains of sponge spicules — are in keeping with frequent flooding), or the shortage of combustible material owing to the almost complete eradication of forests. Chronological control is much less secure for the late Holocene record from Luojiang: conditions post-4071 ± 20 BP at Luojiang were characterised by reduced tree cover — although not to the same extent as farther north on the delta — and by increases in Poaceae. Rice remains become more prevalent in the sediment record, while charcoal abundances indicate that the incidence of vegetation fires remained relatively low.

Deforestation around Qingpu is evident and levels of *Oryza* comp. pollen and *Oryza* phytoliths increase from ca 2400 BP. Both wild and domesticated forms of *Oryza* were present at this time, along with intermediate forms (Itzstein-Davey et al., 2007b). A change in agricultural practices is apparent ca 2100 BP, notably an increased importance of domesticated rice and the cultivation of *Osmanthus*, the latter indicated by an increased abundance of *Osmanthus* pollen. *Osmanthus* is a small evergreen tree, and is often cultivated for its aromatic properties (Mabberly, 1987).

5.2. Environmental changes as driver of and constraint on early food production in the lower Yangtze

Palaeoecological data from the three study sites discussed here indicate geographic differences in the onset of vegetation changes attributable to humans, and in the pace of subsequent developments in food production. Evidence of deforestation and of the presence of potential food sources in the lower Yangtze, including rice and possibly also foxtail millet, is apparent by ca 7000 BP and may represent incipient agriculture. More substantial human impacts, including possible evidence of increased importance of rice as a food source, are apparent from ca 4700 BP at Guangfulin, from sometime after 4071 ± 30 BP at Luojiang, and from ca 2400 BP, and particularly from ca 2100 BP, at Qingpu.

An apparently late onset of relatively substantial environmental impacts as a result of human activity is surprising, given the large number of archaeological sites in the lower Yangtze dating to the early Neolithic. This could be due to the highly localised nature of the sedimentary records considered here. A late onset is also indicated by existing palaeoecological data from other sites on the delta, however. The first human influence apparent in the sediment record from site CM97 on Chongming Island is in the form of the appearance of *Fagopyrum* (buckwheat) pollen, ca 4500 BP (Yi et al., 2003, 2006). At site Zk01 increases in pollen possibly from domesticated rice and also from plants associated with disturbed vegetation in sediments post-dating an AMS ^{14}C date of 3934 ± 106 BP are thought to represent anthropogenic activity (Shu et al., 2007). Furthermore, a marked increase in Poaceae ca 3000 BP at site ZX-1 was attributed to the commencement of rice agriculture (Chen et al., 2005). More recently still, increased abundances of pollen from Poaceae and other herbs ca 1300 BP have been attributed to human disturbance and agricultural expansion at sites HQ98 and CM 97 (Yi et al., 2003, 2006), while widespread vegetation disturbance and soil erosion in the Yangtze catchment from ca 2000 BP, leading to a sudden increase in Yangtze River sediment discharge, is thought to have been caused by humans (Hori et al., 2001). A late onset also accords with Fuller et al. (2007, in press), who argue that early occupants of the delta engaged in hunting and gathering until well into the middle Holocene, utilising both wild and cultivated forms of rice as part of a broad subsistence base that also included a wide range of nuts and fish.

A livelihood strategy in which hunting and gathering are prominent is likely to have been a more effective response to highly variable and unpredictable hydrological conditions than strategies placing a greater reliance on sedentary forms of food production. Frequent and severe flooding will have hindered both the establishment and persistence of settled communities and of productive agriculture from early in the Holocene. Rapidly rising RSL during the early-to-mid Holocene, possibly surpassing current height according to simulations of a geophysical model, together with a dense network of channels and tidal creeks (Yan and Huang, 1987; Li et al., 2002), higher monsoonal rainfall, the occasional typhoon and tidal surge and relatively low levels of sediment accretion because of a largely forested catchment would have led to the frequent inundation of low-lying parts of the delta plain (Hori et al., 2002). In addition to a temporal trend of improved technologies, increased agricultural production and pronounced social stratification (Chang, 1986; Shao, 2005; Cao et al., 2006), Neolithic settlements on the delta are characterised by alterations in their pattern of distribution (Stanley and Chen, 1996; Stanley et al., 1999; Yu et al., 2000), and presumably this dynamism in settlement pattern was in part because of rising water tables and an increased risk of flooding (Zhu et al., 2003; Zong, 2004). Increased frequency and severity of flooding could have disrupted settlement and food production at Guangfulin ca 2400 BP, and frequent flooding by brackish water from around the same time may explain a continued importance of wild rice around Qingpu (and quite possibly around the other sites too). The cultivation of domesticated rice — a glycophyte-is hampered by high soil salinity, while some wild varieties of rice seem able to thrive in brackish water (Zeng and Shannon, 2000; Latha et al., 2004).

Environmental conditions in the lower Yangtze during the early and middle Holocene could therefore have acted both as a trigger (a combination of wetlands and warm temperatures provided suitable habitat for wild rice) and constraint (high variability, in particular due to a high frequency of flooding) to food production and domestication. Not until the Iron Age (Eastern Zhou), with the widespread availability of draught animals and iron tools (Rostoker et al., 1983; Lu, 2005) and reduced incidence of flooding as a result of sediment accretion and stabilised or falling RSL (Wang et al., 2001), could farmers manipulate their environment to the extent that they were able to reap the full benefits of sedentary agriculture underpinned by domesticated crops, while at the same time extending and deepening the environmental impacts of their activities.

6. Conclusion

Sediment-based palaeoecological data from three locations in the lower Yangtze reveal spatial and temporal differences in the level of human activity, including food production. The environmental impacts of early human populations appear to have been relatively localised. Although agriculture in the lower Yangtze dates to at least 7000 BP, food production during the mid Holocene may not have been an extensive activity, is likely to have been combined with hunting and collection from the wild and to have included the cultivation of wild varieties of rice, and could have been constrained by frequent inundation. Evidence of the onset of profound human-induced environmental impacts, associated with extensive, sedentary agriculture, occurs much later in the Holocene and roughly coincides with the Eastern Zhou (Iron Age, ca 2800–2200 BP), a period associated in the lower Yangtze with technological advances in agriculture, and relatively stable hydro-geomorphological conditions.

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