Holocene coastal evolution preceded the expansion of paddy field rice farming

Ting Ma[a], Barry V. Rolett[b,1], Zhuo Zheng[a,1], and Yongqiang Zong[c]

[a]School of Earth Science and Engineering and School of Geography and Planning, Sun Yat-Sen University, 510275 Guangzhou, China; [b]Department of Anthropology, University of Hawai'i at Manoa, Honolulu, HI 96822; and [c]Department of Earth Sciences, University of Hong Kong, Hong Kong SAR, China

Edited by Dorian Q. Fuller, University College London, London, United Kingdom, and accepted by Editorial Board Member Anthony J. Bebbington August 13, 2020 (received for review November 2, 2019)

Rice agriculture is the foundation of Asian civilizations south of the Yangtze River. Although rice history is well documented for its lower Yangtze homeland area, the early southward expansion of paddy rice farming is poorly known. Our study investigates this process using a compilation of paleoenvironmental proxies from coastal sediment cores from southeast China to Thailand and Island Southeast Asia. We propose that a shortage of land suitable for paddy fields, caused by marine transgression, constrained rice agriculture during the mid-Holocene. Rapid expansion of coastal plains, particularly in deltaic basins, over the past three millennia has coincided with increases in land suitable for rice cultivation. Our study also helps explain the past population movements of rice farmers.

early agriculture | Holocene paleoenvironment | rice | land cover change | pollen

The early expansion of rice agriculture is significant because the migrations of rice farmers may have played a vital role in contributing to the genetic and linguistic diversity of southeastern Asia (1–4). Models based on archaeological evidence suggest that domesticated rice (*Oryza sativa* subsp. *japonica*) spread from a Yangtze River homeland area across China and mainland Asia, largely following the coast and major rivers (4, 5). Rice, with Neolithic cultural elements such as distinctive styles of pottery, was carried across the Taiwan Strait around 5 ka before it appeared in mainland Southeast Asia (SEA) during the next millennium (4).

Regional evidence for the ecology of early rice cultivation remains quite uneven. Where it is best defined, in the lower Yangtze River area, emerging archaeological data point to an early emphasis on wet rice agricultural systems. The oldest field systems were situated in natural freshwater wetland environments and consisted of simple pits with basic water control features and an area no larger than 10 m^2 (6). These date to around 6 ka. The next two thousand years witnessed the local development of larger field systems based on bunded, rectilinear paddy fields engineered for efficient irrigation and drainage, indicating a trend toward increasingly intensive cultivation methods and higher yields (7–9). Simple stone plows and harvesting knives came into use during this time, but metal implements and domesticated draft animals did not appear until much later (9). By contrast, south of the Yangtze rice homeland area, archaeological evidence for early paddy rice fields is lacking. Yet a growing number of studies point to the likelihood of low yield rain-fed, rather than irrigated, rice gardens during the Neolithic era (6, 10, 11).

Recent genetic research indicates complex patterns in the southward spread of early rice farming populations showing that migrating farmers did not simply replace groups of indigenous SEA hunter-gatherers. Rather, indigenous populations admixed with multiple waves of migrating farmers originating from the north (1–3). Similarly, ongoing archaeological research suggests that despite the introduction of rice by migrating farmers who settled among hunter-gatherer communities, agriculture remained a comparatively small component of subsistence strategies for 1,000 y or more (10, 12, 13). In this model, both environmental and social factors may have played a role.

Current knowledge of the history of the southward expansion of paddy field rice agriculture is clouded by the poor preservation of plant remains in tropical archaeological sites, the limited number of specialized archaeobotanical studies carried out, and the fact that these studies are site specific, so that the results are generally insufficient to provide a broad regional perspective. South of the Yangtze there are currently no more than 20 sites yielding direct archaeobotanical evidence of rice during the period from ~5 to 3 ka. There are directly dated carbonized rice remains from several sites but often the evidence can only establish the presence of rice, without offering insight into the cultivation strategies employed (14–16).

In comparison with the archaeobotanical evidence, pollen rain is a reliable proxy for regional land cover and the quantitative analysis of Poaceae pollen from sediment cores offers a significantly better method for reconstructing regional level histories of rice agriculture (17–19). For example, studies of modern pollen assemblages in delta sediments show the main sources to be vegetation growing on the delta and in adjacent uplands (20, 21). Thus, pollen records from the geological archives of deltaic basins and coastal plains capture broad regional signals, making them valuable for studying long-term environmental change, including human-induced land cover change.

Here we analyze fossil pollen data for Poaceae and other taxa from 23 sediment cores collected in coastal areas ranging from 10 to 26°N latitude across subtropical and tropical Asia (Fig. 1).

Significance

Our study reveals a remarkable relationship between Late Holocene coastal evolution and the rise of rice agriculture across coastal Asia. Around 2,000 to 3,000 y ago, the emergence of coastal plains under freshwater conditions created expansive areas suitable for rice. We estimate that over the past three millennia the extent of coastal land suitable for wetland rice cultivation grew from about 16,000 km^2 to 96,000 km^2. Intensive paddy field farming took hold rapidly as coastal landscapes changed. Thus, large-scale rice farming was not established in southern China and Southeast Asia until rather late in the Holocene. This model helps explain ancient DNA evidence suggesting a major Bronze Age demographic expansion of rice farmers of northern East Asian descent.

Author contributions: T.M., B.V.R., and Z.Z. designed research; T.M., B.V.R., and Z.Z. performed research; T.M., B.V.R., and Z.Z. analyzed data; T.M., B.V.R., Z.Z., and Y.Z. wrote the paper; and T.M. performed the majority of the lab work.

The authors declare no competing interest.

This article is a PNAS Direct Submission. D.Q.F. is a guest editor invited by the Editorial Board.

[1]To whom correspondence may be addressed. Email: rolett@hawaii.edu or eeszzhuo@mail.sysu.edu.cn.

This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.1919217117/-/DCSupplemental.

First published September 14, 2020.

We also present paleoenvironmental proxy data recording the long-term history of coastal landforms. Our study provides insights into the complex history of rice agriculture south of the Yangtze River. The data support a two-part hypothesis. First, it suggests that during the mid-Holocene, although paddy rice agriculture became established in the lower Yangtze area, its expansion along coastlines to the south was constrained by shortages of low-lying freshwater flatlands suitable for paddy fields. The second part of the model proposes that paddy field farming expanded southward rapidly at around 3 to 2 ka, as part of a process related to the beginning of fast-paced deltaic shoreline progradation and the formation of broad coastal plains. This hypothesis was initiated to explain data for the Fuzhou Basin (10, 22–24) and the Pearl River Delta (18, 25). The model has since been adapted to the Philippines and other parts of Island Southeast Asia (16, 26).

Results

Land Cover History. Our study focuses on five key proxy taxa for identifying anthropogenic forest disturbance and rice agriculture in subtropical and tropical Asia: Poaceae, Fagaceae, *Pinus* type-*massoniana*, *Dicranopteris*, and *Artemisia*. In our study area, high frequencies of Poaceae reflect the expansion of grasses, while suggesting the presence of cultivated rice, as well as weeds growing in paddy fields. Modern analog studies reveal that fossil pollen assemblages with abundant Poaceae, accompanied by high levels of heliophilous pioneer species, match the signatures of soil surface samples from traditional rice agricultural systems in southern China (18). A common method for separating *Oryza* spp. rice pollen from other Poaceae pollen involves the use of a size threshold (17–19). Fagaceae (including *Cyclobalanopsis* and *Castanopsis*-*Lithocarpus*) is an indicator of broadleaved evergreen forests. High levels of Fagaceae characterize undisturbed forests, while *Pinus* type-*massoniana* is an evergreen conifer heliophilous species that grows well on poor soils and is prominent in secondary forests. *Dicranopteris*, a pioneer species, is a heliophilous fern that thrives in areas disturbed by forest clearance and which have been repeatedly burned; it is closely linked with land clearing for agriculture (21). The herb *Artemisia* is also a pioneer species. Most common in the northern sector of our study area, it spreads quickly in fallow agricultural fields (27).

For the time period prior to 3 ka, the pollen spectra generally indicate heavily forested landscapes dominated by Fagaceae, with low levels of grasses (Figs. 2 and3 and *SI Appendix*, Fig. S1). This indicates limited anthropogenic disturbance throughout periods of hunter-gatherer settlement and the Neolithic era, when domesticated rice first appears as part of a mixed economy still reliant on wild resources and possible vegeculture (28). Remarkable increases in Poaceae (including rice-type Poaceae) occur between ~2.7 and 2 ka (Fig. 2 and *SI Appendix*, Fig. S3), coinciding with simultaneous declines in the frequency of broadleaved evergreen taxa (Fig. 3 and *SI Appendix*, Fig. S1). Accompanied by abrupt rises in the frequency of pioneer plants (Fig. 3*B* and *SI Appendix*, Fig. S2), these trends signal deforestation and the intensification of rice agriculture as part of the development of a strongly anthropogenic landscape. Overall timing of the succession from natural biomes to markedly anthropogenic land cover provides paleoenvironmental support for the hypothesis that a massive southward dispersal of rice farmers of northern East Asian descent occurred during the Bronze Age (1, 2). Although there is also evidence for contact between SEA and India beginning around 2 ka, it does not indicate influence in the form of large-scale human migration (26).

Fire played a significant role in the succession to anthropogenic land cover, as documented by sediment coring studies that have analyzed charcoal particles deposited together with pollen and fern spores. High concentrations of charcoal particles after 3 ka reveal sharp increases in regional-scale burning (*SI Appendix*, Fig. S2). The timing of these increases coincides with abruptly rising levels of Poaceae in coastal and deltaic sediments. We infer that rice cultivation expanded sharply in coastal areas around the same time; four pollen assemblages for which rice-type Poaceae pollen has been counted show that it accounts for up to 30% or more of the total Poaceae pollen present during the time period from 2.5 to 2 ka (*SI Appendix*, Fig. S3). On a broader timescale, prior to 2.5 ka, the relative frequency of all Poaceae pollen in comparison with other taxa is uniformly low (Fig. 2), suggesting that cultivated rice was a small part of the regional land cover.

In a departure from the general trend, data for the apex area of the Pearl River Delta (sites SH-1, Longpu, and GY1) shows remarkable declines in arboreal pollen and increases in Poaceae pollen at around 4.3 to 3.3 ka (Figs. 2 and 3*A*). This transition is earlier than the similar series of vegetation successions recorded in other areas and it is notable that all three sites are located along tributaries upstream from the Pearl River Delta (Fig. 4 *A*, A1). We suggest that in this area, and in others, intensive rice agriculture took root first in freshwater wetlands upstream from saline environments of the deltaic basin.

Holocene Evolution of Coastal Plains. We turn now to the evolution of coastal landforms that supported the southward expansion of paddy field rice agriculture. The modern coasts of southern China and SEA are characterized by rocky headlands and small estuarine and lagoonal plains, with large river deltas providing extensive low-lying flatlands suitable for irrigated rice cultivation. In the early Holocene, relative sea level rose rapidly and the sea inundated channels incised during the last glacial sea level lowstand (33, 34). Marine transgression constrained the amount of land suitable for paddy field agriculture. Relative sea level ceased to rise by ~7 ka along the China coast (33) and by 4.5 ka along the

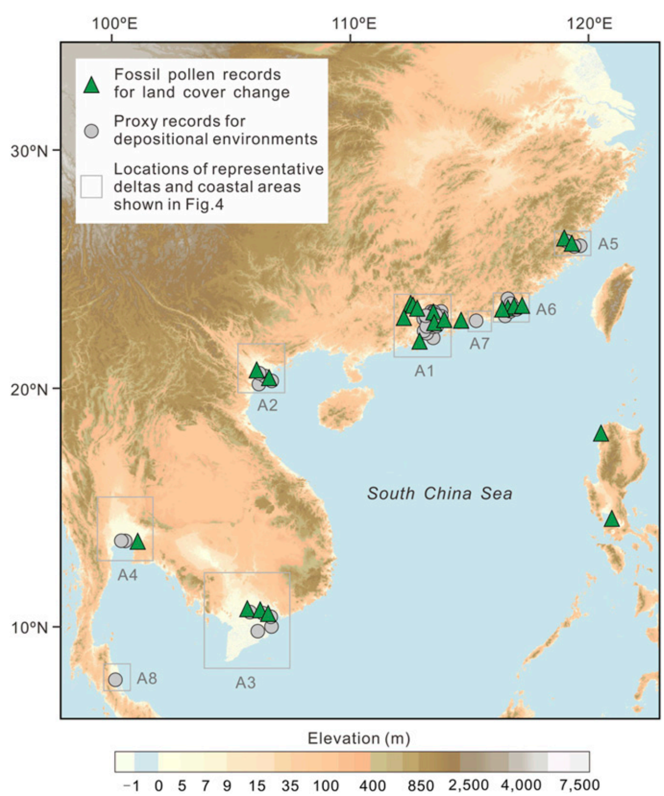

Fig. 1. Physiographic map of southern China, mainland SEA, and the Philippines showing the locations of sediment cores yielding paleoenvironmental proxy data analyzed for changes in land cover and coastal depositional environments. See *SI Appendix*, Tables S1 and S2 for sediment core information.

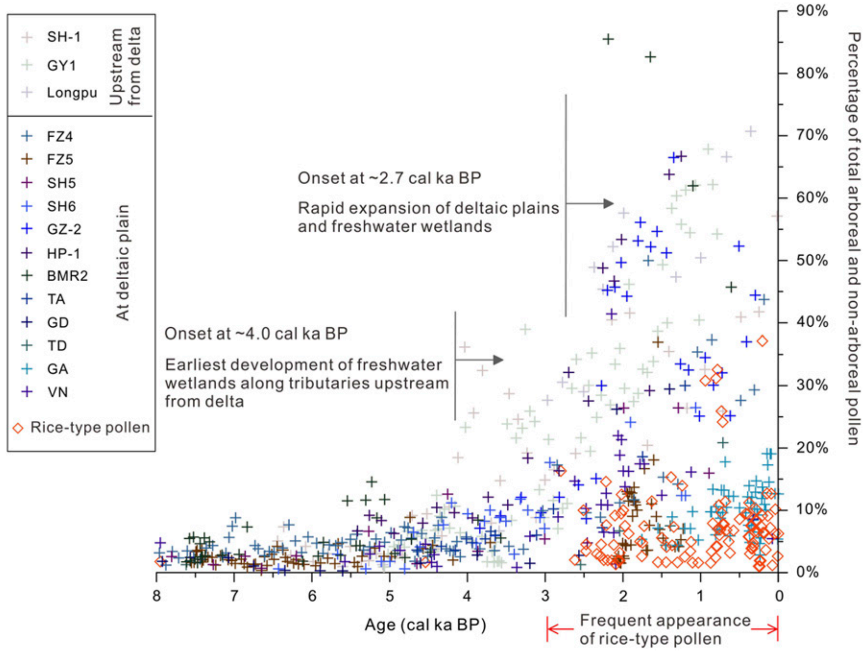

Fig. 2. Records of Poaceae pollen change. Crosses show the time series plots of total Poaceae for sediment cores from southern China and SEA. Diamonds show records of rice-type Poaceae pollen from sites FZ4 (South China), GZ-2 (South China), VN (Vietnam), GA (Vietnam), and Paoay Lake (Philippines). See *SI Appendix*, Fig. S3 for additional data on rice-type Poaceae pollen, focusing on the 2.5- to 2-ka time interval.

coast of Southeast Asia (35). Since the mid-Holocene, increasing sediment supply has resulted in gradually accelerating coastal progradation. However, by 4 ka, only limited flatlands with freshwater supply had emerged in the head area of the coastal basins, while the estuarine/deltaic basins of the Min (22), Han (36), Pearl (29, 34), Song Hong (Red) (30), Mekong (31, 37), and Chao Phraya (32) rivers were all under high salinity conditions (Fig. 4). We estimate that for the time period ∼5 to 3 ka the approximate extent of low-lying freshwater flatlands suitable for wetland rice cultivation was ∼16,000 km^2 (*SI Appendix*, Fig. S4).

Shorelines started to prograde rapidly after 3 ka, particularly in the past 2,500 y, due partly to human activity (29, 30, 32, 34, 37) (Fig. 4*D*). Notably, the progradation rate before 3 ka was significantly slower than during the past three millennia. Progressively,

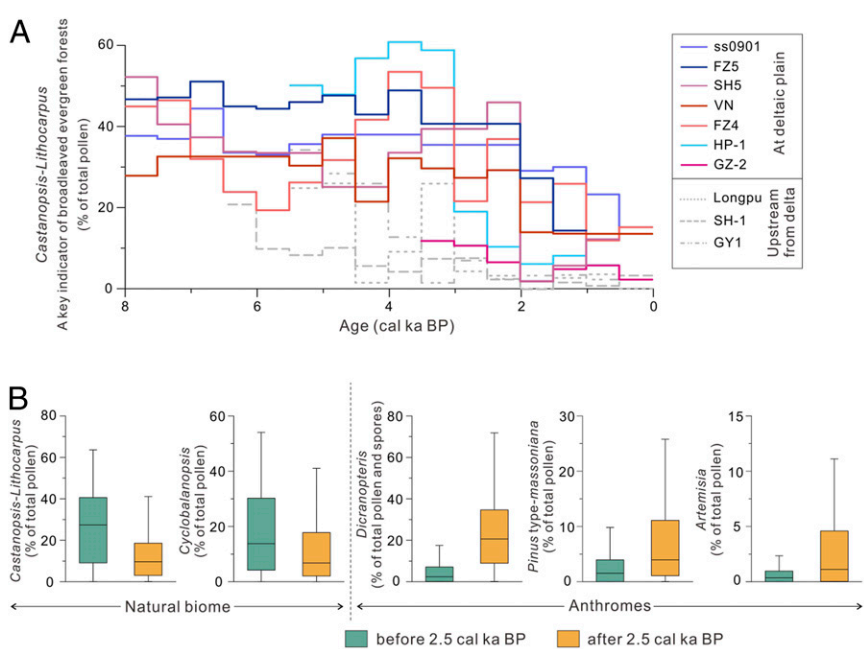

Fig. 3. Deforestation and vegetation ecosystem change revealed by pollen data. (*A*) Time series of pollen frequencies for *Castanopsis-Lithocarpus* (the dominant tree species of subtropical forests in the study area) as a percent of total arboreal and nonarboreal pollen. (*B*) Biome change based on a comparison of data for the time periods before and after 2.5 ka. Frequencies for each taxon are calculated based on the total arboreal and nonarboreal pollen, except for *Dicranopteris* which is calculated based on the total of pollen and spores. Boxes show the first and the third quartiles, center values show medians, and whiskers show the first quartile − IOR*1.5 and the third quartile + IOR*1.5.

brackish water marshlands shifted to freshwater conditions, which expanded in the head area of coastal basins (22, 30, 36). This is important because *O. sativa* does not tolerate salt water. Coastal progradation and the expansion of low-lying flatlands under freshwater conditions created ideal environments for the development of large rice paddy field systems. Concordant paleoenvironmental proxies show that a majority of the coastal plains began to form in general synchrony between 3 and 2 ka. Markers for the transition from marine- to alluvial-dominated phases include marine diatoms, foraminifera, and mangrove pollen as depicted in the sediment core records (Fig. 4*C*). The Haifeng and Songkhla-Pattalung sediment cores, from coastal plains without large river flow, also show similar timing in the transition from brackish water to freshwater conditions (Fig. 4 *A*, A7 and A8). We estimate that the approximate extent of land that is suitable now for paddy field rice agriculture, and which formed after the Holocene marine transgression, is ~96,000 km^2 (*SI Appendix*, Fig. S4). Most of this area—equal to more than 2.5 times the size of Taiwan—emerged after 3 ka.

Discussion

Unlike coastlines to the south, the lower Yangtze rice homeland area is unusual for its mid-Holocene deltaic setting that supported the world's first civilizations founded upon wetland rice (17, 19). Beyond the homeland area, however, how did rice farming contribute to Neolithic economies? Pollen records, such as those for the Pearl River Delta (one of world's largest rice-producing regions), clearly indicate that regional-scale human-induced vegetation change in general, and large-scale rice agriculture in particular, was negligible during the Neolithic. This finding has been challenged by data from a single marine core, which suggests a strong anthropogenic influence on vegetation beginning at 6 ka (38). However, results based on this core are problematic because of the low pollen concentrations, poor temporal resolution, and complicated terrigenous pollen source due partly to ocean currents.

Given paleogeographic evidence for the Neolithic era scarcity of land suitable for paddy fields south of the Yangtze, rain-fed gardens were probably the dominant form of agriculture where rice contributed significantly to the diet prior to 3 ka. Nevertheless, our pollen data suggest some exceptions, such as upstream tributaries of the Pearl and other major rivers, where localities with small natural wetlands likely supported earlier wetland rice farming. Similarly, inland riverine regions may have also provided freshwater wetlands for local-scale paddy rice farming during the Neolithic, but the largely mountainous terrain of inland southern China and SEA (Fig. 1) could not support rice field systems comparable in scale to those that developed in coastal areas. Outside the southeastern Asian mainland, islands such as Taiwan and the Philippines also lacked coastal plains suitable for extensive paddy rice cultivation during the mid-Holocene (16, 26). Neolithic rice remains, such as those found in sites along paleoshorelines in west Taiwan, indicate that some small wetlands on the edge of islands may have encouraged the practice of Neolithic wet rice farming (26). However, any such local wetlands were highly limited in surface area. Poaceae pollen records for the northern Philippines reveal that large-scale intensive rice farming did not begin until around 2.5 ka BP (39).

Taken together, the data support the hypothesis that, across southern China and southeastern Asia, rice agriculture remained a comparatively small component of subsistence strategies prior to the last two millennia. Thus, our study suggests that despite the introduction of rice by migrating Neolithic farmers, the southward expansion of paddy rice agriculture was highly constrained by physiographic factors. As landscapes changed, beginning 3 to 2 ka, intensive paddy field farming took hold rapidly following the formation of deltaic and coastal plains. This interpretation is consistent with genetic models suggesting that the present-day populations of SEA were influenced by two incoming waves of rice farming immigrants, including a major Bronze Age demographic expansion of farmers from East Asia into SEA. In this context, it is significant that historical records document major southward migrations of the Han Chinese beginning during the period of Warring States (480 to 221 BCE) and intensifying during the first millennium CE. Immigrating Han settlers spurred intensification of production by introducing new plowing methods involving socketed metal tools and domesticated water buffalo, as part of a process that revolutionized rice agriculture (40). Thus, coastal evolution resulting in the creation of expanses of land suitable for irrigated rice agriculture set the stage for the massive migration of Sinitic (Han) farmers into southern China and northern Vietnam, beginning around 2,500 y ago. Without this evolution of coastal landscapes, the large-scale establishment of Han communities may not have been possible.

Materials and Methods

Pollen Data. A total of 23 pollen records were reviewed from a collection of both raw and digitized pollen spectra. These records are for lowland sites in the coastal area of southern China and SEA. They include most of the published coastal lowland southern China and SEA pollen records with reliable age dating (Fig. 1 and *SI Appendix*, Table S1). Among them, there are four pollen records presented here, including the data for sites FZ5, NA9, Longpu, and SH-1.

Charcoal Data. In our study area, there are six published pollen records that include charcoal data (*SI Appendix*, Fig. S2). These records are for lowland sites in the coastal area of southern China, Vietnam, and the Philippines. The analyses did not distinguish microcharcoal from macrocharcoal.

Statistical Analyses for Pollen Data. Pollen taxa were measured as a percent of the pollen sum (including arboreal pollen and nonarboreal pollen). Percentages of ferns (*Dicranopteris*) were calculated based on the sum of all pollen and spores. For the *Castanopsis-Lithocarpus* time series in Fig. 3*A*, percentages of *Castanopsis-Lithocarpus* were calculated as 50% quantiles by time intervals of 500 y, in order to smoothout noisy data. To quantify the regional biome changes in Fig. 3*B*, we synthesized data from the 23 pollen records reviewed in this study, avoiding site-specific processes. For each pollen or fern taxa, palynomorph samples were divided into two groups, one dating to after 2.5 ka and a second dating to 8 to 2.5 ka. A comparison of the groups is presented by boxplots.

Evolution of Deltas and Coastal Plains (Fig. 4 *A* and *B*). Topography of deltas and bays was determined from Shuttle Radar Topography Mission (SRTM) data (41). The area of freshwater lowlands emerged after 5 ka was calculated by ArcGIS 10.2, based on the estimated paleoshorelines for around 6 to 5 ka. Holocene relative sea level changes along the coastlines of China and Southeast Asia have been driven mainly by global ice-volume changes, glacial isostatic adjustment, and local geological-tectonic processes (33, 35). The history of Holocene coastal progradation in the China/Southeast Asia region is related to a complex range of factors, including relative sea level change and sediment supply. The approach employed for estimating paleoshorelines involves drawing upon sediment core records. Sediment core records, including analyses of paleoenvironmental proxies, are used to identify change over time in local depositional environments indicative of the change from estuarine to deltaic facies (25, 29). For Fig. 4*A*, locations of the paleoshorelines are estimated on the basis of previous research for the Pearl River Delta (29), the Song Hong Delta (30), the Mekong River Delta (31), and the Chao Phraya Delta (32). The current population of the Pearl River Delta Plain is based on 2017 residence registration data for cities, including Guangzhou, Shenzhen, Foshan, Zhuhai, Zhongshan, and Dongguan (42).

Estimates for Change over Time in Sediment Depositional Environment (Fig. 4*C*). Data were collected from raw and digitized data sources for foraminifera, diatom, and mangrove pollen records with reliable age dating (*SI Appendix*, Table S2). Samples were grouped by time period, with each time period representing a 1,000-y age span (e.g., 2 to 3 ka). For each time period, we counted the number of samples revealing proxy evidence for marine and estuarine depositional environments. For foraminifera records, each sample containing foraminifera was counted as one occurrence. For diatom records, each sample for which marine and brackish water diatoms comprise >50% of the total number of diatoms, were counted as one occurrence. For mangrove records,

ENVIRONMENTAL SCIENCES

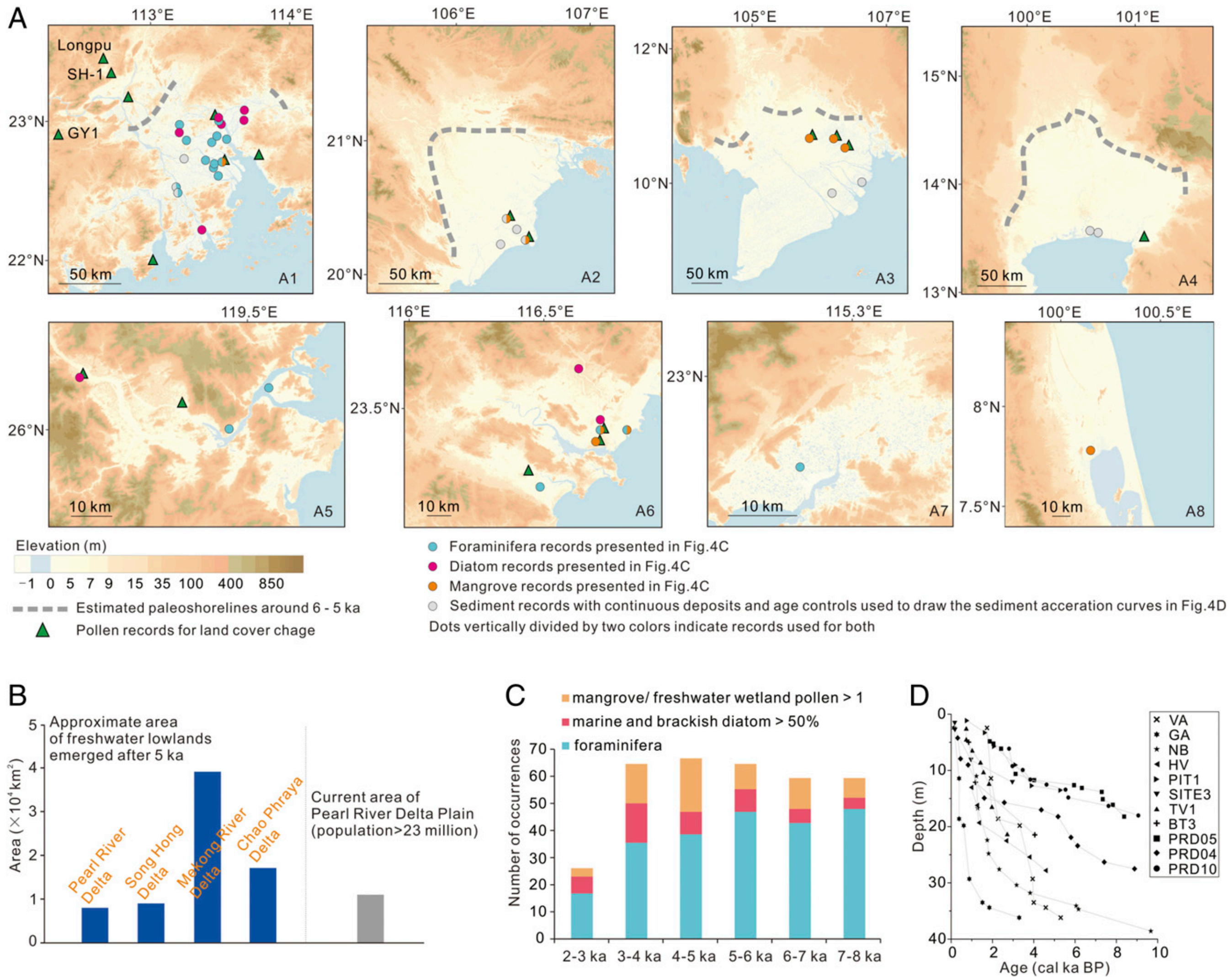

Fig. 4. The evolution of deltas and coastal plains. (*A*) Topography of representative deltas and coastal areas in China, Vietnam, and Thailand. (A1) Pearl River Delta (China); (A2) Song Hong Delta (Vietnam); (A3) Mekong River Delta (Vietnam); (A4) Chao Phraya Delta (Thailand); (A5) Fuzhou Basin (China); (A6) Han River Delta (*Upper*) and Lian River Delta (*Lower*) (China); (A7) Haifeng plain (China); and (A8) Songkhla-Pattalung plain (Thailand). Locations of the deltas and coastal areas are also shown in Fig. 1. Estimated paleoshorelines around 6 to 5 ka are shown for the Pearl River Delta (29), the Song Hong Delta (30), the Mekong River Delta (31), and the Chao Phraya Delta (32). See *SI Appendix*, Tables S1 and S2 for sediment core information. (*B*) Approximate area of freshwater lowlands emerged after 5 ka in large deltas. (*C*) Change over time in sediment depositional environment, as indicated by multiple proxies. (*D*) Sediment accretion curves (age–depth plots) for representative major deltas. See *Materials and Methods* for additional information.

each sample containing more mangrove pollen than freshwater wetland pollen (mangrove/freshwater wetland pollen >1) were counted as one occurrence.

Age-Depth Models. Chronologies for the proxy records were established by radiocarbon dating. ^{14}C ages were calibrated or recalibrated to calendar years before the present (BP = AD 1950) using IntCal13 or Marine13 (43) (*SI Appendix*, Table S3). For sediment cores with pollen, foraminifera, and diatom records, Bayesian age-depth models were produced using Bchron (44, 45). Exceptions are the Laguna de Baye pollen record and foraminifera records for cores PRD17 and PRD20, for which we used published chronologies (39, 46), as the uncalibrated age estimates are unavailable. The age-depth models were used to establish the land cover time series in Figs. 2 and 3 and *SI Appendix*, Figs. S1, S2, and S3, and the depositional environment time series in Fig. 4*C*.

Data and Materials Availability. All of the previously published data derive from the sources cited. Pollen data for sites FZ5, NA9, Longpu, and SH-1 in this study are available in *SI Appendix*.

All study data are included in the article and supporting information.

ACKNOWLEDGMENTS. We thank Charles Higham for valuable discussions relating to Southeast Asian archaeology. T.M. expresses gratitude to Prof. Yuxiang Dong for the guidance of her postdoctoral research at Sun Yat-Sen University. This work was supported by the National Key Research and Development Program of China (Grant 2016 YFA0600501), National Natural Science Foundation of China (Grants 41630753, 41701222, and 41230101), and the Andover Foundation for Archaeological Research (through grants from L. T. Clay).

1. M. Lipson *et al*., Ancient genomes document multiple waves of migration in Southeast Asian prehistory. *Science* **361**, 92–95 (2018).
2. H. McColl *et al*., The prehistoric peopling of Southeast Asia. *Science* **361**, 88–92 (2018).
3. M. A. Yang *et al*., Ancient DNA indicates human population shifts and admixture in northern and southern China. *Science* **369**, 282–288 (2020).
4. P. Bellwood, Holocene population history in the Pacific Region as a model for worldwide food producer dispersals. *Curr. Anthropol.* **52**, S363–S378 (2011).

5. F. Silva *et al*., Modelling the geographical origin of rice cultivation in Asia using the Rice Archaeological Database. *PLoS One* **10**, e0137024 (2015).
6. D. Q. Fuller, L. Qin, Water management and labour in the origins and dispersal of Asian rice. *World Archaeol.* **41**, 88–111 (2009).
7. Y. Zhuang, P. Ding, C. French, Water management and agricultural intensification of rice farming at the late-Neolithic site of Maoshan, Lower Yangtze River, China. *Holocene* **24**, 531–545 (2014).
8. A. Weisskopf *et al*., Phytoliths and rice: From wet to dry and back again in the Neolithic Lower Yangtze. *Antiquity* **89**, 1051–1063 (2015).
9. L. Qin, D. Q. Fuller, "Why rice farmers don't sail: Coastal subsistence traditions and maritime trends in early China" in *Prehistoric Maritime Cultures and Seafaring in East Asia*, C. Wu, B. V. Rolett, Eds. (Springer Nature, Singapore, 2019), pp. 159–191.
10. T. Ma *et al*., New evidence for Neolithic rice cultivation and Holocene environmental change in the Fuzhou Basin, southeast China. *Veg. Hist. Archaeobot.* **25**, 375–386 (2016).
11. D. Q. Fuller *et al*., The contribution of rice agriculture and livestock pastoralism to prehistoric methane levels: An archaeological assessment. *Holocene* **21**, 743–759 (2011).
12. H. Barton, The reversed fortunes of sago and rice, *Oryza sativa*, in the rainforests of Sarawak, Borneo. *Quat. Int.* **249**, 96–104 (2012).
13. M. Wu, W. Ge, Z. Chen, Diets of a late Neolithic maritime settlement: Carbon and nitrogen stable isotope analysis of human bones from the Tanshishan site. *Acta Anthropol. Sin.* **35**, 246–256 (2016).
14. X. Yang *et al*., New radiocarbon and archaeobotanical evidence reveal the timing and route of southward dispersal of rice farming in south China. *Sci. Bull.* **63**, 1495–1501 (2018).
15. Z. Deng, H. C. Huang, X. Fan, Y. Huang, H. Lu, The ancient dispersal of millets in southern China: New archaeological evidence. *Holocene* **28**, 34–43 (2017).
16. M. T. Carson, H. C. Hung, Learning from paleo-landscapes: Defining the land-use systems of the ancient Malayo-Polynesian homeland. *Curr. Anthropol.* **56**, 790–813 (2018).
17. P. Atahana *et al*., A. Brooks, Holocene-aged sedimentary records of environmental changes and early agriculture in the lower Yangtze, China. *Quat. Sci. Rev.* **27**, 556–570 (2008).
18. S. Yang *et al*., Modern pollen assemblages from cultivated rice fields and rice pollen morphology: Application to a study of ancient land use and agriculture in the Pearl River Delta, China. *Holocene* **22**, 1393–1404 (2012).
19. Y. Zong *et al*., Fire and flood management of coastal swamp enabled first rice paddy cultivation in east China. *Nature* **449**, 459–462 (2007).
20. K. Wang, Y. Zhang, Y. Sun, The spore-pollen and algae assemblages from the surface layer of sediments of the Yangtze River Delta. *Acta Geogr. Sin.* **37**, 261–273 (1982).
21. Z. Zheng, Study of human disturbance to the vegetation in recent thousands of years in the coastal areas of Southeast China. *Ecol. Sci.* **17**, 29–36 (1998).
22. B. V. Rolett, Z. Zheng, Y. Yue, Holocene sea-level change and the emergence of Neolithic seafaring in the Fuzhou Basin (Fujian, China). *Quat. Sci. Rev.* **30**, 788–797 (2011).
23. Y. Yue *et al*., Holocene vegetation, environment and anthropogenic influence in the Fuzhou Basin, southeast China. *J. Asian Earth Sci.* **99**, 85–94 (2015).
24. B. V. Rolett, "Late Holocene evolution of the Fuzhou Basin (Fujian, China) and the spread of rice farming" in *Climates, Landscapes and Civilizations*, L. Giusan, D. Q. Fuller, K. Nichol, R. K. Flad, P. D. Clift, Eds. (Geophysical Monograph Series, American Geophysical Union, Washington, DC, 2012), Vol. 198, pp. 137–143.
25. Y. Zong *et al*., Changes in sea level, water salinity and wetland habitat linked to the late agricultural development in the Pearl River Delta plain of China. *Quat. Sci. Rev.* **70**, 145–157 (2013).
26. P. Bellwood, *First Islanders: Prehistory and Human Migration in Island Southeast Asia*, (John Wiley & Sons, 2017).
27. Z. Zheng *et al*., Dust pollen distribution on a continental scale and its relation to present-day vegetation along north-south transects in east China. *Sci. China Earth Sci.* **50**, 236–246 (2007).
28. C. C. Castillo, D. Q. Fuller, P. J. Piper, P. Bellwood, M. Oxenham, Hunter-gatherer specialization in the late Neolithic of southern Vietnam: The case of Rach Nui. *Quat. Int.* **489**, 63–79 (2018).
29. Y. Zong, G. Huang, A. D. Switzer, F. Yu, W. W. S. Yim, An evolutionary model for the Holocene formation of the Pearl River Delta, China. *Holocene* **19**, 129–142 (2009).
30. S. Tanabe *et al*., Holocene evolution of the Song Hong (red river) Delta system, northern Vietnam. *Sediment. Geol.* **187**, 29–61 (2006).
31. V. L. Nguyen, T. K. O. Ta, M. Tateishi, Late Holocene depositional environments and coastal evolution of the Mekong River Delta, southern Vietnam. *J. Asian Earth Sci.* **18**, 427–439 (2000).
32. S. Tanabe *et al*., Stratigraphy and Holocene evolution of the mud-dominated Chao Phraya Delta, Thailand. *Quat. Sci. Rev.* **22**, 789–807 (2003).
33. H. Xiong, Y. Zong, P. Qian, G. Huang, S. Fu, Holocene sea-level history of the northern coast of South China Sea. *Quat. Sci. Rev.* **194**, 12–26 (2018).
34. Y. Zong *et al*., The role of sea-level rise, monsoonal discharge and the palaeo-landscape in the early Holocene evolution of the Pearl River Delta, southern China. *Quat. Sci. Rev.* **54**, 77–88 (2012).
35. C.-Y. Tam *et al*., A below-the-present late Holocene relative sea level and the glacial isostatic adjustment during the Holocene in the Malay Peninsula. *Quat. Sci. Rev.* **201**, 206–222 (2018).
36. Y. Zong, Postglacial stratigraphy and sea-level changes in the Han River Delta, China. *J. Coast. Res.* **8**, 1–28 (1992).
37. T. K. O. Ta *et al*., Holocene delta evolution and sediment discharge of the Mekong River southern Vietnam. *Quat. Sci. Rev.* **21**, 1807–1819 (2002).
38. Z. Cheng, C. Weng, S. Steinke, M. Mohtadi, Anthropogenic modification of vegetated landscapes in southern China from 6,000 years ago. *Nat. Geosci.* **11**, 939–943 (2018).
39. J. Stevenson, F. Siringan, J. A. N. Finn, D. Madulid, H. Heijnis, Paoay Lake, northern Luzon, the Philippines: A record of Holocene environmental change. *Glob. Change Biol.* **16**, 1672–1688 (2010).
40. C. Higham, *Early Mainland Southeast Asia: From First Humans to Angkor*, (River Books, Bangkok, 2014).
41. A. Jarvis, H. I. Reuter, A. Nelson, E. Guevara, Hole-filled seamless SRTM data V4. http://srtm.csi.cgiar.org. Accessed 20 June 2018.
42. Statistics Bureau of Guangdong Province, *2018 Guangdong Statistical Yearbook*, (China Statistics Press, Beijing, 2018).
43. P. J. Reimer *et al*., IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* **55**, 1869–1887 (2013).
44. J. Haslett, A. Parnell, A simple monotone process with application to radiocarbon-dated depth chronologies. *Appl. Stat.* **57**, 399–418 (2008).
45. A. C. Parnell, J. Haslett, J. R. M. Allen, C. E. Buck, B. Huntley, A flexible approach to assessing synchroneity of past events using Bayesian reconstructions of sedimentation history. *Quat. Sci. Rev.* **27**, 1872–1885 (2008).
46. J. Yin, C. Liu, J. Wu, Y. Huang, Foraminifera records and palaeoenvironmental change since the late pleistocene in the central Pearl River Delta. *J. Palaeogeogr.* **18**, 677–690 (2016).