HUMAN-ENVIRONMENTAL INTERACTIONS IN PREHISTORIC PERIODS

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HUMAN-ENVIRONMENTAL INTERACTIONS IN PREHISTORIC PERIODS

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Climate Conditions on the Tibetan Plateau During the Last Glacial Maximum and Implications for the Survival of Paleolithic Foragers

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Environmental conditions on the Tibetan Plateau (TP) during the last glacial maximum (LGM) are poorly known. Existing studies of environmental proxies and climate model simulations are contradictory, with interpretations varying between cold-dry and cold-wet environmental conditions which differentially influenced lake volumes, loess deposition and vegetation communities across the TP. Genetic and archaeological studies suggest anatomically modern paleolithic foragers initially occupied the TP between 60 and 30 ka, and may have seasonally occupied the TP during the LGM. Hence, a better understanding for LGM environmental conditions is needed in order to estimate whether paleolithic foragers could have survived on the TP during the extreme LGM cold stage. Here we report the investigation of lacustrine sediments and beach deposits within two paleoshorelines around Dagze Co on the southern TP, ~22 and ~42 m higher than the present lake level. Optical age estimates suggest the sediments were deposited during the LGM and mid-Holocene, respectively. TraCE-21 climate model simulation results suggest that net annual LGM precipitation in the Dagze Co basin was lower than the mid-Holocene, but about the same as that of the past 1,000 years. Combining the optical age estimates with TraCE-21 and CAM4 climate model simulation results, we deduce that increased summer precipitation and glacier meltwater supply, combined with decreased lake surface evaporation, produced LGM lake levels ~22 m higher than present. We also synthesized paleoenvironmental records reported across the TP spanning the LGM. This synthesis suggests that the LGM climate in the northern TP was cold and dry, but that some of the southern TP was cold and wet. These relatively wetter LGM conditions in the southern TP may have favored the growth of cold-resistant plants which, in turn, may have supported larger herbivore populations, and provided food for paleolithic foragers. We conclude that seasonal or short-term human occupation of the TP during the LGM was thus more likely in the southern TP than in the north.

Keywords: tibetan plateau, last glacial maximum, high lake levels, climatic conditions, paleolithic foragers

INTRODUCTION

A recent study of a human mandible fossil found in Xiahe County, in the northeastern TP, indicates that Denisovans occupied the TP before 160 ka (during the penultimate glacial period), much earlier than contemporary Tibetans who arrived in the region much later (Chen et al., 2019; Zhang et al., 2020). Both genetic research (Lu et al., 2016) and archaeological investigations (Zhang et al., 2018a; Zhang et al., 2018b) suggest that anatomically modern human foragers conquered high elevations and at least seasonally colonized the Tibetan Plateau (TP) between 60 and 30 ka. Genetic research indicates there was some genetic continuity between initial Paleolithic people on the TP and modern Tibetans, with the former contributing ~6% of the present Tibetan gene pool (Zhao et al., 2009; Lu et al., 2016). Research has further suggested that Paleolithic people successfully overcame the TP's harsh climate during the last glacial maximum period (LGM, between ~26 and ~19 ka (Clark et al., 2009)) and made a genetic contribution (albeit limited) to contemporary inhabitants (Zhao et al., 2009). This is supported by archaeological evidence from the southern TP, including human handprints and footprints on hot spring travertine at Quesang and a fireplace remnant dated to within the LGM (Zhang and Li, 2002). At the Nwya Devu site stone artifacts within alluvial sands and gravels were mainly deposited from 40–30 ka, but extending to the LGM (Zhang et al., 2018b). However, optical dating and U-series dating of the travertine at the Quesang site is controversial (Meyer et al., 2017; Zhang and Li, 2017). Zhang et al. (2017) suggest that low temperatures, hypoxia and low bioproductivity would have impeded year-round hunter-gatherer occupation of the high TP until the development of agriculture after ~5.2 ka, moreover, Dong et al. (2020) contend that hunter-gatherer groups in China may have adapted to climate change by mobility and subsistence strategy adjustments before 10,000 BP. At present, it appears that Paleolithic foragers first colonized the TP sometime before 30 ka. However, whether they stayed on the TP and adapted to the extremely cold LGM climate or needed to move down to surrounding low elevation regions during the LGM before reoccupying the TP again after the last deglacial (Madsen et al., 2006) is still unknown.

It is difficult to address these alternatives since environmental conditions on the TP during the LGM remain poorly known. Over the course of the past 30 years, extensive investigations of TP paleoenvironmental changes have been conducted by scientists within China and from abroad. However, most are focused on the last deglaciation and Holocene stages, with only a few records spanning the LGM (An et al., 2012; Liu et al., 2019; Chen et al., 2020 and references there in). Ice cores older than the Holocene are scarce on the TP, with only the Guliya ice cap records extending through the LGM (Thompson et al., 1997). Loess is widely distributed across the TP, but has only been continuously accumulated since the last deglacial (e.g., Lai et al., 2009; Qiang et al., 2013; Stauch, 2015; Qiang et al., 2016; Liu et al., 2017). There are more than one thousand lakes scattered across the TP, and lacustrine sediments are the most widely studied proxy records used to reconstruct paleoenvironmental changes. However, the majority of these studies only cover the last deglacial and Holocene periods (Chen et al., 2020 and the references there in). Existing paleoenviornmental records indicate that lakes on the TP shrank during the LGM, with some large lakes becoming almost completely desiccated (Madsen et al., 2008; An et al., 2012; Yan and Wünnemann, 2014; Jin et al., 2015; Liu et al., 2015; Zhu et al., 2015). Loess was eroded by strong westerly winds and the advancement of glaciers during the LGM (Liu et al., 2017; E et al., 2018). Ice wedge casts indicative of permafrost developed widely across the northern TP, and vegetational communities were substantially degraded (Pan and Chen, 1997; Liu and Lai, 2013). All these paleoenvironmental records suggest that the climate of the TP became very cold and dry during LGM. However, a global atmospheric general circulation model (GCM) and a regional climate model with detailed land surface process simulation results (RegCM2) suggest that TP climates were likely cold and wet during the LGM, mainly due to a decrease in evaporation and an increase of water vapor inflow through its south boundary (Yu et al., 2003). This would have resulted in an increase in runoff over the TP caused mainly by a decrease in evapotranspiration (Yu et al., 2003; Zheng et al., 2007). Recently, Li and Morrill (2013) compiled lake level information of monsoonal and arid Central Asia regions and compared them with Paleoclimate Modeling Intercomparison Project Phase 2 (PMIP2) simulated lake level variations during the LGM. They found that some parts of the southern and western TP had LGM lake levels higher than today, while the levels of eastern and northern TP lakes declined substantially. Kuhle (1998) reconstructed the glacial equilibrium line altitude (ELA) during the LGM, concluding the ELA was 1,200–1,500 m lower than today and proposed a 1,000–2,700 m thick ice sheet covered the whole Tibetan Plateau during the LGM. However, this interpretation has been widely disputed (Shi, 2004; Lai et al., 2009; Yan et al., 2018). In summary, controversies still exist about the climatic and environmental conditions on the TP during the LGM, in particular whether or not climatic conditions on the TP differed spatially. More research is needed to resolve these questions.

Closed-basin lakes in the TP are natural water reservoirs and are sensitive to hydrological changes. Understanding lake level fluctuations and the driving forces which cause them, can thus help clarify past hydrological changes in the TP. At a global scale, lake level variations between glacial and interglacial periods are primarily controlled by thermodynamics and dynamic changes deriving from large scale cooling or warming, land-sea and meridional temperature gradients, sea level, and ice sheet topography (McGee, 2020). Shoreline deposits and lacustrine sediments are often used to track past lake level variations in closed-basin lakes. Paleoshorelines can provide much clearer evidence of former lake size changes than can core records (Quade and Broecker, 2009) because lake surface areas and depths can be directly measured. These proxy variables adjust rapidly to prevailing hydrological changes and reflect shifts in the water budget for the lake basins as determined by the changing relationship between precipitation and evapotranspiration (McGee, 2020). A closed-basin lake receives water from river inflow, direct precipitation, and groundwater, and loses water primarily through evaporation since there are no river outlets. Lake highstands can occur when one of the following relationships are met:

(1) W_{in} increase, E_L increase, and $\Delta W_{in} > \Delta E_L$;
(2) W_{in} increase, E_L no change or E_L decrease;
(3) W_{in} no change or W_{in} decrease, E_L decrease, and $\Delta W_{in} < \Delta E_L$;

Where W_{in} is the sum of water input to the lake (including river runoff, precipitation, and groundwater); E_L is water evaporation from the lake surface; ΔW_{in} and ΔE_L are changes in W_{in} and E_L between beginning and ending time points. It is important to note that lake level fluctuations are not simply responses to precipitation changes, but are associated with basin-wide water budget changes.

Many lakes in the TP are ringed by conspicuous paleoshorelines, suggesting they were much larger in the past. These paleoshorelines were rarely studied before about 2 decades ago because they often lack organic materials for radiocarbon dating. As other dating methods, such as optically stimulated luminescence dating (OSL), U-series dating and cosmogenic nuclide exposure dating, have become increasingly reliable, the number of well-studied and well-dated lake shoreline sequences has increased dramatically. Here, we add to this body of data by reporting the investigation of Dagze Co in the south-central TP. We mapped and sampled paleoshorelines at the southern margin of the Dagze Co, and dated two paleoshorelines using OSL dating in order to determine when the highest paleoshorelines were formed and what the nature of lake surface fluctuations was during the last glacial and especially during the LGM.

The TP covers a wide range of latitudes from 25°N to 40°N. A number of studies of atmospheric water hydrogen and oxygen isotopes (Tian et al., 2001; Yao et al., 2013) suggest the TP can be divided into a westerly influenced northern part and an Indian summer monsoon (ISM) controlled southern part, with the two divided approximately at 33°N latitude. Here we divide the TP into these two sub-regions at 33°N latitude in order to compare shoreline histories of lakes in the two regions and investigate if they were influenced by different atmospheric circulations patterns and had different climate features during the late Quaternary.

SAMPLE COLLECTION AND METHODS

Dagze Co Location and Environmental Parameters

Dagze Co (31.82°–31.98°N, 87.36°–87.65°E, with a modern lake surface elevation of 4,480 m above sea level [asl], **Figure 1**) is now a brackish lake with a salinity of 19.1 g/L. The main anions are CO_3^{2-}, SO_4^{2-} and Cl^-, and the main cations are Na^+ and K^+ (**Supplementary Table S1**). The modern lake area and maximum lake depth are ~299 km^2 and ~38 m (Hou et al., 2017), respectively. The basin catchment area is 12845 km^2 (Hou et al., 2017). Present inflow is mainly from the Bogcarg Zangbo River. The mean annual precipitation is ~316 mm, and the mean annual temperature is ~0.55°C in this region (Hou et al., 2017). About 15 paleoshorelines are well-preserved on the eastern and southern lake margin and can be identified on Google-Earth images and in the field (**Figure 2A**). These shorelines indicate dramatic past water budget changes. We investigated these paleoshorelines during the summers of 2017 and 2018, and collected OSL dating samples from sand and silt-rich portions of cleaned profiles. Here we focus on the highest paleoshoreline (S15) and on another medium height paleoshoreline [S10] (**Figures 1**, **2A**). The surveyed elevation of the highest paleoshoreline is 4,521.6 m asl, consistent with a previous report that the highest paleoshoreline is 4,522 m asl (Qiao et al., 2010).

Sample Collection

Profile 17–10 (87.5628°E, 31.8119°N) is located on paleoshoreline S10, about 22.4 m above the modern lake level (ALL) (**Figure 2**). This shoreline is spectacular and can be easily identified in the field. However, it lacks beach gravels in the upper part of the profile (**Figures 2C**, **3**), and we speculate surface morphological features of this shoreline may have been formed by wave action during the Holocene lake recessive phase. A thin layer of gravel pavement covers the surface of the shoreline, overlying interbedded fine sand, silt, and coarse sand layers that extend downward to 1.1 m depth (**Figure 3**). These fine sand, silt, and coarse sand layers all have ripple laminations or sub-horizontal bedding suggesting they are near shore lacustrine sediments deposited when lake levels were several meters above this section according to the empirical relationships between water depths and sediments obtained from Qinghai Lake (Liu et al., 2018). Fine sand layers alternate with varied thickness of red silt layers with no obvious bedding below 1.1 m (**Figure 3**; **Supplementary Figure S1,2**). Although the red silt layers may be of alluvial or fluvial origins, they were well sorted and look different from alluvial deposits that are composed of poorly sorted mixtures of gravels, sands and silts (**Supplementary Figure S3**). This suggests they were reworked by lake water sometimes after they were deposited, and that their OSL ages are related to the reworking processes. Two beach gravel layers are located at the lower part of the section. The upper beach gravel layer is 20 cm thick (2.0–2.2 m) and the lower beach gravel layer is only ~5 cm thick (2.70–2.75 m) (**Figure 3**). The beach gravels are 3–5 cm in diameter, well sorted, moderately rounded, and no bedding can be observed (**Figure 3**; **Supplementary Material S2**). These gravel layers did not contain enough sand-sized sediments for OSL age estimates and could not be dated. OSL dating samples 17-10-1, 17-10-2, 17-10-3, 17-10-4, 17-10-5 and 17-10-6 were collected from sand lenses or sand rich layers at depths of 2.55, 1.95, 1.6, 1.3. 0.9, and 0.6 m (**Figures 2C**, **3**), respectively. Another exposed section containing lacustrine sediments was found at approximately the same elevation of section 17–10 but ~10 km to the east (**Supplementary Figure S3**). It is ~1.7 m high and its sedimentary structures correlate well with the upper part of section 17–10. The upper 0.45 m consist of alluvial deposits composed of gravels, sands and silts. These are underlain by light greyish nearshore lacustrine fine sands extending downward to an unknown depth (**Supplementary Figure S3**). We therefore

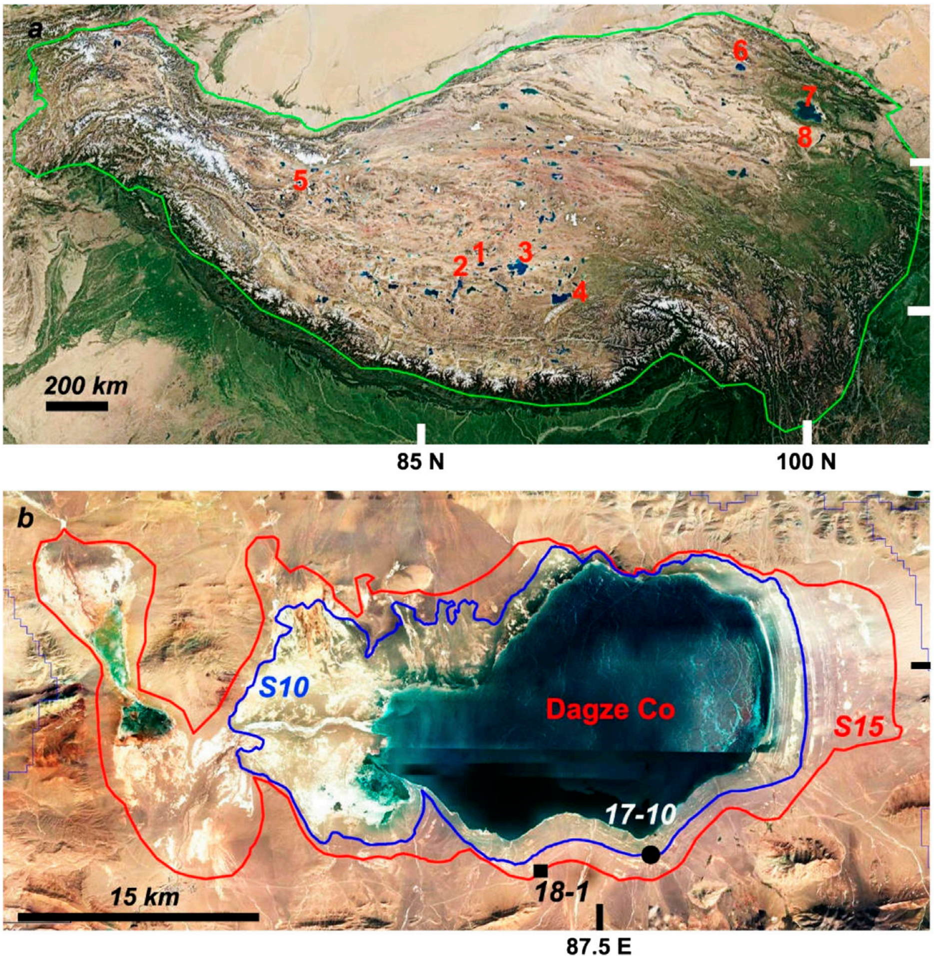

FIGURE 1 | (A) Location of Dagze Co and other lakes mentioned in the text; Dagze Co-1, Dangqiong Co-2, Seling Co-3, Nam Co-4, Longmu Co-5, Hala Lake-6, Qinghai Lake-7, Dalianhai Lake-8. The green-line is the outline of the TP. **(B)** Enlargement showing Dagze Co. The blue and red lines are the outlines of the LGM and mid-Holocene lake margins, respectively. The black dot and square are the 17–10 and 18–1 sampling sites. S10 and S15 (the highest in the basin) are high stand paleoshorelines that are 22.4 and 41.6 m higher than present lake level, respectively. Satellite images are from Google-Earth.

think that these nearshore lacustrine sediments are related to the expansion of Dagze Co. and are not lagoon or alluvial deposits. The sedimentary features and sediment compositions of section 17-10 are quite similar to those in a spectacular paleoshoreline located at the southern margin of Longmu Co. That paleoshoreline is ~4 m high and composed of lacustrine sands lacking beach gravels, and is thought to have formed during the Holocene lake regression period (**Supplementary Figure S4**; Liu et al., 2016).

Profile 18–1 (87.4915° E, 31.8033° N) is on paleoshoreline S15, ~41.6 m ALL. This shoreline is the highest visible paleoshoreline surrounding the lake and extends from the southern to eastern lake margin. The top 0.2 m of the profile consists mainly of aeolian deposits with scattered coarse sand and small gravel with no visible bedding (**Figure 4**). Beach gravels with oblique bedding and diameters ranging from 2 to 5 cm are deposited between 0.2 and 1.0 m depth. A layer of medium to coarse sand with sub-horizontal bedding is 1.0–1.1 m below the surface (**Figure 4**). This sand layer is underlain by alluvial deposits composed of poorly sorted angular gravels, sands and silts extending to an unknown depth. OSL dating sample (18-1A) was taken from the beach gravels in an area where there is a large sand component, and another sample (18-1B) was collected from the middle of the sand layer ~1.05 m below the surface (**Figure 4**).

OSL Dating

Samples were transported to the Luminescence Dating Laboratory of the Qinghai Salt Lake Institute, Chinese Academy of Sciences, and were pretreated under red safe light. Carbonates and organic materials were removed from the raw samples using 10% HCl and 30% H_2O_2, respectively. Medium and coarse sands were then separated through dry sieving and subjected to heavy liquid separation to obtain purer quartz. More detailed pre-processing information can be found in Liu et al. (2015).

The equivalent dose (D_e) of purified quartz was determined using the single-aliquot regenerative-dose (SAR, Murray and Wintle, 2000). OSL measurements were carried out using an

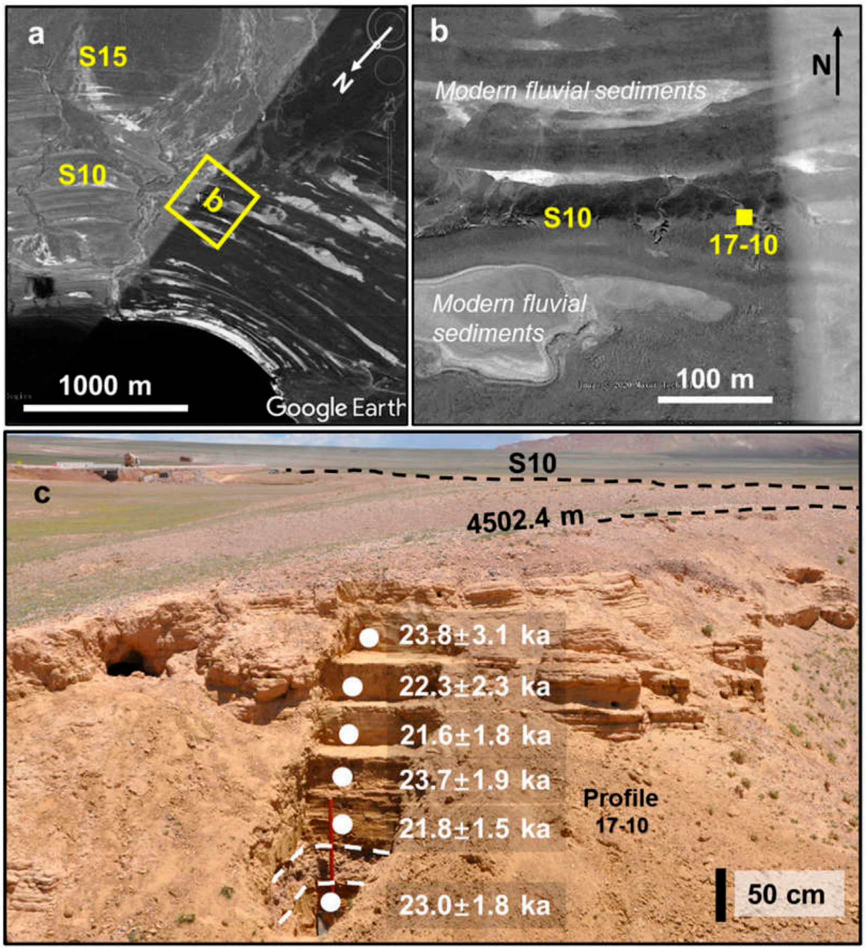

FIGURE 2 | (A) View of Dagze Co and the paleoshorelines located on the southern lake margin. **(B)** enlargement of the hollow square region outlined in yellow in **(A)**, the yellow solid square represents the location of profile 17–10. **(C)** Profile 17–10 and associated OSL ages. The view is toward the east.

automated Risø TL/OSL DA-20 reader. The preheat and cutheat temperatures were determined by preheat plateau and dose recovery test experiments, set at 200°C and 160°C (**Supplementary Figure S5**), respectively. The D_e was then measured by luminescence response. Natural luminescence (L_n) was measured first, then numerous regenerative dose luminescences (L_x) were measured sequentially, and corrected for sensitivity changes by the luminescence response (T_x) to a constant test dose (T_D) (Shi et al., 2017). The L_x/T_x ratios were used to construct the regeneration dose growth curve, and the L_n/T_x ratio (natural luminescence to test dose response luminescence ratio) was projected onto the growth curve to calculate the D_e (**Figure S6**, Murray and Wintle, 2000). Signals of the initial 0.64 s of stimulation were integrated for growth curve construction after subtraction of the last 10 s signals. Several samples show broad D_e distributions and have large over-dispersion values (**Figure S7**), suggesting they may have been heterogeneously bleached before deposition. In order to diminish the influence of partial bleaching on age estimation, the single-aliquot age selection model for D_e determination proposed by Arnold et al. (2007) was used to decide whether the 3-parameter minimum-age model (MAM-3) or the central-age model (CAM) was applied to calculate the D_es. R-language based luminescence data analysis package “numOSL” was used to select the suitable age model to calculate the D_es (Peng et al., 2013). Three out of 8 samples' D_e were determined by using MAM-3, and the remaining 5 D_es were determined by using CAM (**Table 1**).

Concentrations of U, Th and K were measured by the neutron activation analysis of dried and ground bulk samples (**Supplementary Table S2**). The radionuclide contents were converted to α and β dose rates according to the conversion factors proposed by Guérin et al. (2011). The cosmic ray dose rate was determined as a function of sampling depth, altitude and geomagnetic latitude (Prescott and Hutton, 1994). The average water content for paleoshoreline sediments during the burial period may have varied which is hard to estimate. Some sampling positions were dry and some others were wet when we dug out fresh profiles. We therefore calculated ages using water contents of 10 ± 5, 15 ± 5 and 20 ± 5% for each sample, and then selected ages of 10 ± 5% water content for samples collected from relative

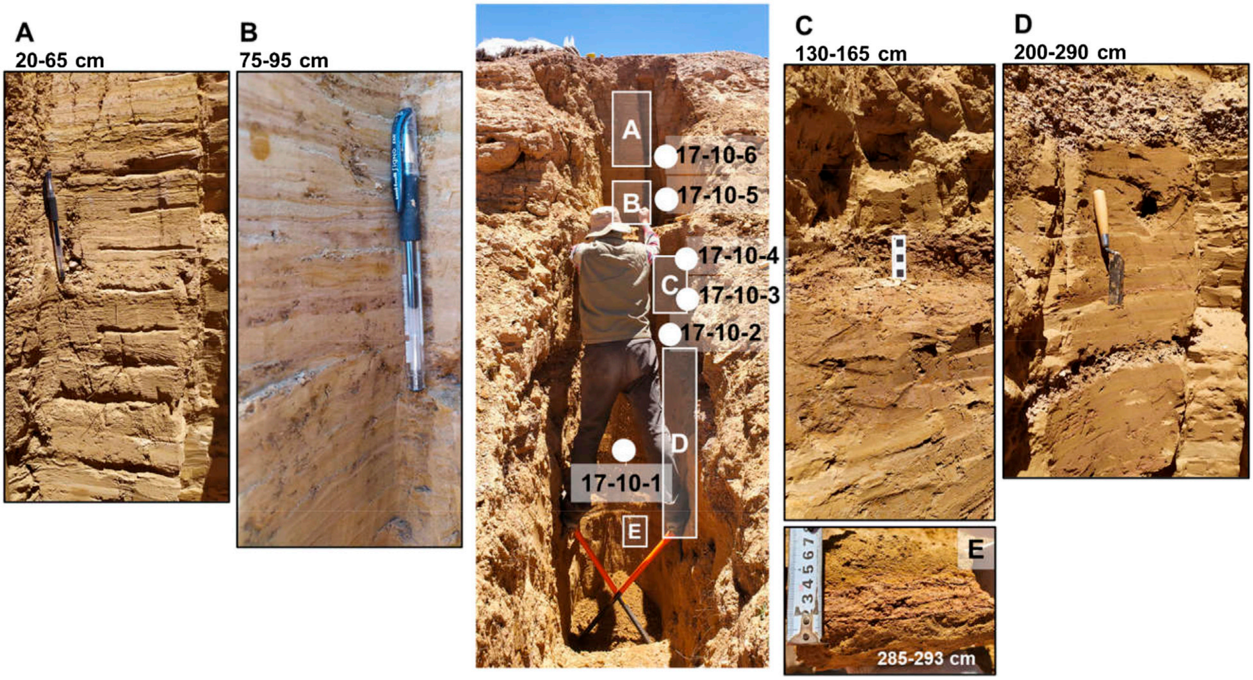

FIGURE 3 | Sedimentary structure details and composition of the 17–10 locality. The entire section is shown in the middle of the figure, with enlarged portions shown on the left and right sides.

dry strata and ages of 15 ± 5% water content for samples collected from wet strata as their best approximate ages (**Table 1**).

LGM Climate Simulations

Glaciers over the western and southern TP expanded substantially during the LGM, with the total glacial coverage possibly reaching 70×10^4 km^2 according to a 1 km-resolution ice sheet model which assumes cooling of 6°C and a precipitation decrease of 50% over the TP (Yan et al., 2018). Recently, Liu et al. (2020) simulated the impact that glacier expansions over the western and southern TP had on Eurasian climate changes during the LGM using Community Atmosphere Model version 4 (CAM4). They discuss the influence of enlarged glaciers in the Himalayas and Pamir regions on local and regional temperature and precipitation changes during the LGM in contrast to areas where glaciers did not expand. Here, we use part of the simulation results of Liu et al. (2020) to investigate seasonal temperature and precipitation changes when glaciers expanded over the TP during the LGM.

The transient climate evolution of the last 22 ka (referred to as TraCE-21) with the Community Climate System Model 3 (CCSM3) simulation results were used to calculate the annual and seasonal precipitation amounts, net annual precipitation amounts, annual and seasonal temperature changes for three time periods (22–20, 8–6, 1–0 ka) over Qinghai Lake on the northeastern TP, Dagze Co on the southern TP and Longmu Co on the western TP. The TraCE-21 simulation is forced by realistic external forcing, including orbital insolation, greenhouse gases, ice sheets and freshwater fluxes (Liu et al., 2009). The model consists of four components (atmospheric-model, oceanic-model, land-model and sea ice-model) coupled together (Yan et al., 2020). The spatial resolution of the TraCE-21 simulation is 3.75°× 3.75° (Liu et al., 2009).

RESULTS

OSL dating results show that higher Dagze Co lake levels occurred at during the LGM and mid-Holocene (**Table 1**; **Supplementary Figure S8**). Nearshore lacustrine sediments at S10 (22.4 m ALL) were deposited between 23.8 and 21.6 ka (**Figure 2C**; **Supplementary Figure S8**). The sedimentary structure features (coarse sands with ripple laminations in the upper part of profile 17–10 and two beach gravel layers in the lower part) suggest they were deposited when lake levels were fluctuating a few meters above or near paleoshoreline S10 during the LGM (**Figure 3**). The typical shoreline morphological features near the surface of S10 suggest they formed during the Holocene by waves which transformed older lacustrine sediments during a rapid regression of the lake. The speed of this regression resulted in only a few beach gravels being deposited at the surface at some locations or none at all at others. The lake area during the LGM highstand period was ~530 km^2 (~1.8 times the modern lake size). The high LGM lake level of Dagze Co, at an elevation of ~4,500 m asl in the southern TP, confirms that an ice sheet covering the entire TP did not exist during the LGM.

The highest paleoshoreline (S15) is 41.6 m ALL. Two optical ages for samples collected from beach sediments and a sand layer

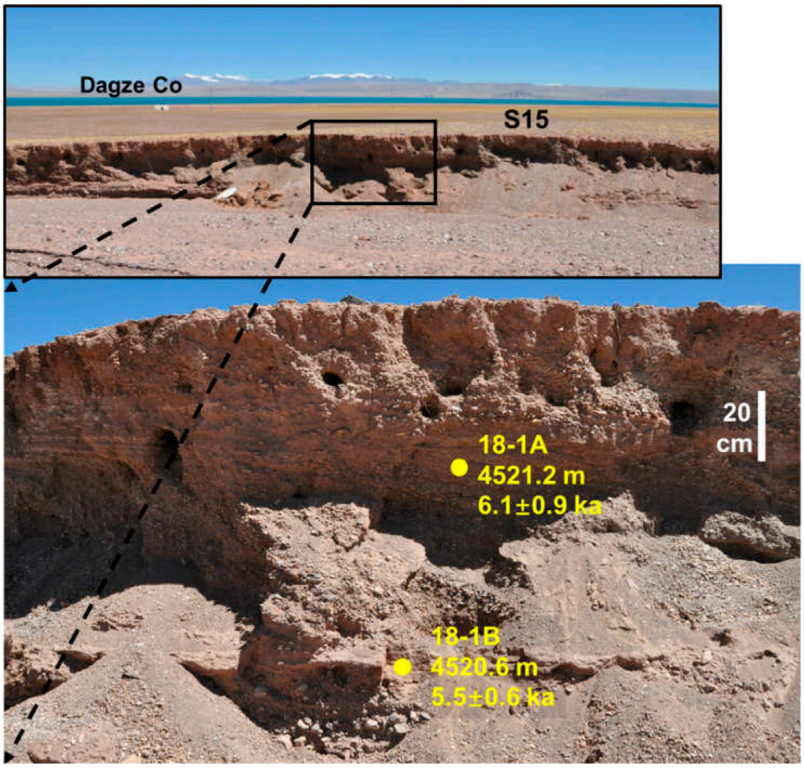

FIGURE 4 | Paleoshoreline S15 and profile 18–1. This shoreline is the highest visible paleoshoreline surrounding the lake and extends from the southern to the eastern lake margin. OSL dating sample 18-1A was collected from the beach gravels where there is a large sand component. OSL dating sample 18-1B was collected from the middle part of the medium sand layer.

are 6.1 ± 0.9 and 5.5 ± 0.6 ka, respectively, suggesting Dagze Co reached its highest lake level during the mid-Holocene (**Figure 4**; **Supplementary Figure S8**; **Table 1**). The lake greatly expanded at its highest lake level stage (**Figure 1B**), with the lake area reaching ~839 km^2, 2.8 times its present size. Dagze Co would have overflowed to the west into lower basins when it reached the highest level at S15 as evidenced by a remnant channel connecting Dagze Co with the western basins. The dividing crest between Dagze Co and the western basins is approximately the same elevation as paleoshoreline S15. Hence, water balance ratios in the Dagze Co basin were likely sufficient to sustain the lake at the same elevation of paleoshoreline S15 or slightly higher during the early Holocene ISM intensification stage when several other lakes on southern TP experienced their highest Holocene lake levels (Liu et al., 2016; Shi et al., 2017; Chen et al., 2020).

DISCUSSION

Asymmetrical Humidity Variations Between the Northern and Southern TP During the LGM

The Antarctic and Artic ice sheets expanded and mountain glaciers around the world also advanced as the global mean surface air temperature declined by ~4°C during the LGM (Clark et al., 2009; Annan and Hargreaves, 2013). The reconstructed surface temperature over the TP and its adjacent regions was 5–8°C colder than today during the LGM (Xu et al., 2013; Zhang et al., 2020). Although there are several paleoenvironmental proxy records spanning the LGM in the northern TP (An et al., 2012; Yan and Wünnemann, 2014; Jin et al., 2015; Wu et al., 2020), most studies in the southern TP cover only the last deglacial and Holocene periods, with only a few extending to the latest stage of the LGM (Gasse et al., 1991; Zhu et al., 2015; Ma et al., 2019; Chen et al., 2020 and references cited there in).

During the LGM, the northern TP became colder, drier and windier, and lakes within this region were much reduced or even desiccated (An et al., 2012; Yan and Wünnemann, 2014; Wu et al., 2020). An intensified East Asian Winter Monsoon (EAWM) entered the western Qaidam Basin through several low altitude mountain passes and moved eastward to influence most areas of the northeastern TP, keeping the Asian summer monsoon (ASM) at bay and causing mean annual precipitation to decrease further (Yang et al., 2017). As a result, lakes in the northeastern TP significantly regressed; the water level of Hala Lake was ~50 m lower than today (**Figure 5A**, Yan and Wünnemann, 2014), Qinghai Lake almost dried up due to a weakened ASM that caused a decrease in precipitation (**Figure 5B**, Madsen et al., 2008; Liu et al., 2015; Jin et al., 2015), and Dalianhai Lake was also

TABLE 1 | Summary of shoreline codes, elevations, aliquot numbers, equivalent doses, age models, water contents, dose rates, ages and selected ages used in the context. Uncertainties of individual quartz ages contain both random and systematic components. "MAM-3" is the abbreviation of the 3-parameter minimum-age model, and "CAM" is the abbreviation of the central-age model (Arnold et al., 2007).

Sample code	Shoreline num	Sample ele (m.a.s.l)	Grain size (μm)	Aliquot num	De (Gy)	Age model	Water content (%)	Dose rate (Gy/ka)	Age (ka)	Age selected
17-10-1	S10	4,499.9	90–125	50	56.9 ± 2.3	CAM	20 ± 5	2.32 ± 0.16	24.5 ± 1.9	
							15 ± 5	2.47 ± 0.17	23.0 ± 1.8	✓
							10 ± 5	2.63 ± 0.18	21.7 ± 1.7	
17-10-2	S10	4,500.5	38–63	50	66.9 ± 1.0	MAM-3	20 ± 5	2.88 ± 0.19	23.3 ± 1.6	
							15 ± 5	3.07 ± 0.21	21.8 ± 1.5	✓
							10 ± 5	3.26 ± 0.22	20.5 ± 1.4	
17-10-3	S10	4,500.8	63–90	50	64.1 ± 2.0	CAM	20 ± 5	2.55 ± 0.19	25.2 ± 2.0	
							15 ± 5	2.71 ± 0.20	23.7 ± 1.9	✓
							10 ± 5	2.87 ± 0.21	22.3 ± 1.8	
17-10-4	S10	4,501.1	90–125	50	59.6 ± 1.8	CAM	20 ± 5	2.45 ± 0.20	24.4 ± 2.1	
							15 ± 5	2.60 ± 0.21	22.9 ± 2.0	
							10 ± 5	2.76 ± 0.22	21.6 ± 1.8	✓
17-10-5	S10	4,501.5	90–125	50	62.5 ± 2.1	CAM	20 ± 5	2.49 ± 0.26	25.1 ± 2.7	
							15 ± 5	2.64 ± 0.26	23.7 ± 2.5	
							10 ± 5	2.80 ± 0.27	22.3 ± 2.3	✓
17-10-6	S10	4,501.8	38–63	50	76.6 ± 8.4	MAM-3	20 ± 5	2.85 ± 0.19	26.9 ± 3.4	
							15 ± 5	3.03 ± 0.20	25.3 ± 3.2	
							10 ± 5	3.22 ± 0.21	23.8 ± 3.1	✓
18-1A	S15	4,521.2	90–125	50	15.0 ± 1.1	MAM-3	20 ± 5	2.18 ± 0.28	6.8 ± 1.0	
							15 ± 5	2.31 ± 0.29	6.4 ± 0.9	
							10 ± 5	2.45 ± 0.30	6.1 ± 0.9	✓
18-1B	S15	4,520.6	90–125	44	14.8 ± 0.6	CAM	20 ± 5	2.40 ± 0.24	6.2 ± 0.7	
							15 ± 5	2.55 ± 0.25	5.8 ± 0.6	
							10 ± 5	2.70 ± 0.26	5.5 ± 0.6	✓

substantially reduced during the LGM (Wu et al., 2020). Ice wedge casts widely developed across the northern TP in response to the sharp cooling (Pan and Chen, 1997; Madsen et al., 2008; Liu and Lai, 2013). Loess, which accumulated on the northeastern TP during and prior to the LGM, was largely eroded away by strong winds and expanded glaciers (Liu et al., 2017; E. et al., 2018). In the Qaidam Basin, extensive evaporite deposits in Qarhan salt-lake dating to after 25–24 ka resulted from an increasingly arid climate (Chen and Bowler, 1985). These evaporite depositions persisted until the early Holocene when the climate became humid again (Chen and Bowler, 1985). A recent study also suggests the westerly jet stream strengthened significantly during the LGM, the East Asian Summer Monsoon was weaker than during the interglacial, and temperatures and precipitation during the LGM were lower than those during the mid-Holocene in the northern QTP (Li et al., 2020).

Limited paleoenvironmental records from lacustrine sediments and aeolian sands in the southern TP extending to the end of the LGM also indicate a cold and dry climate with the Westerlies prevailed yearly round (Lai et al., 2009; Zhu et al., 2015; Ma et al., 2019). However, the Guliya ice core record from the western TP indicates that while dust concentrations were high during marine isotope stage 4, concentrations were only moderate during the LGM, suggesting the climate was cold and wet (Wu et al., 2004). Moreover, optical dating and cosmological nuclide dating ages of paleoshorelines indicate Seling Co, Dangqiong Co and Nam Co had LGM lake levels higher than present (**Figure 5**; Li et al., 2009; Kong et al., 2011; Zhou et al., 2020), consistent with an interpretation of a cold and wet climate. Our optical dating results from Dagze Co also show the lake enlarged during the LGM, with a lake level reaching ~22 m above the present.

More than a decade ago, Yu et al. (2003) compiled paleolake data and used a global atmospheric general circulation model (GCM) coupled with a land surface process model to explore LGM climatic conditions for the whole China. They suggested a positive net annual precipitation (P-E) was produced by a decrease in evaporation and an increase in precipitation during the LGM, causing lakes in western China to substantially expand. Subsequently, Zheng et al. (2007) utilized a regional climate model (RegCM2) to simulate the climatic conditions in China at 21 and 6 ka. Their results indicate that the TP climate was wet-cold during the LGM, but wet-warm at 6 ka. Recently, Li and Morrill (2013) compiled lake level information for the monsoonal and arid regions of Central Asia and compared them with PMIP2 simulated LGM lake level variations. They found that the LGM lake levels were higher than today in some parts of southern and western TP, while lake levels in the eastern and northern TP declined substantially at the same time. Although only a few lake records in the southern TP reflect LGM high lake levels, they are consistent with these climate simulation results.

In summary, it is clear that climate conditions in the northern TP were cold and dry during the LGM, while the climate conditions were cold and wet in some parts of the southern TP. Why the entire TP was predominantly influenced by the

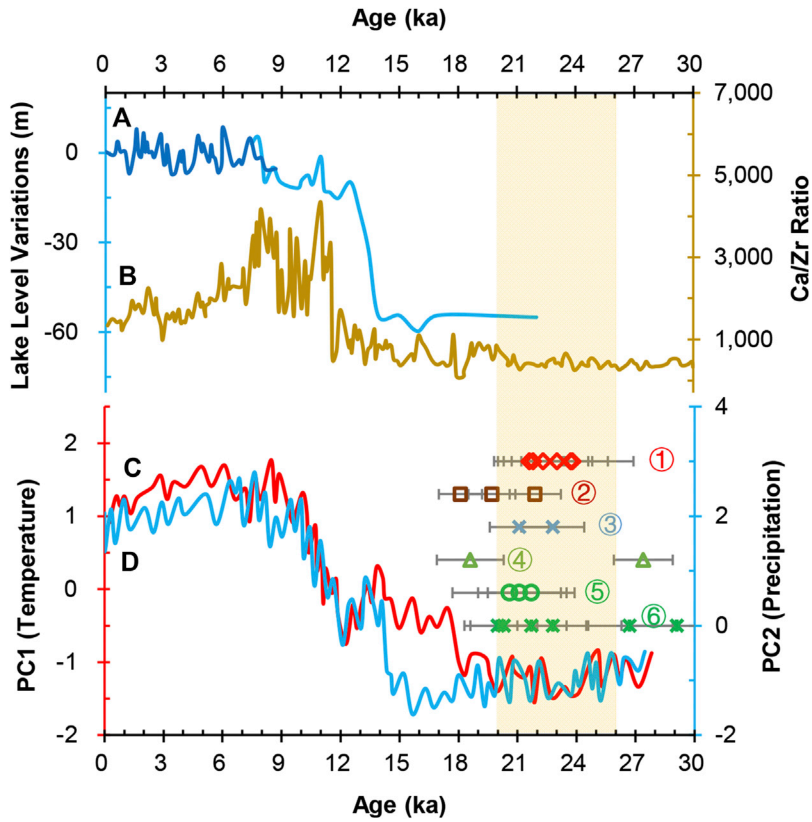

FIGURE 5 | (A) Reconstructed lake level variation curve of Hala Lake (Yan and Wünnemann, 2014). **(B)** Ca/Zr ratio of lacustrine sediments from Qinghai Lake, representing changes in lake hydrology. Higher values represent more runoff into the lake (Jin et al., 2015). **(C)** and **(D)** represent temperature and precipitation changes over Tengchong Qinghai, Yunnan province (Zhang et al., 2020). Precipitation is mainly related to the Indian summer monsoon. The LGM highstand paleoshoreline ages of Dagze Co (this study) ①, Nam Co (Zhou et al., 2020) ②, Dangqiong Co (Kong et al., 2011) ③ and Seling Co (Li et al., 2009) ④. Ages of the travertine layer containing embedded in human fingerprints and footprints at the Quesang archaeological site (Zhang and Li, 2002) ⑤ and ages of fluvial deposits containing paleolithic stone artifacts at the Nwya Devu archaeological site (Zhang et al., 2018b) ⑥. The light-yellow band represents the time range of the LGM.

Westerlies during the LGM, but had asymmetrical humidity variations in the northern and southern TP is discussed below.

Asymmetrical Forcing of Net Annual Precipitation during the LGM in the Northern and Southern TP

During the LGM, ice sheets and sea ice expanded in high latitude areas of the Northern Hemisphere, the annual average temperatures dropped dramatically, the latitudinal temperature gradient between the poles and the equator increased, the Intertropical Convergence Zone migrated southward, mid-latitude Westerlies were enhanced, and, most importantly, the ASM significantly weakened (**Figure 5D**; An et al., 2012; Deplazes et al., 2013). As a consequence, the TP was predominantly influenced by the Westerlies, and monsoonal precipitation markedly decreased (An et al., 2012; Zhu et al., 2015). Surface atmosphere temperatures over the TP were also 5–8°C colder than at present (**Figure 5C**, Xu et al., 2013; Zhang et al., 2020), and the annual freezing period was prolonged, factors which significantly reduced lake surface evaporation (Li and Morrill, 2013). There was a substantial expansion of glaciers over southern and western TP in response to this decline in the annual average temperature, but glacier expansion in the central and northern TP was much more limited (Yan et al., 2018; Yan et al., 2020). The expansion of glaciers in the southern TP not only supplied more meltwater to lower elevation lakes during the summer time, but also reduced atmospheric heating over the TP, in turn, weakening the ASM (Liu et al., 2020). The influence of glacial expansion over the TP on LGM climates was explored using the CAM4 climate model (Liu et al., 2020). Simulation results suggest that an expansion of glaciers over the southern and western TP would lead to a decrease in surface air temperatures during both the summer and winter seasons over most regions of the TP (**Figures 6A,B**). Summer precipitation rates in the western and southern TP would increase slightly, but decrease a little in the eastern and northeastern TP (**Figure 6C**). Winter precipitation rates would decrease slightly over most of the TP (**Figure 6D**). This slight increase in summer precipitation, coupled with the decline in summer temperatures and an increase in cold glacier meltwater supply together reduced lake surface evaporation, favoring the appearance of high lake levels in the southern TP. On the other hand, the slight decrease in summer precipitation coupled with the more limited glacier meltwater supply, caused a drier

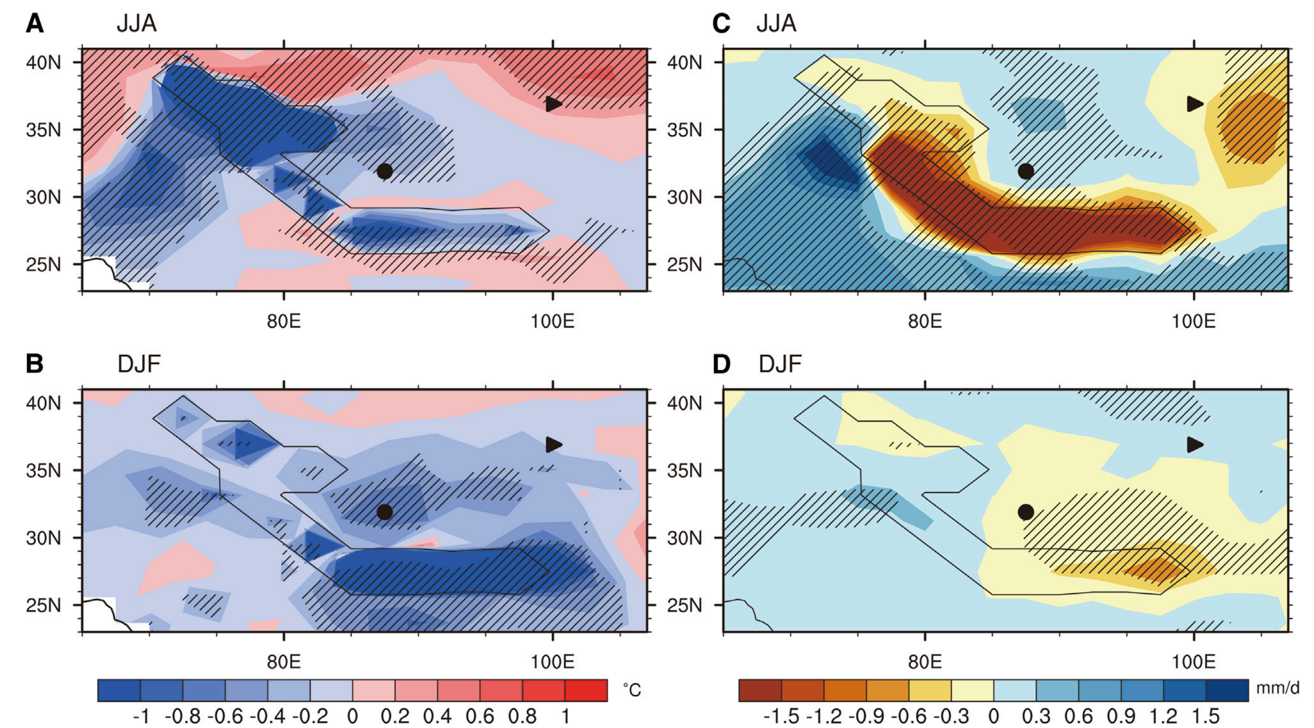

FIGURE 6 | Changes in summer (June-August) and winter (December-February) surface temperatures **(A and B)** and precipitation rates **(C and D)** due to the glacier expansions over the TP during the LGM. The thin black line polygon is the region where glaciers expanded. Regions where the temperature or precipitation rate changed at the 0.05 level of significance are hatched. The black dot represents the location of Dagze Co on the southern TP, while the black triangle represents the location of Qinghai Lake on the northern TP. This figure is modified from Liu et al. (2020).

northern TP and a substantial regression of northern TP lakes. We therefore conclude that the differential development and expansion of the glaciers and associated climatic impacts is the major reason for the difference in net annual precipitation between the northern and southern TP during the LGM.

To further explore the spatial precipitation and evaporation changes over the TP during the LGM, we used the TraCE-21 model (Liu et al., 2009) simulation results to obtain annual and seasonal precipitation, net annual precipitation, and annual and seasonal surface atmosphere temperatures over the southern, western and northeastern TP at the LGM, the mid-Holocene (8–6 ka) and the past one thousand years. We selected spatial extents (3.75°× 3.75°) over the southern, western and northeastern TP regions to cover Dagze Co, Longmu Co and Qinghai Lake, respectively. Model results indicate that LGM annual precipitation, net annual precipitation, and seasonal precipitation over the southern TP were similar to the past 1 ka. The annual mean temperature was ~4°C lower than the past thousand years, while summer and autumn temperatures were ~5.5 and ~4.5°C lower (**Tables 2**, **3**), respectively. Hence, the increased net water budgets and higher lake levels over the southern TP were caused by enhanced recycling of local moisture, increased summer contributions of glacial meltwater and reduced summer and autumn lake surface evaporation. Summer and autumn precipitation over the northern TP were dramatically reduced during the LGM, and both the annual and summer mean temperatures dropped by ~2 and ~5°C relative to the past 1,000 years (**Tables 2**, **3**), respectively. We therefore speculate that the large amplitude reduction of summer and autumn precipitation are the main reasons the northern TP became more arid compared to the southern TP. Moreover, limited glacial expansion over the northern and northeastern TP resulted in comparatively little meltwater reaching the lakes, adding to the marked LGM lake regressions in the region. Both the mean annual and seasonal precipitation over the western TP increased during the LGM, while the annual and summer mean temperatures dropped by ~4 and ~7°C relative to the past 1,000 years (**Tables 2**, **3**), respectively. The increased annual precipitation and reduced annual and summer mean temperatures, favored the expansion of regional glaciers, consistent with the interpretation of large-scale glacier advances over the western TP during the LGM (Yan et al., 2018). Because the ASM weakened and it transported limited moisture to the TP during the LGM, the increased annual precipitation in the western TP may be related to the enhanced Westerlies that brought more moisture from the Atlantic Ocean, Europe and Central Asia.

The simulated annual mean surface atmosphere temperatures for northern, southern and western TP during the mid-Holocene were all lower than the past 1,000 years. However, the summer season temperatures for all these regions were higher than the past 1,000 years (**Table 3**), suggesting that the seasonality was

TABLE 2 | Simulated annual precipitation, net annual precipitation and seasonal precipitation based on the TraCE-21 model. The data were downloaded from webpage http://202.195.239.65:8888/, then reanalyzed.

Lake name	Age (ka BP)	Precipitation (mm/month)					
		Annual	Net annual	Spring (MAM)	Summer (JJA)	Autumn (SON)	Winter (DJF)
Dagze Co	22–20	46.81 ± 1.03	20.99 ± 0.77	41.21 ± 0.99	35.08 ± 2.00	65.37 ± 2.01	45.56 ± 1.67
	8–6	53.85 ± 1.34	24.81 ± 1.05	44.18 ± 1.88	36.50 ± 2.39	88.17 ± 3.55	46.57 ± 1.70
	1–0	47.44 ± 1.43	19.18 ± 1.17	41.44 ± 1.37	31.19 ± 2.67	68.87 ± 2.89	48.28 ± 1.56
Longmu Co	22–20	35.86 ± 0.63	17.90 ± 0.48	35.69 ± 0.94	16.53 ± 1.13	43.61 ± 1.71	47.61 ± 1.07
	8–6	33.27 ± 0.80	15.81 ± 0.63	41.87 ± 1.58	7.18 ± 0.77	47.26 ± 2.29	36.79 ± 1.65
	1–0	30.92 ± 0.60	13.48 ± 0.51	34.78 ± 0.92	10.88 ± 1.01	37.08 ± 1.59	40.93 ± 0.95
Qinghai lake	22–20	83.38 ± 0.85	42.67 ± 0.74	68.66 ± 1.35	174.06 ± 3.30	72.74 ± 1.72	18.05 ± 0.70
	8–6	107.84 ± 1.73	73.59 ± 1.34	64.03 ± 2.20	244.35 ± 5.84	101.28 ± 2.18	21.68 ± 1.07
	1–0	103.24 ± 2.63	67.58 ± 2.54	71.66 ± 1.75	219.29 ± 6.56	96.21 ± 3.67	25.79 ± 0.55

TABLE 3 | Simulated annual and seasonal surface atmosphere temperatures based on the TraCE-21 model. The data were downloaded from webpage http://202.195.239.65:8888/, then reanalyzed.

Lake name	Age (ka BP)	Surface Atmosphere Temperature (°C)				
		Annual	Spring (MAM)	Summer (JJA)	Autumn (SON)	Winter (DJF)
Dagze Co	22–20	−10.46 ± 0.09	−14.31 ± 0.24	3.84 ± 0.40	−7.07 ± 0.30	−24.33 ± 0.28
	8–6	−7.43 ± 0.12	−12.75 ± 0.16	9.64 ± 0.37	−3.92 ± 0.49	−22.70 ± 0.24
	1–0	−5.97 ± 0.45	−10.28 ± 0.79	9.43 ± 0.51	−2.47 ± 0.29	−20.56 ± 0.41
Longmu Co	22–20	−7.39 ± 0.06	−10.72 ± 0.25	6.62 ± 0.29	−4.92 ± 0.30	−20.53 ± 0.20
	8–6	−3.77 ± 0.16	−8.67 ± 0.13	14.49 ± 0.46	−1.42 ± 0.46	−19.49 ± 0.36
	1–0	−2.84 ± 0.21	−6.18 ± 0.54	12.82 ± 0.19	−0.73 ± 0.16	−17.26 ± 0.25
Qinghai lake	22–20	−4.70 ± 0.13	−2.36 ± 0.24	5.24 ± 0.09	−3.76 ± 0.25	−17.93 ± 0.33
	8–6	−2.45 ± 0.14	−2.47 ± 0.13	10.62 ± 0.22	−1.53 ± 0.35	−16.45 ± 0.31
	1–0	−1.64 ± 0.07	−0.64 ± 0.17	9.11 ± 0.08	−0.96 ± 0.14	−14.07 ± 0.17

more significant over the TP during the mid-Holocene. Mid-Holocene summer and autumn precipitation was higher than both the LGM and the past 1,000 years in the northern and southern TP (**Table 2**), consistent with the highest paleoshoreline age at Dagze Co and the high lake levels recorded at several other lakes (Liu et al., 2016; Shi et al., 2017; Chen et al., 2020). However, the mid-Holocene winter and spring precipitation over the southern and northern TP was similar to the LGM and the past 1,000 years, suggesting that the Holocene high lake levels were caused by an intensified ASM that brought abundant rainfall during the growing season. In contrast, the western TP net annual and summer precipitation decreased substantially (**Table 2**), suggesting that the moisture of the western TP was related primarily to the Westerlies.

Implications for Paleolithic People Living on the Southern TP During the LGM

During the LGM, multiple proxies indicate that the climate of the northern TP was colder, drier and windier, while the southern TP, or at least parts of it, was colder and wetter. The finding of some genetic continuity between initial paleolithic foragers and modern Tibetans is not enough to infer that paleolithic people may have overcome the harsh LGM climate and occupied the high interior plateau regions of the TP as proposed by Zhao et al. (2009) since any exchange of genetic material may have occurred on the lower elevations TP margins. Two archaeological sites in the interior southern TP are dated to be within or spanning the LGM, providing some support for the inference from genetic research (Quesang and Nwya Devu sites) (**Figure 5**; Zhang and Li, 2002; Zhang et al., 2018b). Some other Upper Paleolithic archaeological sites on the TP have also been reported to have been occupied within or slightly earlier than LGM, such as Lenghu No. 1 (Brantingham et al., 2007), Xiao Qaidam (Huang et al., 1987) and Seling Co. (Yuan et al., 2007). However, reports of most of these sites only reflect Paleolithic tools from the ground surface, and buried and dated deposits were not identified, making the ages of these sites difficult to determine. More investigations are required to confirm Paleolithic people occupied the TP during climate harsher LGM.

The modern distribution of biotic communities across the TP, and thus the distribution of plant and animal resources on which past Tibetan populations depended, is directly related to a differential monsoon strength which is rapidly reduced from the southeast to northwest across the TP (Madsen et al., 2017; Guedes and Aldenderfer 2019). We here propose that this southeast to northwest difference was magnified during the LGM. While the extreme conditions of the colder, drier and windier LGM climate made it even more difficult than it is now for Upper Paleolithic foragers to live in the interior of the northern TP during the LGM, these hostile conditions also extended into the TP margins of the northeastern TP, such as around Qinghai Lake. Currently there are no known archaeological sites older than ~15 ka above ~3,000 m on the northeastern TP margins in areas where Holocene and modern agro-pastoralist sites are common (e.g., Madsen et al., 2006; Wang et al., 2020). Prehistoric foragers seem to have moved down to the surrounding lower elevational regions during the LGM and only moved up and re-occupied the interior northern TP again during the deglacial period when the climate started to become warmer and wetter (Madsen et al., 2017). However, Upper Paleolithic foragers may have seasonally occupied the interior regions of the southern TP since the relatively wetter LGM climate may have favored the growth of forage for large herbivores, which in turn provided major subsistence resources for prehistoric hunters that were absent or reduced in the northern TP. Moreover, sparsely distributed hot springs and caves on the southern TP may also have helped foragers overcome the cold weather. These speculations require substantial comprehensive investigations of LGM flora and fauna on the southern TP to be confirmed, but evidence of large mega-fauna, including mammoth and wooly rhinoceros fossils, has been found in lacustrine sediments around several early and middle Pleistocene paleolakes during cold and wet glacial periods (e.g., Zheng et al., 1985; Han et al., 2013). Moreover, recent research suggests archaic hominins may have occupied the TP in the Middle Pleistocene epoch (before 160 ka) and successfully adapted to high-altitude hypoxic environments long before the regional arrival of modern *Homo sapiens* (Chen et al., 2019). The questions of when and how people permanently settled the TP is complex and more studies are needed to get a comprehensive understanding of this process.

CONCLUSION

In this study, we report the dating of exposed highstand lacustrine sediments and beach sediments surrounding Dagze Co, and show that there were high levels of the lake during the LGM and mid-Holocene. The LGM high lake level (22.4 m ALL) was caused by intensified local moisture recycling, increased glacier meltwater and decreased lake surface evaporation in the context of extensive glacial expansions over the southern and western TP. Holocene highstands differed in that these lake level increases were mainly in response to an intensified ASM during the early-middle Holocene. We combined reported high lake level ages within the TP during the LGM with climate model simulation results, and find that LGM climatic conditions on the southern TP were cold and wet, providing an environment suitable for cold-resistant plant growth and the production of forage for herbivores. These large herbivores, in turn, provided food on which Paleolithic foragers could live. However, the northern TP was cold, dry and windy during the LGM, and these harsher climatic conditions made the human occupation of the interior northern TP much more difficult until after the last deglacial stage. Our results are preliminary and speculative, and more studies are needed to provide a more comprehensive understanding the southern TP environmental conditions and ecosystem compositions during the LGM.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

XJL designed the research. XJL and LC performed the research. XJL, XZL, and DM analyzed the data. XJL, DM, and XZL wrote the manuscript. YGL performed the CAM4 climate modeling, and JP analyzed the OSL dating results with age models.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2020.606051/full#supplementary-material

REFERENCES

An, Z. S., Colman, S. M., Zhou, W. J., Li, X. Q., Brown, E. T., Tomithy Jull, A. J., et al. (2012). Interplay between the Westerlies and asian monsoon recorded in lake Qinghai sediments since 32 ka. *Sci. Rep.* 2, 1–7. doi:10.1038/srep00619

Annan, J. D., and Hargreaves, J. C. (2013). A new global reconstruction of temperature changes at the last glacial maximum. *Clim. Past* 9, 367–376. doi:10.5194/cp-9-367-2013

Arnold, L. J., Bailey, R. M., and Tucker, G. E. (2007). Statistical treatment of fluvial dose distributions from southern Colorado arroyo deposits. *Quat. Geochronol.* 2, 162–167. doi:10.1016/j.quageo.2006.05.003

Brantingham, P. J., Gao, X., Olsen, J. W., Ma, H., Rhode, D., Zhang, H., et al. (2007). A short chronology for the peopling of the Tibetan Plateau. *Dev. Quat. Sci.* 9, 129–150. doi:10.1016/S1571-0866(07)09010-0

Chen, F. H., Welker, F., Shen, C. Z., Bailey, S. E., Bergmann, I., Davis, S., et al. (2019). A late middle Pleistocene denisovan mandible from the Tibetan plateau. *Nature* 569 (7756), 409–412. doi:10.1038/s41586-019-1139-x

Chen, F. H., Zhang, J. F., Liu, J. B., Cao, X. Y., Hou, J. Z., Zhu, L. P., et al. (2020). Climate change, vegetation history, and landscape responses on the Tibetan Plateau during the Holocene: a comprehensive review. *Quat. Sci. Rev.* 243, 106444. doi:10.1016/j.quascirev.2020.106444

Chen, K. Z., and Bowler, J. M. (1985). Preliminary study on sedimentary characterisitcs and evolution of palaeoclimate of Qarhan Salt Lake in Qaidam Basin. *Sci. China Chem.* 28 (11), 1218–1231 [in Chinese, with English summary]. 10.1360/yb1985-28-11-1218

Clark, P. U., Dyke, A. S., Shakun, J. D., Carlson, A. E., Clark, J., Wohlfarth, B., et al. (2009). The last glacial maximum. *Science* 325, 710–714. doi:10.1126/science.1172873

Deplazes, G., Luckge, A., Peterson, L. C., Timmermann, A., Hamann, Y., Hughen, K. A., et al. (2013). Links between tropical rainfall and North Atlantic climate during the last glacial period. *Nat. Geosci.* 6, 213–217. doi:10.1038/ngeo1712

Dong, G. H., Li, R., Lu, M., Zhang, D. J., and James, N. (2020). Evolution of human–environmental interactions in China from the late paleolithic to the bronze age. *Prog. Phys. Geogr.* 44, 233–250. doi:10.1177/0309133319876802

E, C. Y., Sohbati, R., Murray, A. S., Buylaert, J., Liu, X. J., Yang, L., et al. (2018). Hebei loess section in the Anyemaqen Mountains, northeast Tibetan Plateau: a high-resolution luminescence chronology. *Boreas* 47, 1170–1183. doi:10.1111/bor.12321

Gasse, F., Arnold, M., Fontes, J. C., Fort, M., Gibert, E., Huc, A., et al. (1991). A 13000 year climate record from western Tibet. *Nature*. 353 (6346), 742–745. doi:10.1038/353742a0

Guedes, J. D. A., and Aldenderfer, M. (2019). The archaeology of the early Tibetan plateau: new research on the initial peopling through the early bronze age. *J. Archaeol. Res.* 28, 339–392. doi:10.1007/s10814-019-09137-6

Guérin, G., Mercier, N., and Adamiec, G. (2011). Dose-rate conversion factors: update. *Ancient TL* 29, 5–8.

Han, J. E., Shao, Z. G., Meng, X. G., Zhu, D. G., Yu, J., Chen, Q. G., et al. (2013). Discovery and significance of manmuthus fossil in Gonghe basin, Qinghai province. *Geol. Bull. China* 32, 730–733 [in Chinese, with English summary]. doi:10.3969/j.issn.1671-2552.2013.05.005

Hou, J. Z., Tian, Q., Liang, J., Wang, M. D., and He, Y. (2017). Climatic implications of hydrologic changes in two lake catchments on the central Tibetan Plateau since the last glacial. *J. Paleolimnol.* 58, 257–273. doi:10.1007/s10933-017-9976-9

Huang, W. W., Chen, K. Z., and Yuan, B. Y. (1987). "Paleolithics of Xiao Qaidam lake in Qinghai province in China," in Proceedings of the sino-Australian quaternary meeting, Beijing, China: Science Press 168–172.

Jin, Z. D., An, Z. S., Yu, J. M., Li, F. C., and Zhang, F. (2015). Lake Qinghai sediment geochemistry linked to hydroclimate variability since the last glacial. *Quat. Sci. Rev.* 122, 63–73. doi:10.1016/j.quascirev.2015.05.015

Kong, P., Na, C. G., Brown, R., Fabel, D., Freeman, S., Xiao, W., et al. (2011). Cosmogenic ^{10}Be and ^{26}Al dating of paleolake shorelines in Tibet. *J. Asian Earth Sci.* 41, 263–273. doi:10.1016/j.jseaes.2011.02.016

Kuhle, M. (1998). Reconstruction of the 2.4 million km^2 late Pleistocene ice sheet on the Tibetan Plateau and its impact on the global climate. *Quat. Int.* 45–46, 71–108. doi:10.1016/S1040-6182(97)00008-6

Lai, Z. P., Kaiser, K., and Brückner, H. (2009). Luminescence-dated aeolian deposits of late Quaternary age in the southern Tibetan Plateau and their implications for landscape history. *Quat. Res.* 72, 421–430. doi:10.1016/j.yqres.2009.07.005

Li, D. W., Li, Y. K., Ma, B. Q., Dong, G. H., Wang, L. Q., and Zhao, J. X. (2009). Lake-level fluctuations since the Last Glaciation in Selin Co (lake), Central Tibet, investigated using optically stimulated luminescence dating of beach ridges. *Environ. Res. Lett.* 4, 045204. doi:10.1088/1748-9326/4/4/045204

Li, Y., and Morrill, C. (2013). Lake levels in Asia at the Last Glacial Maximum as indicators of hydrologic sensitivity to greenhouse gas concentrations. *Quat. Sci. Rev.* 60, 1–12. doi:10.1016/j.quascirev.2012.10.045

Li, Y., Peng, S. M., Liu, H. B., Zhang, X. Z., Ye, W. T., Han, Q., et al. (2020). Westerly jet stream controlled climate change mode since the last glacial maximum in the northern Qinghai-Tibet Plateau. *Earth Planet Sci. Lett.* 549, 116529. doi:10.1016/j.epsl.2020.116529

Liu, X. J., Lai, Z., Madsen, D., Li, G., Yu, L., Huang, C., et al. (2018). Late quaternary highstands of Qinghai Lake, Qinghai-Tibetan plateau. *Quat. Sci.* 35, 1166–1178 [in Chinese, with English summary]. doi:10.11928/j.issn.1001-7410.2018.05.11

Liu, X. J., Lai, Z. P., Madsen, D. B., and Zeng, F. M. (2015). Last deglacial and Holocene lake level variations of Qinghai Lake, north-eastern Qinghai–Tibetan plateau. *J. Quat. Sci.* 30, 245–257. doi:10.1002/jqs.2777

Liu, X. J., and Lai, Z. P. (2013). Optical dating of sand wedges and ice-wedge casts from Qinghai Lake area on the northeastern Qinghai-Tibetan Plateau and its palaeoenvironmental implications. *Boreas* 42, 333–341. doi:10.1111/j.1502-3885.2012.00288.x

Liu, X. J., Madsen, D. B., Liu, R. Y., Sun, Y. J., and Wang, Y. X. (2016). Holocene lake level variations of Longmu Co, western Qinghai-Tibetan Plateau. *Environ. Earth Sci.* 75, 301. doi:10.1007/s12665-015-5188-7

Liu, X. J., Xiao, G. Q., E, C. Y., Li, X. Z., Lai, Z. P., Yu, L. P., et al. (2017). Accumulation and erosion of aeolian sediments in the northeastern Qinghai-Tibetan Plateau and implications for provenance to the Chinese Loess Plateau. *J. Asian Earth Sci.* 135, 166–174. doi:10.1016/j.jseaes.2016.12.034

Liu, X. J., Zhang, X. J., Lin, Y. L., Jin, L. Y., and Chen, F. H. (2019). Strengthened Indian summer monsoon brought more rainfall to the western Tibetan Plateau during the early Holocene. *Sci. Bull.* 64, 1482–1485. doi:10.1016/j.scib.2019.07.022

Liu, Y. G., Wu, Y. B., Lin, Z. D., Zhang, Y., Zhu, J., and Yi, C. L. (2020). Simulated impact of the Tibetan glacier expansion on the Eurasian climate and glacial surface mass balance during the last glacial. *J. Clim.* 33, 6491–6509. doi:10.1175/JCLI-D-19-0763.1

Liu, Z., Otto-Bliesner, B. L., He, F., Brady, E. C., Tomas, R., Clark, P. U., et al. (2009). Transient simulation of last deglaciation with a new mechanism for bølling-allerød warming. *Science* 325, 310–314. doi:10.1126/science.1171041

Lu, D. S., Lou, H. Y., Yuan, K., Wang, X. J., Wang, Y. C., and Zhang, C. (2016). Ancestral origins and genetic history of Tibetan highlanders. *Am. J. Hum. Genet.* 99, 580–594. doi:10.1016/j.ajhg.2016.07.002

Ma, Q. F., Zhu, L. P., Lu, X. M., Wang, J. B., Ju, J. T., Kasper, T., et al. (2019). Late glacial and Holocene vegetation and climate variations at lake Tangra Yumco, central Tibetan plateau. *Global Planet. Change* 174, 16–25. doi:10.1016/j.gloplacha.2019.01.004

Madsen, D. B., Ma, H. Z., Brantingham, P. J., Gao, X., Rhode, D., Zhang, H. Y., et al. (2006). The late upper paleolithic occupation of the northern Tibetan plateau margin. *J. Archaeol. Sci.* 33, 1433–1444. doi:10.1016/j.jas.2006.01.017

Madsen, D. B., Ma, H. Z., Rhode, D., Brantingham, P. J., and Forman, S. L. (2008). Age constraints on the late quaternary evolution of Qinghai Lake, Tibetan plateau. *Quat. Res.* 69, 316–325. doi:10.1016/j.yqres.2007.10.013

Madsen, D. B., Perreault, C., Rhode, D., Sun, Y. J., Yi, M. J., Brunson, K., et al. (2017). Early foraging settlement of the Tibetan Plateau highlands. *Archaeol. Res. Asia* 11, 15–26. doi:10.1016/j.ara.2017.04.003

McGee, D. (2020). Glacial–interglacial precipitation changes. *Annu. Rev. Mar. Sci.* 12, 525–557. doi:10.1146/annurev-marine-010419-010859

Meyer, M. C., Aldenderfer, M. S., Wang, Z., Hoffmann, D. L., Dahl, J. A., Degering, D., et al. (2017). Permanent human occupation of the central Tibetan Plateau in the early Holocene. *Science* 355, 64–67. doi:10.1126/science.aam9231

Murray, A. S., and Wintle, A. G. (2000). Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. *Radiat. Meas.* 32, 57–73. doi:10.1016/S1350-4487(99)00253-X

Pan, B. T., and Chen, F. H. (1997). Permafrost evolution in the northeastern Qinghai-Tibetan Plateau during the last 150000 years. *J. Glaciol. Geocryol.* 19, 125–132 [in Chinese, with English summary].

Peng, J., Dong, Z. B., Han, F. Q., Long, H., and Liu, X. J. (2013). R package numOSL: numeric routines for optically stimulated luminescence dating. *Ancient TL* 31, 41–48.

Prescott, J. R., and Hutton, J. T. (1994). Cosmic ray contributions to dose rates for luminescence and ESR dating: large depths and long-term time variations. *Radiat. Meas.* 23, 497–500. doi:10.1016/1350-4487(94)90086-8

Qiang, M. R., Chen, F. H., Song, L., Liu, X., Li, M., and Wang, Q. (2013). Late quaternary aeolian activity in Gonghe basin, northeastern Qinghai-Tibetan plateau, China. *Quat. Res.* 79, 403–412. doi:10.1016/j.yqres.2013.03.003

Qiang, M. R., Jin, Y., Liu, X., Song, L., Li, H., Li, F., et al. (2016). Late Pleistocene and Holocene aeolian sedimentation in Gonghe basin, northeastern Qinghai-Tibetan plateau: variability, processes, and climatic implications. *Quat. Sci. Rev.* 132, 57–73. doi:10.1016/j.quascirev.2015.11.010

Qiao, C., Luo, J. C., Sheng, Y. W., Shen, Z. F., Li, J., and Gao, L. J. (2010). Analysis on lake changes since ancient and modern ages using remote sensing in Dagze Co, Tibetan Plateau. *J. Lake Sci.* 22, 98–102 [in Chinese, with English summary]. doi:10.18307/2010.0114

Quade, J., and Broecker, W. S. (2009). Dryland hydrology in a warmer world: lessons from the last glacial period. *Eur. Phys. J. Spec. Top.* 176, 21–36. doi:10.1140/epjst/e2009-01146-y

Shi, X. H., Kirby, E., Furlong, K. P., Meng, K., Robinson, R., Lu, H. J., et al. (2017). Rapid and punctuated late Holocene recession of siling Co, central Tibet. *Quat. Sci. Rev.* 172, 15–31. doi:10.1016/j.quascirev.2017.07.017

Shi, Y. F. (2004). The emergence and abandonment of the ice sheet hypothesis over the Qinghai-Xizang Plateau during the ice age. *Quat. Sci.* 24, 10–18 [in Chinese, with English summary], doi:10.3321/j.issn:1001-7410.2004.01.002

Stauch, G. (2015). Geomorphological and palaeoclimate dynamics recorded by the formation of aeolian archives on the Tibetan Plateau. *Earth Sci. Rev.* 150, 393–408. doi:10.1016/j.earscirev.2015.08.009

Thompson, L. G., Yao, T., Davis, M. E., Henderson, K. A., Mosley-Thompson, E., Lin, P. N., et al. (1997). Tropical climate instability: the last glacial cycle from a Qinghai-Tibetan ice core. *Science* 276, 1821–1825. doi:10.1126/science.276.5320.1821

Tian, L., Masson-Delmotte, V., Stievenard, M., Yao, T., and Jouzel, J. (2001). Tibetan Plateau summer monsoon northward extent revealed by measurements of water stable isotope. *J. Geophys. Res.* 106, 28081–28088. doi:10.1029/2001JD900186

Wang, J., Xia, H., Yao, J. T., Shen, X. K., Cheng, T., Wang, Q. Q., et al. (2020). Subsistence strategies of prehistoric hunter-gatherers on the Tibetan Plateau during the last deglaciation. *Sci. China Earth Sci.* 63 (3), 395–404. doi:10.1007/s11430-019-9519-8

Wu, D., Zhou, A. F., Zhang, J., Chen, J. W., Li, Chen, F. H., et al. (2020). Temperature-induced dry climate in basins in the northeastern Tibetan Plateau during the early to middle Holocene. *Quat. Sci. Rev.* 237, 106311. doi:10.1016/j.quascirev.2020.106311

Wu, G. J., Yao, T. D., Thompson, L. G., and Li, Z. Q. (2004). Microparticle record in the Guliya ice core and its comparison with polar records since the last interglacial. *Chin. Sci. Bull.* 49, 607–611. doi:10.1360/03wd0419

Xu, X. K., Hu, G., and Qiao, B. j. (2013). Last glacial maximum climate based on cosmogenic ^{10}Be exposure ages and glacier modeling for the head of Tashkurgan Valley, northwest Tibetan Plateau. *Quat. Sci. Rev.* 80, 91–101. doi:10.1016/j.quascirev.2013.09.004

Yan, D. D., and Wünnemann, B. (2014). Late Quaternary water depth changes in Hala Lake, northeastern Tibetan Plateau, derived from ostracod assemblages and sediment properties in multiple sediment records. *Quat. Sci. Rev.* 95, 95–114. doi:10.1016/j.quascirev.2014.04.030

Yan, Q., Owen, L. A., Wang, H. J., and Zhang, Z. S. (2018). Climate constraints on glaciation over high-mountain Asia during the last glacial maximum. *Geophys. Res. Lett.* 45, 9024–9033. doi:10.1029/2018GL079168

Yan, Q., Owen, L. A., Zhang, Z. S., Jiang, N. X., and Zhang, R. (2020). Deciphering the evolution and forcing mechanisms of glaciation over the Himalayan-Tibetan orogen during the past 20,000 years. *Earth Planet Sci. Lett.* 541, 116295. doi:10.1016/j.epsl.2020.116295

Yang, Y., Yang, R., Li, X., Han, W., Zan, J., Fang, X., et al. (2017). Glacial-interglacial climate change on the northeastern Tibetan Plateau over the last 600 kyr. *Palaeogeogr. Palaeocl.* 476, 181–191. doi:10.1016/j.palaeo.2017.04.007

Yao, T. D., Masson-Delmotte, V., Gao, J., Yu, W. S., Yang, X. X., Risi, C., et al. (2013). A review of climatic controls on δ^{18}O in precipitation over the Tibetan Plateau: observation and simulations. *Rev. Geophys.* 51, 1–24. doi:10.1002/rog.20023

Yu, G., Xue, B., Liu, J., and Chen, X. (2003). LGM lake records from China and an analysis of climate dynamics using a modelling approach. *Global Planet. Change* 38, 223–256. doi:10.1016/S0921-8181(02)00257-6

Yuan, B. Y., Huang, W. W., and Zhang, D. (2007). New evidence of human activities in the late Pleistocene in the northern Tibetan Plateau. *Sci. Bull.* 52, 1567–1571.

Zhang, D. D., and Li, S. H. (2017). Comment on Permanent human occupation of the central Tibetan Plateau in the early Holocene. *Science* 357, eaam9231. doi:10.1126/science.aam9231

Zhang, D. D., and Li, S. H. (2002). Optical dating of Tibetan human hand- and footprints: an implication for the palaeoenvironment of the last glaciation of the Tibetan Plateau. *Geophys. Res. Lett.* 29, 161–163. doi:10.1029/2001GL013749

Zhang, D. J., Shen, X. K., Cheng, T., Xia, H., Liu, W., Gao, X., et al. (2020). New advances in the study of prehistoric human activity on the Tibetan Plateau. *Chin. Sci. Bull.* 475–482 [in Chinese, with English summary]. doi:10.1360/TB-2019-0382

Zhang, D. J., Xia, H., and Chen, F. H. (2018a). Early human occupation of the Tibetan Plateau. *Sci. Bull.* 63, 1598–1600. doi:10.1016/j.scib.2018.12.004

Zhang, X. L., Ha, B. B., Wang, S. J., Chen, Z. J., Ge, J. Y., Long, H., et al. (2018b). The earliest human occupation of the high-altitude Tibetan Plateau 40 thousand to 30 thousand years ago. *Science* 362, 1049–1051. doi:10.1126/science.aat8824

Zhang, D., Zhang, N., Wang, J., Ha, B., Dong, G., and Chen, F. (2017). Comment on Permanent human occupation of the central Tibetan Plateau in the early Holocene. *Science* 357, eaam8273. doi:10.1126/science.aam8273

Zhang, X., Zheng, Z., Huang, K. Y., Yang, X. Q., and Tian, L. P. (2020). Sensitivity of altitudinal vegetation in southwest China to changes in the Indian summer monsoon during the past 68000 years. *Quat. Sci. Rev.* 239, 106359. doi:10.1016/j.quascirev.2020.106359

Zhao, M., Kong, Q. P., Wang, H. W., Peng, M. S., Xie, X. D., Wang, W. Z., et al. (2009). Mitochondrial genome evidence reveals successful Late Paleolithic settlement on the Tibetan Plateau. *Proc. Natl. Acad. Sci. U. S. A.* 106, 21230–21235. doi:10.1073/pnas.0907844106

Zheng, S. H., Wu, W. Y., Li, Y., and Wang, G. D. (1985). Late cenozoic mammalian faunas of Guide and Gonghe basins, Qinghai province. *Vertebr. Palasiat.* 23, 89–134 [in Chinese, with English summary].

Zheng, Y. Q., Qian, Z. C., He, H. R., Liu, H. P., Zeng, X. M., and Yu, G. (2007). Simulations of water resource environmental changes in China during the last 20000 years by a regional climate model. *Global Planet. Change* 55, 284–300. doi:10.1016/j.gloplacha.2006.10.001

Zhou, J., Zhou, W. J., Dong, G. C., Hou, Y. Y., Xian, F., Zhang, L., et al. (2020). Cosmogenic ^{10}Be and ^{26}Al exposure dating of Nam Co lake terraces since MIS 5, southern Tibetan Plateau. *Quat. Sci. Rev.* 231, 106175. doi:10.1016/j.quascirev.2020.106175

Zhu, L. P., Lu, X. M., Wang, J. B., Peng, P., Kasper, T., Daut, G., et al. (2015). Climate change on the Tibetan Plateau in response to shifting atmospheric circulation since the LGM. *Sci. Rep.* 5, 13318. doi:10.1038/srep13318

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Paleoenvironmental Evolution and Human Activities at the Hejia Site on the Ningshao Coastal Plain in Eastern China

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The eastern China coastal plain is an ideal area for studying the human–environment interaction during the Neolithic period as there are multiple Neolithic sites in this area. Located in the Ningshao Coastal Plain of the south bank of Hangzhou Bay in eastern China, the Hejia Site is part of the late Hemudu Culture sites and includes the late Hemudu Culture, the Liangzhu Culture, and the Qianshanyang Culture. Based on palynology, charcoal, X-ray fluorescence (XRF), and magnetic susceptibility (χ), combined with accelerator mass spectrometry ^{14}C dating and analysis of the archaeological cultural layers, we explored the paleoenvironmental evolution and human activities at the Hejia Site. 1) Pollen records suggest that the vegetation type was evergreen and deciduous broad-leaved mixed forest during the Middle Holocene. Cr/Cu and low-frequency magnetic susceptibility (χ_{lf}) reveal that the climate underwent through warm and wet (Hemudu Culture Period IV)–cool and dry (Liangzhu Culture Period)–warm and wet (Qianshanyang Culture Period) periods. 2) During the Middle Holocene, the intensity of human activities, related to the transformation of the natural environment, increased obviously. The increasing Poaceae pollen (>37 μm) indicates that the ability of prehistoric humans in managing crop fields gradually increased from the late Hemudu Culture Period to the Liangzhu Culture Period. The charcoal concentration results suggest that the occurrence of high-intensity fire events during the late Hemudu Culture Period might be caused by the slash-and-burn operation, while those that occurred during the middle Liangzhu Culture Period might be caused by the increasing fire demand owing to the greater ancestors' lives and production activities in the Liangzhu Culture Period.

Keywords: pollen, charcoal, XRF, paleoenvironment, human activities, Middle Holocene, Hejia Site

INTRODUCTION

The eastern China coastal plain contains a large amount of paleoenvironmental information, for its sensitivity to sea-level fluctuations and climate change. The Middle Holocene (8,200–4,200 cal a BP) experienced a significant deceleration, both in sea-level rise and climate warming (An et al., 2000; Xiong et al., 2020), which also witnessed the most prosperous cultural development and rapidest population growth in the eastern China coastal plain, including the Hemudu Culture

(7,000–5,000 cal a BP), the Majiabang Culture (7,000–5,800 cal a BP), the Songze Culture (5,800–5,000 cal a BP), the Liangzhu Culture (5,000–4,300 cal a BP), the Qianshanyang Culture (4,300–4,100 cal a BP), and the Guangfulin Culture (4,100–3,900 cal a BP) (Stanley and Chen, 1996; Chen, 2006; Li et al., 2007a; Zong et al., 2007; Xu, 2015; Hou, 2016; He et al., 2020a).

Environmental archaeology studies specifically focus on the interplay between human activities and paleoenvironmental changes (Liu et al., 2018; Xia and Zhang, 2019). The Ningshao Coastal Plain, located on the south bank of Hangzhou Bay in eastern China, is considered as an ideal area for studying the prehistoric human–environment interaction. In the past few decades, multiple studies have been conducted on the Ningshao Coastal Plain, ranging from climate change and environmental evolution to the rise and fall of Neolithic Culture (Chen et al., 2005; Yu et al., 2010; Innes et al., 2014). Studies show that the Hemudu Culture was developed in the context of regression in the Ningshao Coastal Plain and then was affected by sea-level fluctuation and climate change (He et al., 2018, He et al., 2020b; Liu et al., 2020). He et al. (2020a) conclude that the Hemudu Culture diffused from the Yaojiang Valley northward to the Zhoushan Islands and southward to the Ningbo Plain owing to a transgression during 6,200–5,600 cal a BP. The remains of rice and farming tools in the Hemudu Culture sites indicate that rice was farmed in this period. The phytolith and pollen data of the Hemudu Culture sites show that rice domestication was completed by approximately 5,600 cal a BP (Li et al., 2010a; He et al., 2020a), and after that, at approximately 5,000 cal a BP, the Liangzhu Culture replaced the Hemedu Culture. Previous studies state that the Liangzhu Culture, as the paramount one of prehistoric cultures in the lower reaches of the Yangtze River (Wu et al., 2012), developed a mature rice farming system when the primitive society was disintegrating and the embryonic state of the country was forming (Li et al., 2010c; Wang et al., 2017). The Liangzhu Culture disappeared at approximately 4,300 cal a BP, and several studies attribute that it was caused by the catastrophic events, such as rapid climate cooling, transgression, and floods (Stanley and Chen, 1996; Innes et al., 2014; Kajita et al., 2018; Wang et al., 2018; Wang et al., 2020). Some studies also suggest that the demise of the Liangzhu Culture may be the result of social factors (Zong et al., 2011). It can be seen that the factors causing the disappearance of Liangzhu Culture are still controversial. The later Qianshanyang and Guangfulin Cultures were less organized and developed (Xu, 2015).

Archaeological sites are the ideal material for exploring human–environment interactions that occurred during the Neolithic period, as they record the activities of prehistoric human life and production as well as paleoenvironmental changes (Cai et al., 2017; Li et al., 2017; Xia and Zhang, 2019). Recently, studies on the human–environment interaction in the Ningshao Coastal Plain focus on the Hemudu Culture Period in the Yaojiang Valley (He et al., 2018; Liu et al., 2018; Liu et al., 2019). However, few studies focus on the Hemudu Culture and later cultural periods for other areas of the Ningshao Plain. The Hejia Site, excavated in 2017, is located in the Fenghua River basin, Ningshao Coastal Plain, the southern bank of Hangzhou Bay, eastern China. The sedimentary layer of this site covers the late Hemudu Culture, the Liangzhu Culture (early, middle, and late), the Qianshanyang Culture, and the Eastern Zhou Dynasty; thus, the Hejia Site is of great significance for the late Hemudu Culture study. On the other hand, the relatively complete stratum of the Hejia Site is an ideal material for studying human–environment interactions. Besides, we expect that cultural responses to paleoenvironmental changes during the Middle Holocene in the Ningshao Coastal Plain could be revealed. In this study, multi-proxy indicators including pollen, charcoal, X-ray fluorescence, and environmental magnetism from the profile of the Hejia Site were analyzed to explore the environmental evolution and human activities in the Middle Holocene on the Ningshao Coastal Plain in eastern China, which provides a more comprehensive understanding of the environmental background of the prehistoric culture and the cultural responses to the environmental changes.

GEOGRAPHICAL BACKGROUND AND SITE DESCRIPTION

The Ningshao Coastal Plain is located in the subtropical region of the south bank of Hangzhou Bay in eastern China and is under the influence of the East Asian Monsoon. The average annual temperature and average annual precipitation are approximately 16.3°C and 1,400 mm, respectively (Ningbo Chorography Codification Committee, 1995; Zheng et al., 2016). Regional vegetation is characterized by subtropical mixed forests of evergreen and deciduous trees, including *Cyclobalanopsis*, *Castanopsis sclerophylla*, *Castanopsis*, *Liquidambar formosana*, *Quercus aliena*, *Quercus acutissima*, and *Pinus massoniana* (Wu, 1980).

The Hejia Site (latitude 29°45′6″N and longitude 121°26′30″E) lies in the Hejia village beside the Fenghua River, in the Ningshao Coastal Plain, on the south bank of Hangzhou Bay in eastern China. The cultural layer of the Hejia Site was approximately 140 cm and divided into four cultural periods: the Hemudu Culture IV (5,500–5,000 cal a BP), the Liangzhu Culture (5,000–4,300 cal a BP), the Qianshanyang Culture (4,300–4,100 cal a BP), and the Eastern Zhou Dynasty (2,171–2,720 cal a BP) (Luo and Zhao, 2019; He et al., 2020a; Huang, et al., 2021; Hou, 2016; Luo et al., 2020).

MATERIAL AND METHODS

Material

We sampled from the north wall of unit T0103 (referred to as T0103N) of the Hejia Site using U-shaped pipes in the field, with a length of 140 cm divided into 7 cultural layers (**Figure 1C**). Then, the samples contained in U-shaped pipes were sent to the X-ray fluorescence (XRF) core scanning laboratory of the Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, for scanning it. After that, it was sent to the

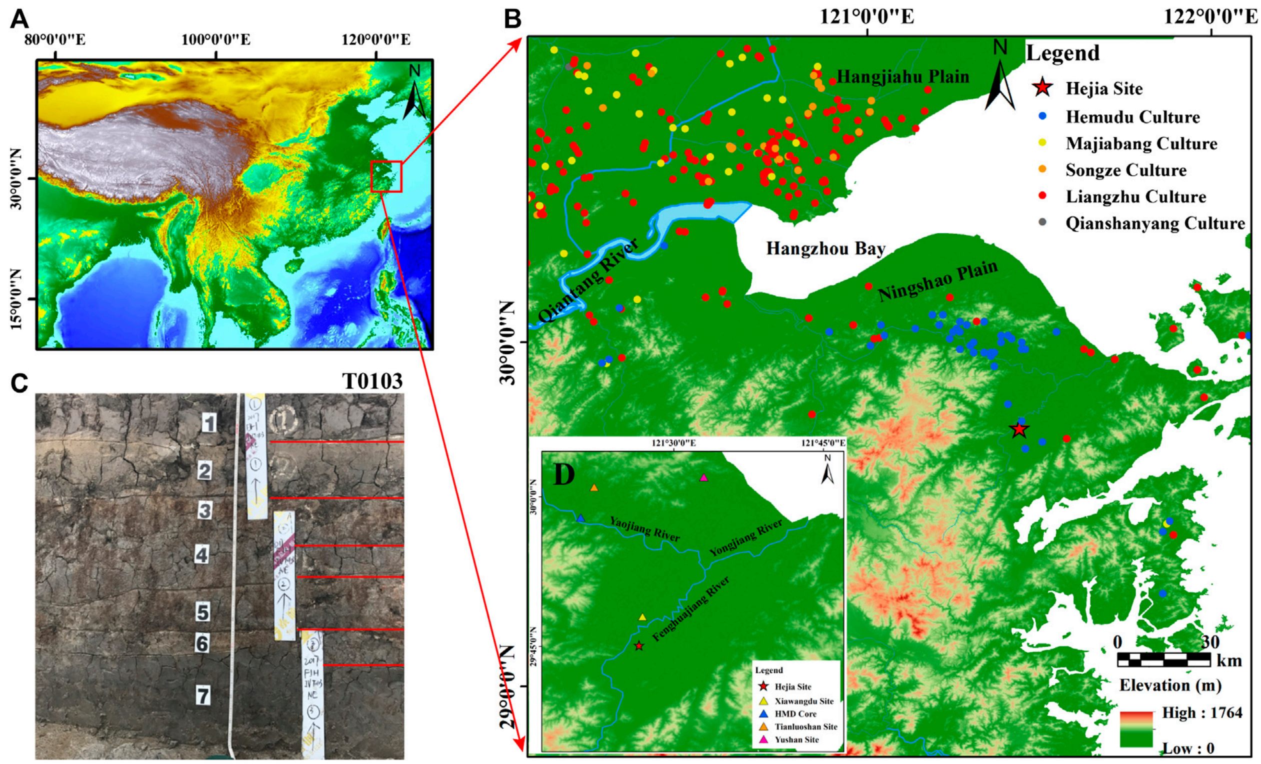

FIGURE 1 | Location maps and the photograph of the Hejia Site. **(A)** Location of the study area. **(B)** Location of the Hejia Site (red star) and the distribution of archaeological sites of the Hemudu Culture, Majiabang Culture, Songze Culture, Liangzhu Culture, and Qianshanyang Culture (Li et al., 2012; Liu et al., 2016; Luo and Zhao, 2019; He et al., 2020a). **(C)** The sampled profile in the north wall of unit T0103 of the Hejia Site. **(D)** Distribution of core and key archaeological sites of Hemudu Culture.

laboratory of Palynology and Paleocology of the School of Geography and Ocean Science, Nanjing University. The upper 55 cm combined historic and modern sediment included layers 1–3 (not collected). The lower 85 cm included layers 4–7 and was subsampled at 1 cm intervals. A total of 85 samples were collected.

METHODS

Accelerator Mass Spectrometry ^{14}C Dating

Four samples were collected from the north wall of the Hejia profile, and the plant residues or charcoal in the samples were selected as the dating materials. For samples from which plant residues or charcoal could not be recovered, we used HF treatment to process the pollen concentrate as the dating material (Li et al., 2007b). After pretreatment, the materials were sent to the Beta Analytic Laboratory (USA) for accelerator mass spectrometry (AMS) radiocarbon dating. The ages were calibrated using the IntCal13 data set (Reimer et al., 2013).

Magnetic Susceptibility

Magnetic susceptibility is an important proxy for the reconstruction of paleoclimate, especially the low-frequency magnetic susceptibility (χ_{lf}) (Han et al., 1996; Li and Yang, 2001). The samples were successively separated, oven-dried at 40°C for 24 h, and weighed. The values of the magnetic susceptibility (χ) were measured on 10 g samples. The χ of all 85 samples was measured at a low frequency (χ_{lf}) using a Bartington MS2 meter at the Earth Surface Process and Environmental Evolution Laboratory of the School of Geography and Ocean Science, Nanjing University.

X-Ray Fluorescence Scanning

Geochemical element analysis is an important method to study the environmental evolution and human activity information in sediments (Li et al., 2010b; Wu et al., 2017). Although the element intensity obtained by XRF scanning cannot obtain the absolute content of the element, it can well reflect the change of the relative content of the element (Yao, 2016). The samples were scanned with a Multi-Sensor Core Logger (MSCL-S) in the X-ray fluorescence (XRF) core scanning laboratory of the Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, at a resolution of 1 cm. The initial data were analyzed by using the bAxil Batch software to obtain the relative value of the element peak surface area that reflects the trends of the elements in the sediment of the Hejia Site.

TABLE 1 | AMS ^{14}C dating results of the unit T0103 of the Hejia Site.

Lab code	Sample number	Depth (cm)	Material	$^{13}\delta C$ (‰)	Conventional age (a BP)	Calibrated age (2σ) (cal. a BP)	Medium age (cal. a BP)
Beta563927	HJ76–77	76–77	Pollen concentrate	−22.4	4,440 ± 30	5,076–4,956	5,016
Beta509289	HJ100–101	100–101	Charcoal	−26.7	4,490 ± 30	5,294–5,039	5,167
Beta509290	HJ110–111	110–111	Charcoal	−28.5	4,450 ± 30	5,088–4,960	5,024
Beta516923	HJ139–140	139–140	Pollen concentrate	−20.7	5,140 ± 30	5,945–5,879	5,912

Pollen and Charcoal Analysis

Studies reveal that the pollen assemblage from the natural sedimentary layers of archaeological sites can reflect the information of past vegetation evolution, and the pollen sources from the cultural layer can be used to reconstruct information about environmental changes and human activities of archaeological sites to a certain extent (Xu et al., 2002; Li et al., 2009). Pollen and charcoal samples were performed at approximately 6-intervals at depths of 55–103 cm, except for the 103–140 cm, at 3 cm, yielding 19 samples in total. Samples were processed according to the standard procedure developed by Moore et al. (1991). The identification of pollen and spores was performed under a 400× microscope regarding modern and Quaternary atlases (Institute of Botany and South China Institute of Botany, 1982; Wang et al., 1995; Tang et al., 2016). For each sample, 150–300 grains were counted because of the low concentration in some samples. The pollen concentration was calculated by adding Lycopodium spores to each sample as a marker. Pollen percentages for trees, shrubs, and upland herbs were calculated based on the terrestrial pollen taxa, and the pollen percentages for wetland herbs and fern spores were calculated based on the sums of all counted palynomorphs.

Poaceae pollen was divided into two size categories (<37 μm and >37 μm), and the larger size category (>37 μm) was identified as the cultivated crop (Tweddle et al., 2005). The pollen diagrams were constructed with Tilia 2.0 software. A stratigraphically constrained cluster analysis was applied by CONSISS incorporated in Tilia 2.0 to help pollen zonation, combined with the analysis of the archaeological cultural layers.

Charcoal in each sample was counted following the method of Millspaugh and Whitlock (1995). Two size categories, macro-charcoal (>125 μm) and micro-charcoal (<125 μm), were identified to indicate local and regional fires, respectively (Carcaillet et al., 2001).

RESULTS

Lithology and Chronology

We divided the lower 85 cm section of the Hejia profile into four parts according to the soil properties and cultural attributes of the strata, as determined by archaeological teams from Nanjing University and Ningbo Municipal Institute of Cultural Heritage Management. From the bottom to the top, zone 1 (140–103 cm) consists of white-gray silt clay and belongs to the late Hemudu Culture Period, zone 2 (103–95 cm) consists of red-brown clay silt that belongs to the early Liangzhu Culture Period, zone 3 (95–77 cm) consists of blue-gray silt clay belonging to the middle Liangzhu Culture Period, and zone 4 (77–55 cm) consists of black-brown clay silt that belonging to periods from the late Liangzhu Culture to the Qianshanyang Culture.

The ^{14}C dating results are shown in **Table 1** and **Figure 2A**. Two of the samples were charcoal, and the other two were pollen concentrates. There are many reasons for the notable deviation of the dating results, such as biological disturbance, cross-contamination of old carbon during sampling, erosion, and re-sedimentation (Stanley and Chen, 2000; Pederson et al., 2005; Liu and Deng, 2009; Liu et al., 2009). When compared with other sites in the vicinity and the archaeological cultural stratification, we observe that the dating results from the pollen concentrates were older, which was speculated to be the influence of "old charcoal" in the organic matter of the sediment. Besides, the problematic dating data might also be caused by human activities due to the archaeological site selected in this study.

Previous studies demonstrate that the late Hemudu Culture developed from 6,000 to 5,000 cal a BP, the Liangzhu Culture ranged from 5,000 to 4,300 cal a BP (Liu et al., 2016; He et al., 2020a), and the Qianshanyang Culture ranged from 4,300 to 4,100 cal a BP (Hou, 2016). Compared with the dating results of nearby sites in the study area, we find that the corresponding age of the strata all had the phenomenon of some errors or age inversion due to the difference in dating materials. But overall, the basic framework of the strata is correct. The dating results of the samples of HJ 100–101 and HJ 110–111 are 5,294–5,039 cal a BP and 5,088–4,960 cal a BP, respectively, and are consistent with the late Hemudu Culture. When compared with the strata of nearby sites and with the stratification of archaeological cultures (**Figure 2**), it can be observed that the Hejia Site belongs to the sedimentary strata of the Middle Holocene.

Pollen Assemblage

A total of 53 pollen taxa (genera and family) were identified including 30 arboreal taxa, 18 herbaceous taxa, and 5 fern taxa. No algae were found. The pollen assemblages of the Hejia profile can be divided into four pollen zones from the bottom to the top. The divisions are based on the sediment and cluster analysis of pollen using CONISS by Tilia 2.0 software and the chronological framework of the Hejia Site established by archaeological cultural dating (**Figure 3**).

Zone I (140–103 cm, the Hemudu Culture Period IV): the trees and shrubs accounted for 35.7% (average) and were dominated by the evergreen *Quercus* (17.6%), *Castanopsis* (1.93%), deciduous *Quercus* (1.1%), and *Pinus* (4.85%). The proportion of upland herbs (64.3%) exceeded that of the trees

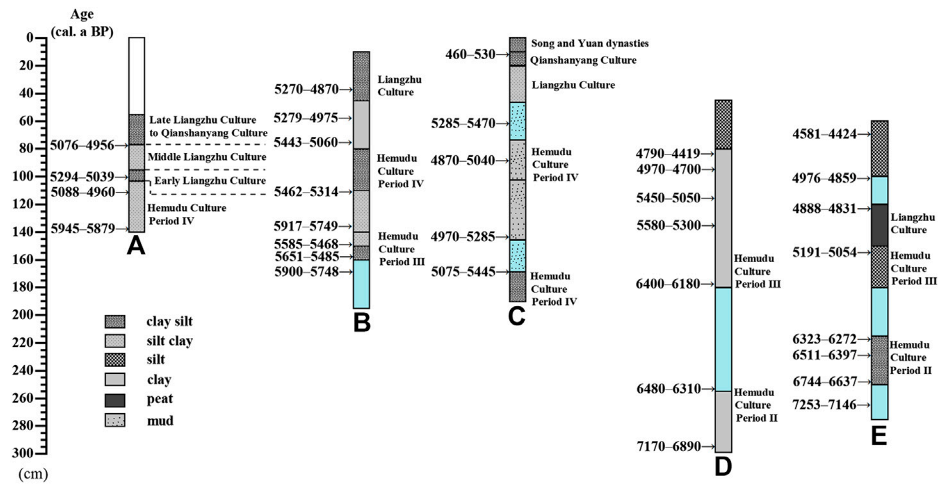

FIGURE 2 | Comparisons of the litho-chronostratigraphy and archaeological layers in this study area: **(A)** the Hejia Site (this study), **(B)** the profile T0602W of the Xiawangdu Site (He et al., 2020a), **(C)** the profile T0103W of the Xiawangdu Site (Huang et al., 2021), **(D)** the Tianluoshan Site (Zheng, et al., 2012), and **(E)** the Yushan Site (He et al., 2018). The marine intrusion or extreme event is displayed in blue shadow according to the references (Zheng, et al., 2012; He et al., 2018; He et al., 2020a; Huang et al., 2021).

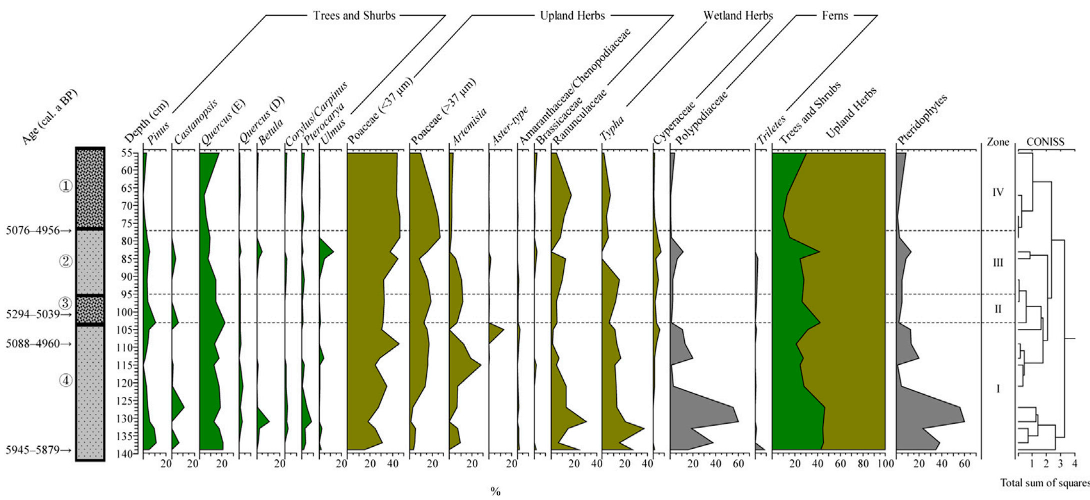

FIGURE 3 | Sporopollen percentage of the Hejia Site. ① the late Liangzhu Culture to the Qianshanyang Culture Period, ② the middle Liangzhu Culture Period, ③ the early Liangzhu Culture Period, and ④ the Hemudu Culture Period IV.

and shrubs and was mainly composed of Poaceae, *Artemisia*, and Ranunculaceae. Poaceae was dominated by the smaller size category (<37 μm, 28%) and exhibited an increasing trend. The larger size category of Poaceae (>37 μm) accounted for 9.6%. Ranunculaceae accounted for 11.7%. Wetland herbs were mainly composed of *Typha* (17.6%), and the ferns were dominated by Polypodiaceae (23.6%).

Pollen zone II (103–95 cm, the early Liangzhu Culture Period): the proportion of trees and shrubs (34.2%) decreased. Evergreen *Quercus,* deciduous *Quercus,* and *Pinus* accounted for 18.7%, 0.9%, and 7.3%, respectively. Poaceae was the main species of upland herbs. Compared with Zone I, Poaceae (<37 μm and >37 μm) increased, accounting for 32.1% and 15.8%, respectively. Ranunculaceae decreased to 4.7%. *Typha* (9.2%) was the dominant wetland herb, and ferns (3.3%) accounted for a relatively small proportion.

Pollen zone III (95–77 cm, the middle Liangzhu Culture Period): trees and shrubs decreased by approximately 6.6% compared with the former zone. Evergreen *Quercus* and *Pinus* fell to 10.1% and 4.0%, respectively. *Ulmus* increased to 4.5%. The upland herbs (72.4%) were dominated by Poaceae, with a greater increase in smaller-sized Poaceae (<37 μm, 40.4%). Brassicaceae increased to 1.0%, and Ranunculaceae increased to 7.6%. The wetland herbs were mainly composed of Cyperaceae and *Typha* and accounted for 4.5% and 5.2%, respectively. Ferns were dominated by Polypodiaceae (5.4%).

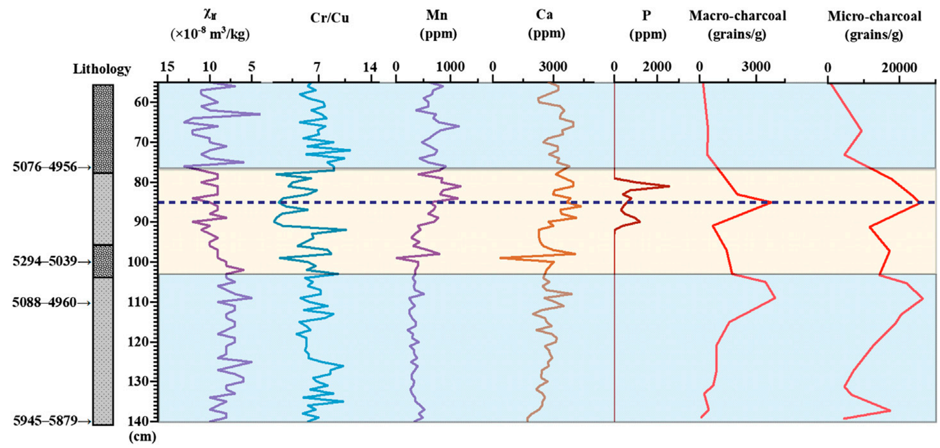

FIGURE 4 | The low-frequency magnetic susceptibility (χ_{lf}), XRF scanning results (Cr/Cu, Mn, Ca, and P), concentrations of macro-charcoal and micro-charcoal in profile T0103 of the Hejia Site.

Zone IV (77–55 cm, the late Liangzhu Culture to the Qianshanyang Culture Period): trees and shrubs (17.8%) decreased significantly and then increased. Evergreen *Quercus* showed an increasing trend. The proportion of upland herbs increased to 82.2%. Smaller-sized Poaceae (<37 μm) increased by 4%, while there was a downward trend in larger-sized Poaceae (>37 μm). Brassicaceae, *Artemisia*, and Ranunculaceae accounted for 1.1%, 2.7%, and 11.2%, respectively. *Typha and* Polypodiaceae accounted for 4.1% and 1.7%, respectively.

Magnetic Susceptibility, XRF, and Charcoal Analysis

Based on the variations in magnetic susceptibility, high-resolution XRF elemental records of Cr/Cu, Mn, Ca, P, and charcoal concentration, combined with archaeological and cultural stratification, the profile can be divided into four stages from the bottom to the top (**Figure 4**).

Stage I (140–103 cm, the Hemudu Culture Period IV): the χ_{lf} was initially at a low level of 7.76×10^{-8} m^3/kg and then increased slightly. The Cr/Cu value was high (6.5) initially and then decreased where the relative values of Mn and P were 339 and 0 ppm, respectively. The Ca value fluctuated near the average value of 2,600 ppm and then experienced a small growth. The average value of the micro-charcoal concentration was 13,901 grains/g, with two successive peaks at 137 and 109 cm. The average value of the macro-charcoal concentration was 1,478 grains/g and gradually reached the highest point at 109 cm. The average value of the micro-charcoal concentration was 14,051 grains/g.

Stage II (103–95 cm, the early Liangzhu Culture Period): the average value of χ_{lf} was 8.4×10^{-8} m^3/kg, with an upward trend. The values of Cr/Cu, Mn, and Ca fluctuated substantially. The relative value of P was 0 ppm. The average values of the micro-charcoal and macro-charcoal concentrations were 15,797 and 1,579 grains/g, respectively, and both of them displayed an overall upward trend.

Stage III (95–77 cm, the middle Liangzhu Culture Period): the value of χ_{lf} (9.8×10^{-8} m^3/kg) was high. Cr/Cu was at a low value of 4.1. Mn and Ca values were 670 and 3,056 ppm, respectively, and both of them are relatively high. The peak P value was 551 ppm in the profile. The trends of the micro-charcoal and macro-charcoal concentrations were the same and simultaneously peaked at 85 cm.

Stage IV (77–55 cm, the late Liangzhu Culture to the Qianshanyang Culture Period): the value of χ_{lf} (10×10^{-8} m^3/kg) was still high. Cr/Cu was 7.2. Mn and Ca values were 681 and 3,180 ppm, respectively. The P value was low. The micro-charcoal and macro-charcoal concentrations were 4,970 and 353 grains/g, respectively, both of which are low with minor fluctuations.

DISCUSSION

Vegetation and Climate Background of the Hejia Site During the Middle Holocene

Previous studies show that the transgression during the Hemudu Culture IV (5,000–5,500 cal a BP) subsided, and the Ningshao Plain was in a freshwater environment (**Figure 2**) (He et al., 2020a; Wang et al., 2020), which provided an inhabitable environment for the development of the Hemudu Culture. Pollen data from the Hejia Site show that terrestrial herbs were the overwhelmingly dominant species. In the palynological analysis, arboreal pollen is generally used to reconstruct regional vegetation, while herbaceous pollen can represent local ones (Shu, 2007). The sporopollen assemblage from the sites is characterized by a high proportion of herbs, which is suitable for the reconstruction of local vegetation and the living environment of prehistoric ancestors (Shu, 2007). The trees and shrubs in the Hejia Site were dominated by *Quercus* (E), *Castanopsis*, and *Quercus* (D), which reflects that the vegetation in the study area during the Hemudu Culture IV was evergreen and deciduous broad-leaved mixed forest, and the pollen

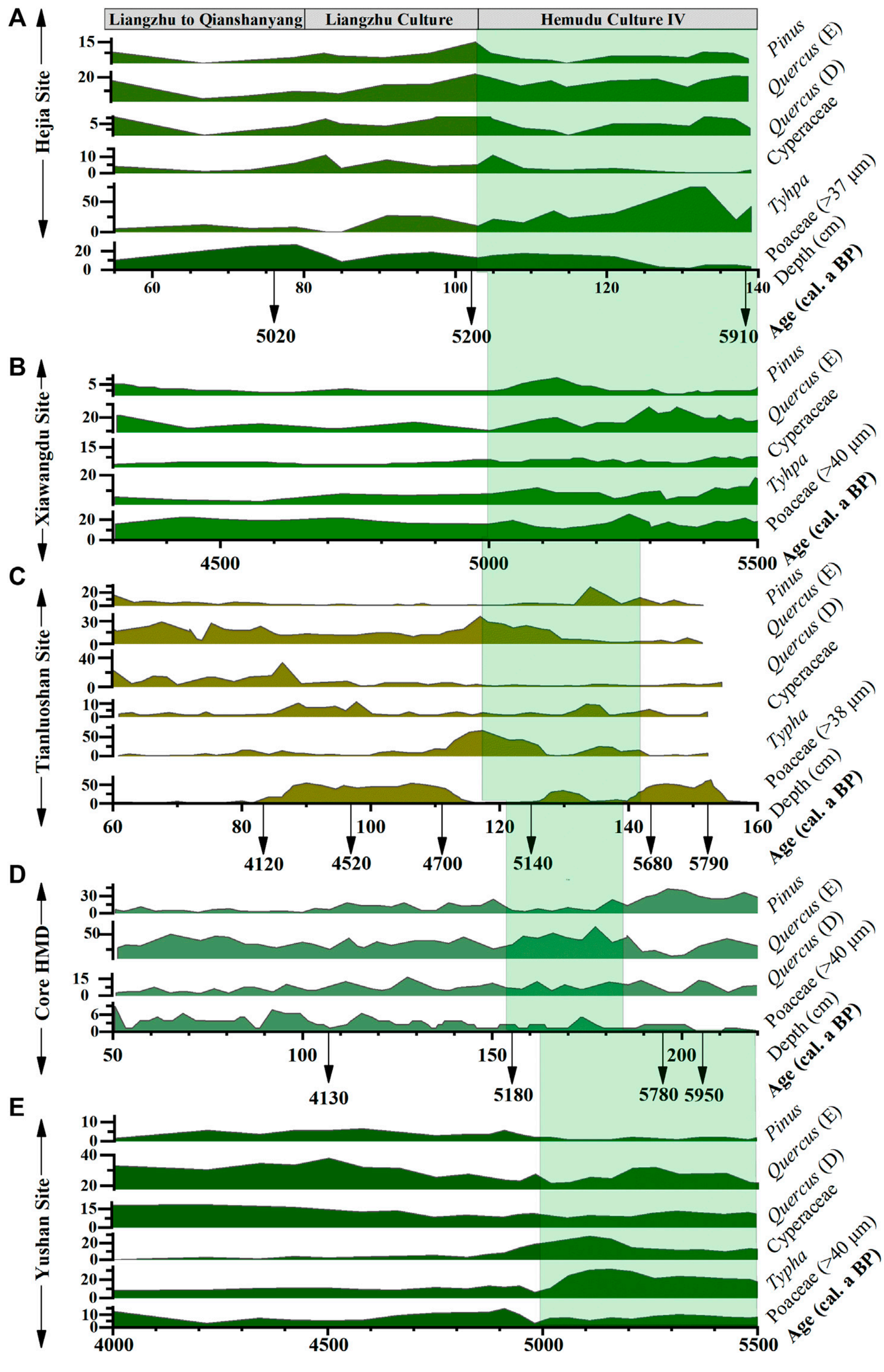

FIGURE 5 | Pollen record comparisons from the nearby sites and core. **(A)** the Hejia Site (this study), **(B)** the Xiawangdu Site (He, et al., 2020a), **(C)** the Tianluoshan Site (Li et al., 2012), **(D)** HMD sediment core (Liu et al., 2016), and **(E)** the Yushan Site (He et al., 2018). Hemudu Culture IV is displayed in green shadow.

composition of evergreen broad-leaved trees was higher. As the super-representation of *Pinus* pollen and the relatively long spreading distance pointed out via previous studies, the low percentage *Pinus* (<20%) in this study is insufficient to indicate the existence of pine forests around it (Xiao, 1996). After comparison, the natural core in the study area (without cultural layers), such as HMD Core where pollen of trees and shrubs was dominated by *Quercus* (E) and *Quercus* (D), also

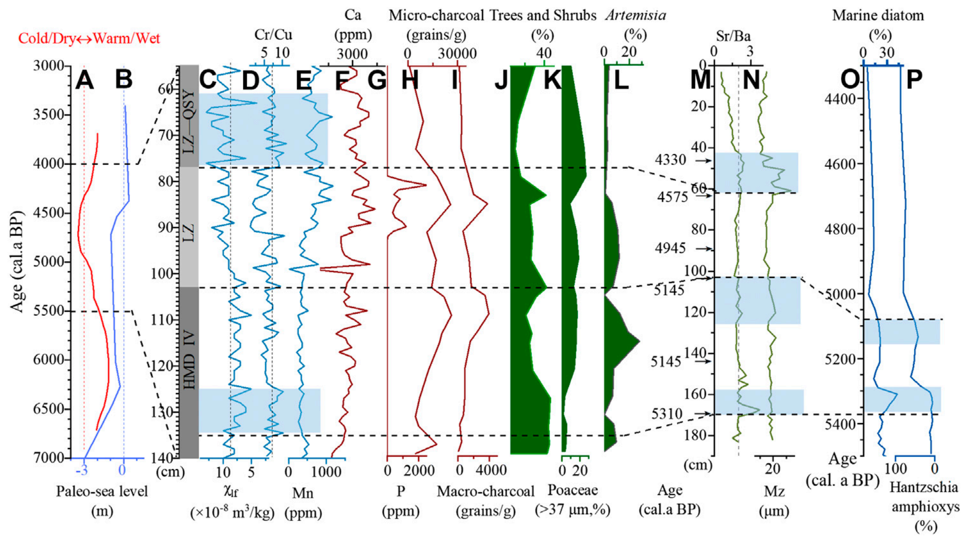

FIGURE 6 | Records of the study area: **(A)** the climate fluctuation curve on the south bank of the Yangtze River Delta (Chen et al., 2005), **(B)** the relative sea-level change in the study area (Wang et al., 2018), and **(C)–(L)** χ_{lf}, Cr/Cu, Mn, Ca, P, micro-charcoal, macro-charcoal concentrations, Tree and Shrubs percentage, Poaceae (>37 μm) and *Artemisia* percentage, respectively (this study). **(M)–(N)** mean grain size (Mz) and Sr/Ba ratios in profile T0103W of the Xiawangdu Site (Huang et al., 2021). **(O)–(P)** the abundances of marine diatoms and the aerophilic freshwater diatom Hantzschia amphioxys in profile T0602W of the Xiawangdu Site (He et al., 2020a).

reveals that the regional vegetation was dominated by evergreen and deciduous broad-leaved mixed forest (**Figure 5D**) (Liu et al., 2016). During the early Hemudu Culture IV, the Poaceae pollen (<37 μm) at the Hejia Site was dominant, and the proportion of *Typha* and Polypodiaceae reached the peak. The sporopollen data of the sites near the Hejia Site show that *Typha* and Cyperaceae were relatively high (**Figure 5**). Furthermore, Huang et al. (2021) infer that the Neolithic Hemudu people at the Xiawangdu Site were located in the low-salinity backswamp based on the analysis of organic and alkaline-earth metal geochemistry of the Xiawangdu Site. The χ_{lf} value of this layer was at a low level (**Figure 6**). Balsam et al. (2011) reveal that on a worldwide basis, magnetic susceptibility (MS) of soils increases with increasing average annual precipitation (AAP) from about 200 mm to 1,100–1,200 mm, and it decreases as AAP increases up to about 1,200 mm. And, studies also show that magnetic susceptibility (MS) in the area south of the Yangtze River decreases as AAP increases up to about 1,100 mm, 12°C, respectively (Han et al., 1996; Gu et al., 2019). The correspondence between surface soil magnetic susceptibility and modern climate has been well applied to the paleoenvironment (Lu et al., 1994). According to Li and Yang's (2001) research on the Xiashu loess profile, the MS value of the sediment was reduced under a hot and humid climate. The average annual temperature and AAP of the study area are approximately 16.3°C and 1,400 mm, respectively (Zheng et al., 2016). Therefore, the low value of χ_{lf} in this profile of the Hejia Site indicates a warm and humid climate rather than a cold and dry climate. The Cr/Cu value is the maximum value of the entire profile. Previous studies show that the change of Cr/Cu has universal significance as an indicator of the environment humidity changes, and the high value of Cr/Cu indicates a humid environment and vice versa (Li et al., 2008, Li et al., 2017). Therefore, the high value of Cr/Cu and the low value of χ_{lf} at the Hejia Site reflect the relatively humid environment in this period. We speculate that the study area may be in a freshwater marsh environment during this period, and the environment is relatively humid. During the late Hemudu Culture IV in the Hejia Site, Poaceae pollen (<37 μm) still possessed an advantage. Meanwhile, the proportions of *Typha* and Polypodiace declined rapidly, and the proportion of Poaceae pollen (>37 μm) and *Artemisia* increased significantly, which reflects that the environment of the Hejia Site may be transformed from a freshwater marsh to grassland in this period. At the same time, the Cr/Cu value decreased and χ_{lf} increased, suggesting that the climate became dry and cool during the late Hemudu Culture IV at the Hejia Site. The multiple indicators of the Hejia Site profile indicate that the study area has extensive vegetation coverage under the warmer and humid climate, with a shift to a cool and dry trend during the Hemudu Culture IV.

During the Liangzhu Culture Period (5,000–4,300 cal a BP), the trees and shrubs in the Hejia Site were still dominated by *Quercus* (E), *Castanopsis*, and *Quercus* (D). The proportion of them decreased significantly, yet the content of *Pinus* increased. The pollen records of the nearby sites and natural core during this period also reflect that *Quercus* (E) decreased as a whole during the early Liangzhu Culture (**Figure 5**). Also, pollen record from Chaohu Lake adjacent to the study area reveals the characteristics of climate cooling after 4,860 cal a BP (Wang et al., 2008). The changes in palynological content during this period reflect that the Liangzhu Culture was in the context of the overall cool climate. Compared with the former stage, the Cr/Cu value reduced, and the χ_{lf} value increased significantly, which together reflect that the climate turned dry during the Liangzhu Culture. Mn, which is mainly enriched in an oxidizing environment, was at a high level during this period. The well consistency between the oxide layer and the peak of Mn indicates the long-time exposure of the strata during the Liangzhu Culture Period (Yao, 2016; Huang et al., 2019). Statistic analysis shows that the number of water wells from the Yangtze River Delta reached its peak at about 134 during the Liangzhu Culture Period (Gao, 2003; Wu and Xu, 2009). This trend was in agreement with our study, reflecting the relatively low water level and relatively dry climate in the study area during the Liangzhu Culture.

From the late Liangzhu Culture to the Qianshanyang Culture when the rising sea-level rose (**Figure 6B**), the percentage of trees and shrubs at the Hejia Site decreased at first and then increased. The regional vegetation type was still evergreen and deciduous broad-leaved mixed forest, and the proportion of *Quercus* (E) generally increased. *Quercus* (E) from the nearby sites also increased, which reveals that the climate was warmer in the study area. Cr/Cu value increased sharply and then showed a downward trend, reflecting a gradual decrease after a sudden increase in humidity. Two valleys appeared in the χ_{lf} values fluctuating substantially, which suggests that the violent climate change to warm and humid. Furthermore, the high value of Sr/Ba and mean grain size (Mz) of profile T0103W of Xiawangdu profile indicate the occurrence of high-energy events during the late Liangzhu Culture (**Figure 6**), providing evidence for this study. No storm deposits during the late Liangzhu Culture are identified in profile T0602W of Xiawangdu profile, owing to its higher elevation at that time (Huang et al., 2021). The increasing frequency of natural disasters, as a result of sea-level rise in the late Liangzhu Culture Period, led to the demise of the Liangzhu civilization (Zhang et al., 2004; Zhu et al., 2011). We propose that the disappearance of the Liangzhu Culture was caused by sea-level rise and extreme weather events.

Human Activities in Relation to Environment Change at the Hejia Site during the Middle Holocene

During the Hemudu Culture IV, the influence of seawater in the Ningshao Plain subsided. Therefore, the study area was in a freshwater environment with a large amount of bare ground (**Figure 2**, **6B**), providing a broader space for human activities. The Hemudu Culture's subsistence strategy transitioned from gathering and hunting to an agricultural economy (Zheng et al., 2019). The domestication of rice was completed during the late Hemudu Culture (He et al., 2020a; He et al., 2018). Established in the context of freshwater marsh, the Hejia Site is conducive to rice cultivation (Ma et al., 2020). Because the pollen structure of rice is similar to other grasses and hard to distinguish, there are differences from the perspective of identification, which also leads to different standards for the identification of the cultivated rice in the study of archaeological sites. Tweddle et al. (2005) evaluate and analyze the pollen in Yorkshire during the Holocene and conclude that Poaceae pollen (>37 μm) has a certain correlation with prehistoric agricultural activities. Charcoal, as a record of fire events, provides useful information for reconstructing human activities (Zhang and Lu, 2006; Scott, 2010; Liu et al., 2020). The increase in the charcoal concentration indicates intensified fire events and vice versa (Zhang and Lu, 2006). During the early Hemudu Culture IV, the proportion of Poaceae (>37 μm) and the concentration of the macro-charcoal of the Hejia Site were extremely low, which reveals the low intensity of human activity. Previous research reveals that an extreme storm event happened in the Xiawangdu Site during the early Hemudu Culture IV due to the peak value of Sr/Ba ratio coincident with the increase in marine diatoms and reduction in the abundance of Hantzschia amphioxys in the profile of the Xiawangdu Site (**Figure 6**) (He et al., 2020a; Huang et al., 2021). Therefore, we speculate that extreme storm events may impede the process of daily activities and rice cultivation of the prehistoric ancestors at the Hejia Site. During the late Hemudu Culture IV, the steep increase in the larger size Poaceae (>37 μm) corresponding to the increasing *Artemisia*, indicating that the area was in the vicinity of paddy fields (Ma et al., 2020). At around 5,230–5,150 cal a BP, the sedimentary record of the Xiawangdu Site showed a relatively short extreme storm event, but there was no relevant evidence in the Hejia Site. We suggest that the Hejia Site may be located relatively further from the river and was not been affected by it. The higher concentration of charcoal corresponding to the decreasing proportion of trees and shrubs also substantiates our assumption. The regular rice cultivation method in the Middle Holocene in the Yangtze River Delta was slash-and-burn (Zong et al., 2007; Shu et al., 2010). Because of the warm and humid climate during this period, the wildfire incidents were infrequent. Therefore, it could be the direct result of the slash-and-burn operation that the increase in charcoal concentration (micro and macro), the decreasing percentage of trees and shrubs, and the increasing percentage of Poaceae (>37 μm). Compared with the proportion of rice pollen in the nearby sites (**Figure 5**), the proportion of rice was generally not high. Besides, the Chenghu Site in the Taihu area is a Songze Culture site at the same time as the Hemudu Culture IV, and the discovery of the rice field at this site provides evidence for the prehistoric people in the Yangtze River Delta to master rice cultivation during that period (Ding and Zhang, 2004). We speculate that the Hemudu ancestors basically mastered rice cultivation, and rice was one of the food sources during the Hemudu Culture IV.

The early and middle Liangzhu Culture was the heyday of the Liangzhu Culture. Studies show that the prosperity occurred when the sea-level was lower and the climate was cool and dry (Chen et al., 2005; Wang et al., 2018). During this period, human beings gained a spacious living field, and the development of the Liangzhu Culture reached its peak. Poaceae was identified as the cultivated crop and accounted for an overall high pollen proportion in the area (**Figure 5**), which reveals that there was mature rice farming during the early and middle Liangzhu Culture (Li et al., 2012; He et al., 2018, He et al., 2020a). Additionally, studies show that the abnormally high P value in the paleostratigraphic deposits might be caused by the accumulation of kitchen debris and other residues that can be used to indicate the living areas of prehistoric humans or indicate that the site was proximal to the living area (Dong et al., 2007; Arrhenius, 2010). In the early and middle Liangzhu Culture, the Ca and P values indicating the intensity of human activities were high. Studies show that the high value of Ca in the stratum of the archaeological sites might be caused by human and animal bones and their excrement (Ma et al., 2006; Li et al., 2017). The

P value, especially, suggests that this was a residential zone of the Liangzhu ancestors. Meanwhile, the macro-charcoal concentration reached its peak, revealing that the fire intensity related to the activities of human life and production was relatively high. Slash-and-burn was the common rice cultivation method in the Yangtze River Delta during the Middle Holocene (Zong et al., 2007), but it appears that the concentration of charcoal peaks at the same time when the percentage of Poaceae (>37 μm) reached the lowest point during the middle Liangzhu Culture speculated that those paddy fields were far from here due to the expansion of human residential areas in this period.

From the late Liangzhu Culture to the Qianshanyang Culture, the climate fluctuated obviously, and the sea-level began to rise (**Figure 6**), which may lead to frequent extreme events. The proportion of larger-sized Poaceae (>37 μm) pollen showed a downward trend, and the concentrations of micro-charcoal and macro-charcoal were lower. The trends suggest a lower intensity of human activities and further indicate that the organization and development of the Qianshanyang Culture were relatively lower than those of the Liangzhu Culture (Xu, 2015).

CONCLUSION

In this study, pollen, charcoal, XRF, and magnetic susceptibility analysis were carried out on the T0103 profile of the Hejia Site, and the conclusions are as follows:

1 A suitable natural environment laid the foundation for the development and the prosperity of the prehistoric culture in the Middle Holocene in the study area. The Middle Holocene vegetation mainly consisted of evergreen and deciduous broad-leaved mixed forests. The climate experienced the warm and wet (Hemudu Culture Period IV)–cool and dry (Liangzhu Culture Period)–warm and wet (Qianshanyang Culture) periods.

2 It is supported by combined human activity proxy indicators including Ca, P, larger-sized Poaceae (>37 μm) pollen, and charcoal concentrations that the enhanced ability of humans to manage crop fields from the late Hemudu Culture Period to the Liangzhu Culture Period. At the Hejia Site, the occurrence of high-intensity fire events during the late Hemudu Culture Period might be caused by slash-and-burn operations, while those that occurred during the middle Liangzhu Culture Period might be caused by the increasing fire demand owing to the greater ancestors' lives and production activities.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**; further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

CM and DZ designed the research. HL, JS, and CM completed writing. YL, FD, and DZ completed the excavation and archaeological cultural dating of the Hejia Site. HL, JS, JS, ZH, GS, and YD completed the experiment, data analysis and sampling in the field.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2020.609912/full#supplementary-material.

REFERENCES

An, Z. S., Porter, S. C., Kutzbach, J. E., Wu, X. H., Wang, S. M., Liu, X. D., et al. (2000). Asynchronous Holocene optimum of the east asian monsoon. *Quat. Sci. Rev.* 19, 743–762. doi:10.1016/S0277-3791(99)00031-1

Arrhenius, O. (2010). Chemical denudation in Sweden. *Tellus* 6, 326–341. doi:10.1111/j.2153-3490.1954.tb01128.x

Balsam, W. L., Ellwood, B. B., Ji, J. F., Williams, E. R., Long, X. Y., and El Hassani, A. (2011). Magnetic susceptibility as a proxy for rainfall: worldwide data from tropical and temperate climate. *Quat. Sci. Rev.* 30, 2732–2744. doi:10.1016/j.quascirev.2011.06.002

Cai, T. S., Zhu, C., Sun, Z. B., Zheng, C. G., Ma, C. M., Zhu, G. Y., et al. (2017). Palaeoenvironments of Holocene archaeological sites in the Yangtze gorges area. *J. Stratigr.* 41, 32–38.

Carcaillet, C., Bouvier, M., Frechette, B., Larouche, A. C., and Richard, P. J. H. (2001). Comparison of pollen-slide and sieving methods in lacustrine charcoal analyses for local and regional fire history. *Holocene* 11, 467–476. doi:10.1191/095968301678302904

Chen, Z. Y., Wang, Z. H., Schneiderman, J., Tao, J., and Cai, Y. L. (2005). Holocene climate fluctuations in the Yangtze delta of eastern China and the

Neolithic response. *Holocene* 15, 915–924. doi:10.1191/0959683605hl862rr

Chen, J. (2006). Initial comment on Guangfulin culture. *Cultural Relics in Southern China* 53–63. doi:10.3969/j.issn.1004-6275.2006.04.011

Ding, J. L., and Zhang, T. J. (2004). Rice paddy of Songze culture unearthed at Chenghu site. *China Cult. Herit* 1, 70–71.

Dong, G. H., Xia, Z. K., Liu, D. C., Wu, Q. L., and Wang, Z. T. (2007). The impact of human activities on the chemical properties of paleosol in Mengjin, Henan Province during civilization. *J. Lanzhou Univ.* 43, 6–10. doi:10.3321/j.issn:0455-2059.2007.01.002

Gao, M. H. (2003). *An environmental study on the lower reaches of the Yangtze River based on archaeological sequence*. PhD dissertation. Shanghai (China): Fudan University.

Gu, Y. J., Li, Y. M., Han, L., and Su, X. (2019). Relationships between surface soil magnetic susceptibility and modern climatic factors in eastern China and their environmental significance. *J. Univ. Chin. Aca. Sciences* 36, 498–509.

Han, J. M., Lu, H. Y., Wu, N. Q., and Guo, Z. T. (1996). The magnetic susceptibility of modern soils in China and its use for paleoclimate reconstruction. *Studia Geophys. Geod.* 40, 262–275. doi:10.1007/BF02300742

He, K. Y., Lu, H. Y., Zheng, Y. F., Zhang, J. P., Xu, D. K., Huan, X. J., et al. (2018). Middle-Holocene sea-level fluctuations interrupted the developing Hemudu culture in the lower Yangtze River, China. *Quat. Sci. Rev.* 188, 90–103. doi:10.1016/j.quascirev.2018.03.034

He, K. Y., Lu, H. Y., Li, Y. N., Ding, F. Y., Zhang, J. P., and Wang, C. (2020a). Cultural response to Middle Holocene sea-level fluctuations in eastern China: a multi-proxy approach. *Boreas* 49, 71–88. doi:10.1111/bor.12421

He, K. Y., Lu, H. Y., Zheng, H. B., Yang, Q., Sun, G. P., Zheng, Y. F., et al. (2020b). Role of dynamic environmental change in sustaining the protracted process of rice domestication in the lower Yangtze River. *Quat. Sci. Rev.* 242, 106456. doi:10.1016/j.quascirev.2020.106456

Hou, N. N. (2016). *A study on the Qianshanyang culture*. PhD dissertation. Changchun (China): Jilin University.

Huang, X. R., Zheng, H. B., Hu, Z. J., Yang, Q., Sun, G. P., Ling, G. J., et al. (2019). The changes of hydrological environment recorded in the section of Tianluoshan Site in Zhejiang Province. *Chin. Sci. Bull.* 64, 963–976.

Huang, J., Li, Y. N., Ding, F. Y., Zheng, T. T., Meadows, M. E., and Wang, Z. H. (2021). Sedimentary records of mid-Holocene coastal flooding at a Neolithic site on the southeast plain of Hangzhou Bay, east China. *Mar. Geol.* 431. doi:10.1016/j.margeo.2020.106380

Innes, J. B., Zong, Y. Q., Wang, Z. H., and Chen, Z. Y. (2014). Climatic and palaeoecological changes during the mid-to-Late Holocene transition in eastern China: high-resolution pollen and non-pollen palynomorph analysis at Pingwang, Yangtze coastal lowlands. *Quat. Sci. Rev.* 99, 164–175. doi:10.1016/j.quascirev.2014.06.013

Institute of Botany and South China Institute of Botany (1982). *Angiosperm pollen flora of tropical and subtropical China*. Beijing, China: Science Press.

Kajita, H., Kawahata, H., Wang, K., Zheng, H. B., Yang, S. Y., Ohkouchi, N., et al. (2018). Extraordinary cold episodes during the mid-Holocene in the Yangtze delta: interruption of the earliest rice cultivating civilization. *Quat. Sci. Rev.* 201, 418–428. doi:10.1016/j.quascirev.2018.10.035

Li, X. S., and Yang, D. Y. (2001). Magnetic susceptibility records of the Xiashu loess since S2 and their comparisons with the marine oxygen isotope records. *Journal of Nanjing University (Natural Sciences)* 37, 766–772. doi:10.3321/j.issn:0469-5097.2001.06.018

Li, C. H., Zhang, G. Y., Yang, L. Z., Lin, X. G., Hu, Z. Y., Dong, Y. H., et al. (2007a). Pollen and phytolith analyses of ancient paddy fields at Chuodun site, the Yangtze River Delta. *Pedosphere* 17, 209–218. doi:10.1016/S1002-0160(07)60027-7

Li, Y. Y., Wei, F., and Zhou, L. P. (2007b). AMS 14C dating using bulk samples, plant residues and pollen concentrates from a peat profile at Kulun, Inner Mongolia. *Quat. Sci.* 27, 499–506. doi:10.3321/j.issn:1001-7410.2007.04.004

Li, Z. X., Zhu, C., Zhu, Q., Ma, C. M., Zhang, G. S., and Ou, Y. J. (2008). Variation of Cr/Cu ratios in Zhongba profile and its indication on palaeoenvironment over last 5 ka. *Sci. Geogr. Sin.* 799–803. doi:10.3969/j.issn.1000-0690.2008.06.015

Li, Y. Y., Hou, S. F., and Mo, D. W. (2009). Records for pollen and charcoal from Qujialing archaeological site of Hubei and ancient civilization development. *J. Palaeogeogr.* 11, 702–710. doi:10.7605/gdlxb.2009.06.011

Li, M. L., Mo, D. W., Mao, L. J., Sun, G. P., and Zhou, K. S. (2010a). Paleosalinity in the Tianluoshan site and the correlation between the Hemudu culture and its environmental background. *J. Geogr. Sci.* 20, 441–454. doi:10.1007/s11442-010-0441-1

Li, X. Q., Ji, M., Zhou, X. Y., Zhao, K. L., Sun, N., and Yang, Q. (2010b). Records of element geochemistry on human activity during 3700 ~ 3400 cal BP at Donghuishan Site, Gansu, China. *Journal of Earth Environment* 1, 48–51.

Li, Y. Y., Wu, J., Hou, S. F., Shi, C. X., Mo, D. W., and Liu, B. (2010c). Palaeoecological records of environmental change and cultural development from the Liangzhu and Qujialing archaeological sites in the middle and lower reaches of the Yangtze River. *Quat. Int.* 227, 29–37. doi:10.1016/j.quaint.2010.05.015

Li, C. H., Zheng, Y. F., Yu, S. Y., Li, Y. X., and Shen, H. D. (2012). Understanding the ecological background of rice agriculture on the Ningshao Plain during the Neolithic Age: pollen evidence from a buried paddy field at the Tianluoshan cultural site. *Quat. Sci. Rev.* 35, 131–138. doi:10.1016/j.quascirev.2012.01.007

Li, Z. X., Wu, G. X., Sun, Y. L., Zhang, M., and Gu, L. (2017). Environmental and anthropogenic records of late longshan period at the wadian site. *Mar. Geol. Quat. Geol.* 180–186.

Liu, Q. S., and Deng, C. L. (2009). Magnetic susceptibility and its environmental significances. *Chin. J. Geophys.* 52, 1041–1048. doi:10.3969/j.issn.0001-5733.2009.04.021

Liu, J. F., Chen, J., Lei, S. X., and Hou, K. M. (2009). Preliminary dating results for Qianhuai palaeochannel sediments in Nanjing city. *Quat. Sci.* 837–844. doi:10.3969/j.issn.1001-7410.2009.04.21

Liu, Y., Sun, Q. L., Fan, D. D., Lai, X. H., Xu, L. C., Finlayson, B., et al. (2016). Pollen evidence to interpret the history of rice farming at the Hemudu site on the Ningshao coast, eastern China. *Quat. Int.* 426, 195–203. doi:10.1016/j.quaint.2016.05.016

Liu, Y., Sun, Q. L., Fan, D. D., Dai, B., Ma, F. W., and Xu, L. C. (2018). Early to middle Holocene sea level fluctuation, coastal progradation and the neolithic occupation in the Yaojiang Valley of southern Hangzhou Bay, eastern China. *Quat. Sci. Rev.* 189, 91–104. doi:10.1016/j.quascirev.2018.04.010

Liu, R., Mei, X., Zhang, J., and Zhao, D. B. (2019). Characteristics of clay minerals in sediments of Hemudu area, Zhejiang, China in Holocene and their environmental significance. *China Geology* 2, 8–15. doi:10.31035/cg2018069

Liu, Y., Deng, L. J., He, J., Jiang, R., Fan, D. D., Jiang, X. Z., et al. (2020). Early to middle Holocene rice cultivation in response to coastal environmental transitions along the South Hangzhou Bay of eastern China. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 555, 109872. doi:10.1016/j.palaeo.2020.109872

Lu, H. Y., Han, J. M., Wu, N. Q., and Guo, Z. T. (1994). Analysis of surface soil magnetic susceptibility in China and their paleoclimatic significance. *Science China* 24, 1290–1297.

Luo, P., and Zhao, D. S. (2019). Excavation report on Hejia site in Fenghua, Ningbo, Zhejiang. *Cult. Rel. in South. China* 1, 56–73.

Luo, W. G., Song, G. D., Hu, Y. Q., and Chen, D. (2020). Tentative determination of a special bronze material by multiple technological test on a xuan-liu dagger-axe from the Xujialing Site, the Eastern Zhou period, Henan Province, China. *J. Cult. Herit*. doi:10.1016/j.culher.2020.06.016

Ma, C. M., Zhu, C., Zhu, G. Y., Wang, J. H., Huang, R., and Gu, W. W. (2006). Magnetic susceptibility and elemental geochemistry analysis of the archaeological strata at the Yuchisi site, Anhui. *J. Stratigr*. doi:10.1007/s11442-006-0415-5

Ma, T., Rolett, B. V., Zheng, Z., and Zong, Y. Q. (2020). Holocene coastal evolution preceded the expansion of paddy field rice farming. *Proc. Natl. Acad. Sci. Unit. States Am.* doi:10.1073/pnas.1919217117

Millspaugh, S. H., and Whitlock, C. (1995). A 750-year fire history based on lake sediment records in central Yellowstone National Park, USA. *Holocene* 5, 283–292. doi:10.1177/095968369500500303

Ningbo Chorography Codification Committee (1995). *Ningbo Chorography*. Beijing, China: Zhonghua Book Company.

Moore, P. D., Webb, J. A., and Collinson, M. E. (1991). Pollen analysis. *J. Ecol.* 80, 216. doi:10.2307/2260877

Pederson, D. C., Peteet, D. M., Kurdyla, D., and Guilderson, T. (2005). Medieval warming, little ice age, and European impact on the environment during the last millennium in the lower hudson valley, New York, USA. *Quaternary Research* 63, 238–249. doi:10.1016/j.yqres.2005.01.001

Reimer, P. J., Baillie, M. G. L., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., et al. (2013). Intcal13 and marine13 radiocarbon age calibration curves 0–50 000 years cal BP. *Radiocarbon* 55, 1869–1887. doi:10.1017/S0033822200048864

Scott, A. C. (2010). Charcoal recognition, taphonomy and uses in palaeoenvironmental analysis. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 291, 11–39. doi:10.1016/j.palaeo.2009.12.012

Shu, J. W., Wang, W. M., Jiang, L. P., and Takahara, H. (2010). Early Neolithic vegetation history, fire regime and human activity at Kuahuqiao, Lower Yangtze River, East China: new and improved insight. *Quat. Int.* 227, 10–21. doi:10.1016/j.quaint.2010.04.010

Shu, J. W. (2007). *Holocene vegetation history, environment changes, and human activity in the Taihu Lake area*. PhD dissertation. Nanjing (East China): Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences.

Stanley, D. J., and Chen, Z. Y. (1996). Neolithic settlement distributions as a function of sea level-controlled topography in the Yangtze delta, China. *Geology* 24, 1083–1086. doi:10.1130/0091-7613(1996)0242.3.CO;2

Stanley, D. J., and Chen, Z. Y. (2000). Radiocarbon dates in China's Holocene Yangtze Delta: record of sediment storage and reworking, not timing of deposition. *J. Coast Res.* 16, 1126–1132. doi:10.2307/4300129

Tang, L. Y., Mao, L. M., Shu, J. W., Li, C. H., Shen, C. M., and Zhou, Z. Z. (2016). *Hand of quaternary pollen and spores in China*. Beijing, China: Science Press.

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

Wang, F. X., Qian, N. F., and Yang, H. Q. (1995). *Pollen flora of China*. Beijing, China: Science Press.

Wang, X. Y., Mo, D. W., Wu, L., Zhang, G. S., Xiao, X. Y., and Han, W. G. (2008). Pollen record from Chaohu Lake in the lower reaches of the Yangtze River and environmental changes since 9870 cal. a BP. *Quat. Sci.* 28, 649–658. doi:10.3321/j.issn:1001-7410.2008.04.017

Wang, X. C., Mo, D. W., Li, C. H., Yu, S. Y., Xue, B., Liu, B., et al. (2017). Environmental changes and human activities at a fortified site of the Liangzhu culture in eastern China: evidence from pollen and charcoal records. *Quat. Int.* 438, 189–197. doi:10.1016/j.quaint.2017.05.001

Wang, Z. H., Ryves, D. B., Lei, S., Nian, X. M., Lv, Y., Tang, L., et al. (2018). Middle Holocene marine flooding and human response in the south Yangtze coastal plain, East China. *Quat. Sci. Rev.* 187, 80–93. doi:10.1016/j.quascirev.2018.03.001

Wang, S., Ge, J. Z., Kilbourne, K. H., and Wang, Z. H. (2020). Numerical simulation of mid-Holocene tidal regime and storm-tide inundation in the south Yangtze coastal plain, East China. *Mar. Geol.* 423, 106134. doi:10.1016/j.margeo.2020.106134

Wu, R. Z., and Xu, J. J. (2009). *The rise and fall of Liangzhu Culture*. Beijing, China: Social Sciences Academic Press.

Wu, L., Shao, S. X., Zhou, Y., He, T. T., Zhu, C., Zheng, C. G., et al. (2012). Response of prehistoric culture to climatic environmental changes since Holocene in Zhejiang, east China. *Acta Geograph. Sin.* 67, 903–916. doi:10.11821/xb201207004

Wu, L., Zhu, C., Ma, C. M., Li, F., Meng, H. P., Liu, H., et al. (2017). Mid-holocene palaeoflood events recorded at the Zhongqiao neolithic cultural site in the jianghan plain, middle Yangtze River valley, China. *Quat. Sci. Rev.* 173, 145–160. doi:10.1016/j.quascirev.2017.08.018

Wu, Z. Y. (1980). *The vegetation of China*. Beijing, China: Science Press.

Xia, Z. K., and Zhang, J. N. (2019). The rise, development and outlook of Huanjingkaogu (environmental archaeology in China). *J. Palaeogeogr*. 21, 175–188. doi:10.7605/gdlxb.2019.01.010

Xiao, J. Y. (1996). Analysis of plant pollen and phytolith from the fifth excavation at the Xudun site. *South. Cult*. 1, 47–50.

Xiong, H. X., Zong, Y. Q., Li, T. H., Long, T. W., Huang, G. Q., and Fu, S. Q. (2020). Coastal GIA processes revealed by the early to middle Holocene sea-level history of east China. *Quat. Sci. Rev*. 233, 106249. doi:10.1016/j.quascirev.2020.106249

Xu, Q. H., Yang, Z. J., Cui, Z. J., Yang, X. L., and Liang, W. D. (2002). A study on pollen analysis of Qiguoshan Section and ancestor living environment in Chifeng Area. *Sci. Geogr. Sin*. 22 (4), 453–457. doi:10.3969/j.issn.1000-0690.2002.04.014

Xu, P. F. (2015). The post-liangzhu culture: a discussion based on the features of the late phase of Liangzhu culture. *South. Cult*. 247, 75–85.

Yao, X. Y. (2016). Application of XRF core scanning technology in sea-level change reconstruction during the Holocene in Ningshao Plain. PhD dissertation. Nanjing (China): Nanjing Normal University.

Yu, S. Y., Zhu, C., Song, J., and Qu, W. Z. (2010). Role of climate in the rise and fall of Neolithic cultures on the Yangtze Delta. *Boreas* 29, 157–165. doi:10.1111/j.1502-3885.2000.tb01208.x

Zhang, J. P., and Lu, H. Y. (2006). Preliminary study of charcoal morphology and its environmental significance. *Quat. Sci*. 26, 7. doi:10.3321/j.issn:1001-7410.2006.05.022

Zhang, Q., Jiang, T., Shi, Y. F., King, L., Liu, C. L., and Metzler, M. (2004). Paleo-environmental changes in the Yangtze Delta during past 8000 years. *J. Geogr. Sci*. 14, 105–112. doi:10.1007/BF02873097

Zheng, Y. F., Sun, G. P., and Chen, X. G. (2012). Response of rice cultivation to fluctuating sea level during the Mid-Holocene. *Chin. Sci. Bull*. 57, 370–378. doi:10.1007/s11434-011-4786-3

Zheng, L. B., Hao, X. D., Zhuo, B., Liu, Y. L., Wang, X. L., Zhu, L. X., et al. (2016). Holocene palaeoenvironment evolution and human activity of the hemudu-tianluoshan sites in yuyao of Zhejiang province. *J. Palaeogeogr*. 894. doi:10.7605/gdlxb.2016.05.067

Zheng, X. Q., Lei, S., Wang, J. H., and Zhao, Z. J. (2019). Analysis of flotation results from the Yushan Site in Ningbo city. Agricultural Archaeology 6, 21–27.

Zhu, L. D., Feng, Y. X., Ye, W., Wang, T. Y., Li, F. Q., and Li, L. X. (2011). Culture development and sea-level change during Liangzhu period. *Prog. Geogr*. 30, 121–128.

Zong, Y., Chen, Z., Innes, J. B., Chen, C., Wang, Z., and Wang, H. (2007). Fire and flood management of coastal swamp enabled first rice paddy cultivation in east China. *Nature* 449, 459–462. doi:10.1038/nature06135

Zong, Y. Q., Innes, J. B., Wang, Z. H., and Chen, Z. Y. (2011). Mid-Holocene coastal hydrology and salinity changes in the east Taihu area of the lower Yangtze wetlands, China. *Quaternary Research* 76, 69–82. doi:10.1016/j.yqres.2011.03.005

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Hydroclimate Variability Influenced Social Interaction in the Prehistoric American Southwest

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When droughts and floods struck ancient agrarian societies, complex networks of exchange and interaction channeled resources into affected settlements and migrant flows away from them. Did these networks evolve in part to connect populations living in differing climate regimes? Here, I examine this relationship with a long-term archaeological case study in the pre-Hispanic North American Southwest, analyzing 4.3 million artifacts from a 250-year period at nearly 500 archaeological sites. I use these artifacts to estimate how the flow of social information changed over time, and to measure how the intensity of social interaction between sites varied as a function of distance and several regional drought patterns. Social interaction decayed with distance, but ties between sites in differing oceanic and continental climate regimes were often stronger than expected by distance alone. Accounting for these different regional drivers of local climate variability will be crucial for understanding the social impacts of droughts and floods in the past and present.

Keywords: drought patterns, archaeological networks, spatial interaction model, empirical orthogonal functions, climate risk management

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1 INTRODUCTION

Exchange networks are part of the broad toolkit of social and physical infrastructure humans use to manage environmental risk in social-ecological systems (Anderies, 2015). The environment can structure these exchange networks by influencing the costs and benefits of social interaction. Recent theoretical and empirical work highlights how spatial, social, and environmental factors interact with networks of exchange and interaction (Fafchamps and Gubert, 2007; Bloch et al., 2008; Nolin, 2010; Verdery et al., 2012; Freeman et al., 2014; Koster and Leckie, 2014; Hao et al., 2015; Schnegg, 2015). Distance is a key factor in such systems, making it difficult to monitor conditions in potential migration destinations (Anderies and Hegmon, 2011) and know the resources and reputation of potential interaction partners (Fafchamps and Gubert, 2007), as well as increasing the metabolic costs of transport (Drennan, 1984). For agricultural societies in water-limited environments, hydroclimate variability–changes in the balance of precipitation and evapotranspiration–may be another key factor. The benefits of interacting with others in different drought regimes can outweigh the costs of traveling longer distances. As a consequence, we might expect a greater "investment of social energy in the maintenance of social ties" between populations experiencing poorly or negatively correlated climate variability (Rautman, 1993). Norms and institutions that maintain ties between different climate regimes are likely to evolve (Durante, 2009). This process is difficult to measure in the present day due to the mismatch between the generational time scale on which cultural evolution occurs and the limited time horizons available to contemporary social sciences. Instead, we can turn to the archaeological record.

Archaeology focuses on the material correlates of human behavior and is unique in addressing how social and physical infrastructure modulate human interactions with the environment over long time spans. Not only do archaeologists catalog the remains of field systems, road networks, canals, and other components of hard infrastructure directly, but also the ceramics, raw materials, and luxury goods that are the material correlates of past networks of exchange and interaction. A powerful idea in archaeology is that, because of the interaction between societies and their biophysical environments, the spatial and temporal patterns of environmental variability can be used to predict "ideal" cultural responses and compared to archaeological observations (Halstead and O'Shea, 1989). Yet in practice it is often difficult to find archaeological data fit for purpose due to the incomplete nature of the archaeological record and the paucity of detailed paleoclimate data at the scales most relevant to human populations.

The North American Southwest is an exception. The climate of this region has been intensively studied by paleoclimatologists and climate modelers (Cook et al., 1999; Sheppard et al., 2002; McCabe et al., 2004; Herweijer et al., 2007; Cook et al., 2011; Bocinsky and Kohler, 2014; Coats et al., 2015; Routson et al., 2016; Ault et al., 2018). Its aridity aids archaeological site preservation and recovery, and nearly two centuries of survey and excavation have yielded extensive, high quality settlement pattern data (Hill et al., 2004). Detailed inventories of material culture at hundreds of archaeological sites provide an unparalleled view of the structure and dynamics of past social networks. This archaeological record attests to extensive exchange networks of durable goods such as ceramics and obsidian (Malville, 2001; Taliaferro et al., 2010; Mills et al., 2013a), and there is evidence for the long-distance transport of limited quantities of maize to the large regional center at Chaco Canyon (Benson et al., 2009; Benson, 2010). The populations of the Southwest also underwent massive social transformation, migration, and population decline in the late 13th century contemporaneous with one of the worst droughts in the last 1,000 years (Hill et al., 2004). Past work has suggested a relationship between the intensity of social interaction and patterns of drought variability, but has been limited by small sample sizes or sparse climate data (Rautman, 1993; Johnson, 1990; Cordell et al., 2007). The question is returning to the fore with the advent of high resolution climate observations and reconstructions, facilitating more detailed accounting of the spatial patterns of drought in the North American Southwest (Strawhacker et al., 2017; Strawhacker et al., 2020), and more detailed archaeological datasets (Borck et al., 2015). Simulations suggest that the precise nature of environmental variability is critical for exchange dynamics (Freeman et al., 2014). With these advances in our ability to map droughts in space and time comes the need to more precisely define what patterns of climate variability are actually important.

Here, I draw on hydroclimate data from the past and present to isolate specific reoccurring climate patterns, or *modes of variability*, in the American Southwest. I then compare these patterns to prehistoric social networks, inferred from a dataset of 4.3 million ceramic artifacts from nearly 500 archaeological sites, to examine the relationship between hydroclimate variability, distance, and social interaction over a 250-year span.

2 METHODS

2.1 Archaeological Interaction Networks

I analyzed data from nearly 500 archaeological sites in the Southwest Social Networks (SWSN) database, a compendium of material-culture data from well-dated sites west of the Continental Divide in Arizona and New Mexico (Mills et al., 2013a; Mills et al., 2013b; Peeples and Haas, 2013; Borck et al., 2015; Hill et al., 2015; Mills et al., 2015). Version 1.0 of the SWSN database cataloged nearly 4.3 million ceramic artifacts and nearly 5,000 obsidian artifacts, providing quantitative estimates of the topology of the region-wide social network during five 50-year time steps spanning the period 1200–1450 CE (Mills et al., 2013a; Mills et al., 2015). Raw site-level ceramic counts were allocated to each time step according to an apportioning procedure that combined the occupation span of each site and the production span of each ware type with a parametric assumption of the wares' changing popularity through time (Mills et al., 2013a; Peeples and Haas, 2013).

I aggregated the point-based SWSN data into 10 km grid cells (**Figure 1A**) so that the network estimates were less sensitive to local settlement dispersal or aggregation as reflected in the assemblages at individual sites (Paliou and Bevan, 2016). The choice of 10 km grid cells reflects a day's round-trip travel, bounding the area for farming and raw material collection around a site, so the procedure effectively smooths over the approximate area of each site's resource catchment (Varien, 1999; Hill et al., 2015). Then I calculated a modified version of the Jensen-Shannon divergence (Masucci et al., 2011) between the empirical frequency distributions of 15 decorated ceramic wares at each of the grid cells as

$$D_{ij} = \frac{H\left(0.5P_i + 0.5P_j\right) - 0.5H\left(P_i\right) - 0.5H\left(P_j\right)}{-\ln 0.5} \tag{1}$$

where D_{ij} is the divergence between the empirical frequency distributions of ceramic wares at sites i and j, P_i is a vector of the proportions of ceramic ware type k in the assemblage at site i, and $H(P) = -\sum_k p_k \ln p_k$ is the Shannon entropy of P measured in nats. This equation measures the similarity of two sites by the distributions of the ceramic types shared by both sites and the types exclusive to each. Analogous to the use of divergence measures in population genetics, divergence here is a (inverse) proxy for information flow. For visualization and analysis, I convert this divergence measure into a similarity metric by taking

$$S_{ij} = 1 - \sqrt{D_{ij}} \tag{2}$$

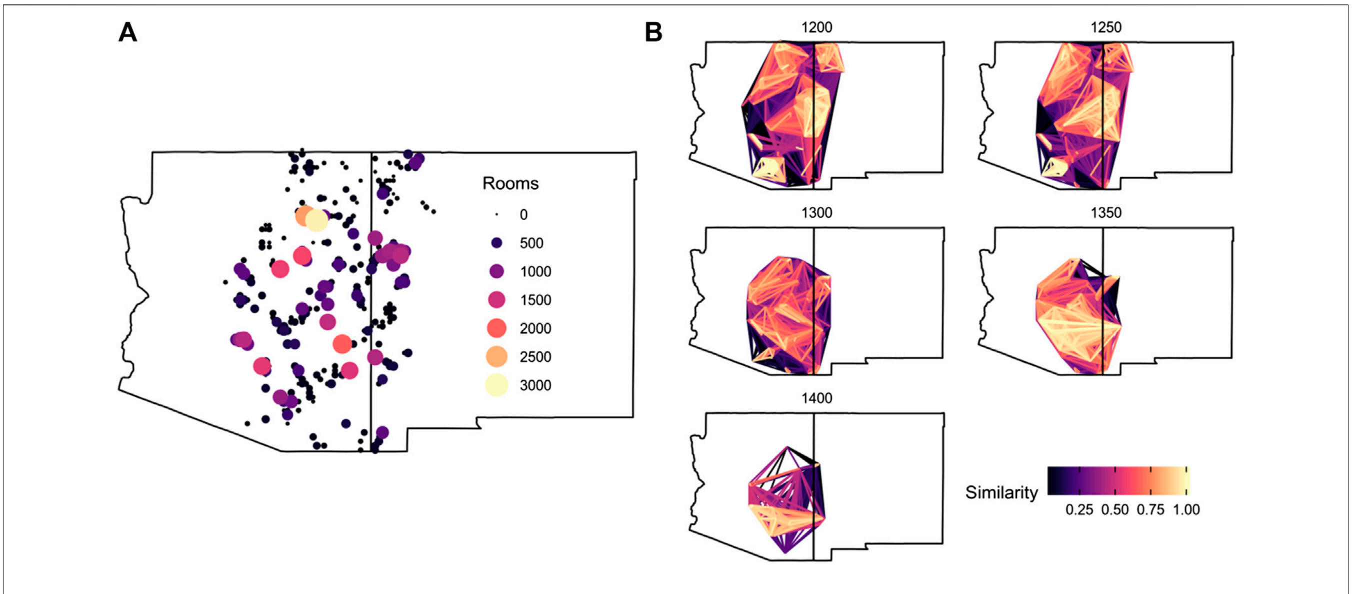

FIGURE 1 | The *Southwest Social Networks* dataset, version 1.0 (Mills et al., 2013a). **(A)** Site locations for all time periods in the dataset, aggregated into 10 km patches to reduce biases from local settlement aggregation and dispersal. Site sizes are estimated from room counts. **(B)** Social networks reconstructed from ceramic assemblage similarity between each pair of sites. A similarity coefficient of one means that the sites share the same decorated ceramic wares in the exact same proportions, and a coefficient of zero means there is no overlap in the ceramic assemblages. The similarity network can be interpreted as the degree of social interaction and cultural transmission between sites, whether via migration, trade, or copying. Networks are shown over successive 50-year time spans, starting at 1200 CE.

The resulting cultural similarity network (**Figure 1B**) is similar to that resulting from other similarity measures such as the Brainerd-Robinson index (Mills et al., 2013a) save for different behavior in the tails of the distribution, but the Jensen-Shannon index provides a more natural interpretation as a measure of information flow. By focusing on a general measure of information flow, aggregate patterns of social interaction can be inferred regardless of the precise mechanisms of that interaction (*e.g.,* trade, migration, shared history or raw materials). The index can thus be loosely interpreted as a probability of interaction between two sites, with identical patterns of ceramic discard at two sites indicating a higher probability of interaction than between sites that share no ware types in common.

2.2 Hydroclimate Variability

To estimate large-scale patterns of interannual drought and flood variability, I analyzed a 122-year record of the Standardized Precipitation-Evapotranspiration Index (SPEI) from across the US states of Arizona, New Mexico, Colorado, Utah, and California (Abatzoglou et al., 2017). The large spatial domain sampled variability across the western US climate zone, ensuring that estimated spatio-temporal climate patterns were not sensitive to the exact location and dimension of the archaeological study area. SPEI is the normalized deviation from the average climatic water balance for a given month on varying time scales (Vicente-Serrano et al., 2010). I focused on the 12-month SPEI calculated in the August of each year, which captures the water balance over the year leading up to each summer growing season. This index was calculated from 4 km temperature and precipitation grids interpolated from weather-station observations using the topographically-sensitive PRISM algorithm (Daly et al., 1997).

Weather can vary for many reasons across space and time, so it is important to separate climatic signal from random noise. Principal Components Analysis (PCA) of spatiotemporal data is a common tool for extracting "modes of variability" in the climate sciences (Lorenz, 1956; Hannachi et al., 2007), but its use for this purpose is rare in archaeology (though see (Weiss, 1982; Cordell et al., 2007)). PCA of a dataset's space-time covariance matrix decomposes it into sets of orthogonal time series (principal components) and spatial patterns (eigenvectors), arranged by their contributions to the total observed variance (eigenvalues). The resulting modes of variability are an efficient means of representing a complex spatiotemporal field by a limited set of patterns.

After multiplying each grid cell by the cosine of its latitude to weight for differences cell area, I performed PCA on the stack of 122 annual SPEI maps via singular value decomposition. Then, I selected the leading modes of variability using both a scree test and North's rule of thumb, which is a method to detect degenerate patterns caused by temporal autocorrelation in the observed data (North et al., 1982). I rotated the leading PC modes using a varimax rotation in order to relax the spatial orthogonality constraints of the PCA analysis and reveal coherent, physically meaningful patterns (Richman, 1986). The resulting eigenvectors were then multiplied by the square root of the corresponding eigenvalues to yield correlation coefficients and were mapped in space. I refer to these resulting spatial patterns as empirical orthogonal functions (EOFs), and their associated time series as principal components (PCs). The PC amplitude time series were then compared to the observational record, and the signs of the eigenvalues and vectors were reversed to match the historical record (so that a positive time series value corresponded to a positive SPEI and *vice versa*). To determine whether these patterns were robust over time, the observed EOFs were compared to the EOFs of a SPEI reconstruction over the past millennium (Steiger et al., 2018) (see SI for details).

2.3 Least-Cost Networks

Distance ultimately constrains social interaction, as the further one travels to interact with a partner the greater will be the cost in time, energy, and other resources. In order to control for the effect of distance on social interaction, I calculated the least-cost network between all sites in the SWSN network. The topography of the study area was represented using a 90 m SRTM DEM, resampled to 250 m to reduce computation time and smooth fine-scale topographic noise. A cost matrix was calculated containing, for each DEM cell, the amount of time in seconds it would take a foot traveler to move to each of the 16 neighboring cells. Time costs were calculated using a version of Tobler's hiking function, which estimates walking speed from terrain slope. The function was modified to make it isotropic (i.e., averaging the uphill and downhill walking speeds) and adding an extra penalty to very steep slopes consistent with human cognitive biases (Pingel, 2010). This cost matrix (time) was then inverted to represent conductance (speed), facilitating a sparse matrix representation and estimation of least cost paths using efficient graph theoretic algorithms (van Etten, 2017). The resulting transition matrix was used to calculate all pairwise isotropic least cost paths between the centroids of each pair of 10 km grid cells containing archaeological materials.

2.4 Spatial Interaction Models

Spatial interaction models are used across the social and natural sciences (Wilson, 1971; Fotheringham and O'Kelly, 1989; Sen and Smith, 1995; Bavaud, 2008; Murphy et al., 2010; Head and Mayer, 2015). In a regression context, a spatial interaction model estimates the pairwise flow–of resources, migrants, or information–among entities as a multiplicative function of predictors influencing the production and attraction of flows as well as measures of their mutual separation or other generalized costs of moving. Archaeologists have used *statistical* spatial interaction models sparingly (Tobler and Wineburg, 1971; Hodder, 1974; Johnson, 1990) because of the rarity of archaeological data on social interaction strength, although the method is common in simulation studies where data quality is less of a restriction (Bevan and Wilson, 2013; Evans et al., 2011; Davies et al., 2014; Paliou and Bevan, 2016). The conceptual justification for the use of spatial interaction models on archaeological networks is similar to that used in molecular ecology (Murphy et al., 2010), with information flows among a spatially-structured metapopulation measured by the divergence of those populations (Mesoudi, 2018).

Data of this type have three features that make traditional statistical spatial interaction modeling difficult. These are: 1) the data are bounded between zero and one; 2) the measures are pairwise symmetric; 3) we have no exact functional expectations for the specific terms in the spatial interaction model because empirical work on this scale and type is rare. To address these issues, I used a generalized additive model (Wood, 2006), a semiparametric extension to generalized linear models useful for more complex spatial interaction models (Lebacher et al., 2018).

Specifically, I fit models of the form

$$logit\left(S_{ijt}\right) = f\left(dist_{ij}\right) + f_t\left(EOF_{ij}\right) + \tau_{it} + \tau_{jt} + \epsilon_{ijt} \qquad (3)$$

where the logit function maps the data from $[0, 1]$ to $[-\infty, +\infty]$, t is the time step, $f()$ is an arbitrary function estimated during model fitting using penalized cubic regression splines, τ_i and τ_j are time-varying random effects for the nodes incident on each edge, and ϵ is Gaussian error. This model assumes only that information flows are at equilibrium with settlement population, not that the populations themselves are at equilibrium (Wilson, 2008). The τ terms account for the non-independence of edges that share a node, and were estimated using a maximum likelihood population effects correlation structure appropriate for pairwise data (Clarke et al., 2002). I compared the AIC, BIC, and R^2 of models fit using maximum likelihood with and without the EOF terms, and refit the best performing model using restricted maximum likelihood (Clarke et al., 2002; Shirk et al., 2018).

3 RESULTS

3.1 Six Drought Patterns Explain 83% of Observed Drought Variability in the American Southwest

I used PCA to decompose the 122-year gridded observational record of western US summer moisture availability into a reduced set of spatio-temporal patterns. The leading six principal component time series together explain 83% of the variance in the observational record. The PCs represent time series that are maximally representative of the entire data set (**Figure 2**). I rotated the six PCs before mapping, in order to capture more physically meaningful patterns and minimize statistical artifacts. PCs beyond the leading six were not retained for rotation and mapping, as they represent spatially and temporally incoherent variability and spurious correlations introduced by sampling error in the observational record. The same PC time series are also present in the coarse-resolution SPEI reconstruction, where they explain 96% of the reconstructed variance over the last millennium (**Supplementary Figures S5, S12, S13**).

3.2 Different Drought Patterns Are Associated With Different Zones of Oceanic or Continental Influence

To reveal the latent spatial structures associated with the temporal modes of variability, I mapped the spatial patterns associated with each of the leading six PCs (**Figure 3**). The results are robust,

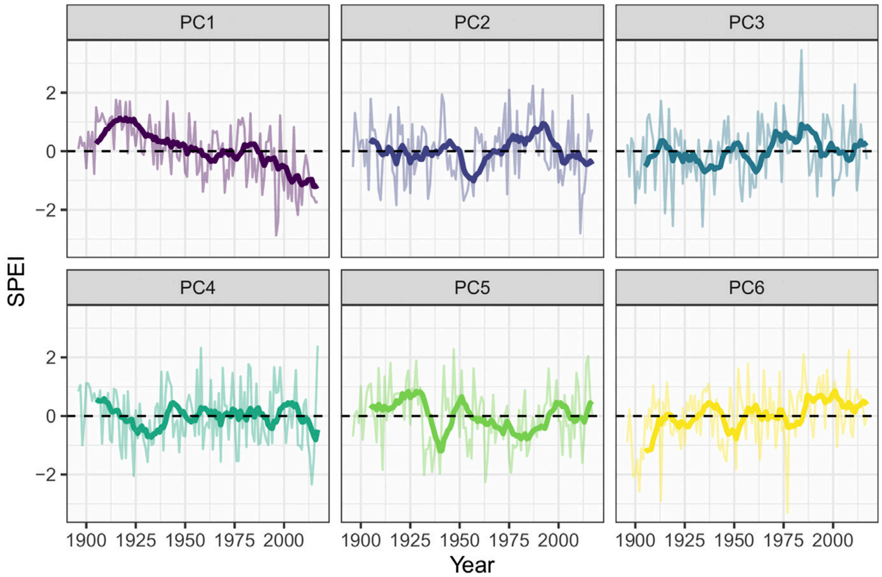

FIGURE 2 | Time series associated with the leading six PCs for the observational period, after varimax rotation. The *y*-axis corresponds to the 12-month Standardized Precipitation-Evapotranspiration Index (SPEI), the normalized deviation from the average climatic water balance for a given month on 12-month time scale. SPEI values can be interpreted as z-scores in a normal distribution (i.e., a value of 1 is one standard deviation wetter than average for that location, −1 is one standard deviation drier). 10-year moving averages superimposed over raw annual values.

recurring patterns of spatially-coherent variability, and can be interpreted as the degree to which the 122-year record at each grid cell correlates with the associated rotated PC time series. These spatial patterns are known as the (rotated) empirical orthogonal functions (EOFs). The patterns are consistent across observations and reconstructions (**Supplementary Figure S9**) and regardless of the exact SPEI time scale used to calculate them, which supports their overall robustness. The spatial and temporal patterns associated with the leading six PCs allows us to trace the sources of each mode of variability back to the global climate system.

The origins of each drought pattern can be determined by examining the EOF maps, along with the correlations of the PCs to global sea surface temperatures and the timing of extreme dry and wet years. EOF1 reflects southwesterly flow from the tropical Pacific, bringing moisture across the low desert zones of California and Arizona. The pattern attenuates with elevation and as distance from the ocean increases. PC1 shows a broad drying trend to the present day, possibly related to increased evaporative demand due to recent warming, although the spatial pattern in the associated EOF is not itself anthropogenic. EOF2 similarly represents southeasterly flow from the Gulf of Mexico, centered on eastern New Mexico. As with EOF1, the pattern attenuates with increasing elevation and distance from the ocean due to orography and continentality, respectively. It represents cyclonic storms coming from the Gulf of Mexico, in turn influenced by variability in Atlantic sea surface temperatures. PC2 shows a major dry period centered on the Texas/New Mexico drought of 1956. EOF3 represents northerly flow associated with polar continental cold fronts, and its associated PC shows a wet peak in the 1983 Salt Lake City floods. EOF4 represents the influence of westerly flow off the Pacific Ocean and the orographic effect of the Sierra Nevada mountains intercepting this flow, and is associated with events such as the 1924 drought in California. EOF5 is centered over the great plains and attenuates across the Rocky Mountains, and was most strongly expressed during the Dust Bowl of the 1920s. EOF6 is centered on the Colorado Plateau, likely reflecting local circulation of hot continental air masses.

3.3 The Intensity of Social Interaction Decays Nonlinearly With Distance

I calculated the cost of moving between each pair of archaeological sites as the shortest amount of time it would take a foot traveler to move between them. I then used a nonlinear regression model to estimate the functional relationship between distance and interaction. The null model for the statistical network analysis was that distance alone explained the intensity of social interaction as measured by the similarity in the decorated ceramic assemblages at each pair of sites. This null model was sufficient to explain 37.8% of the variance in the ceramic similarity data. The empirical distance deterrence function estimated on all time periods using a penalized regression spline predicts a falloff in interaction at distances of more than 100 h (**Figure 4**). As expected, the resulting distance-based network predicts many strong interactions at close distances, and the residuals of the model show long-distance transitive ties.

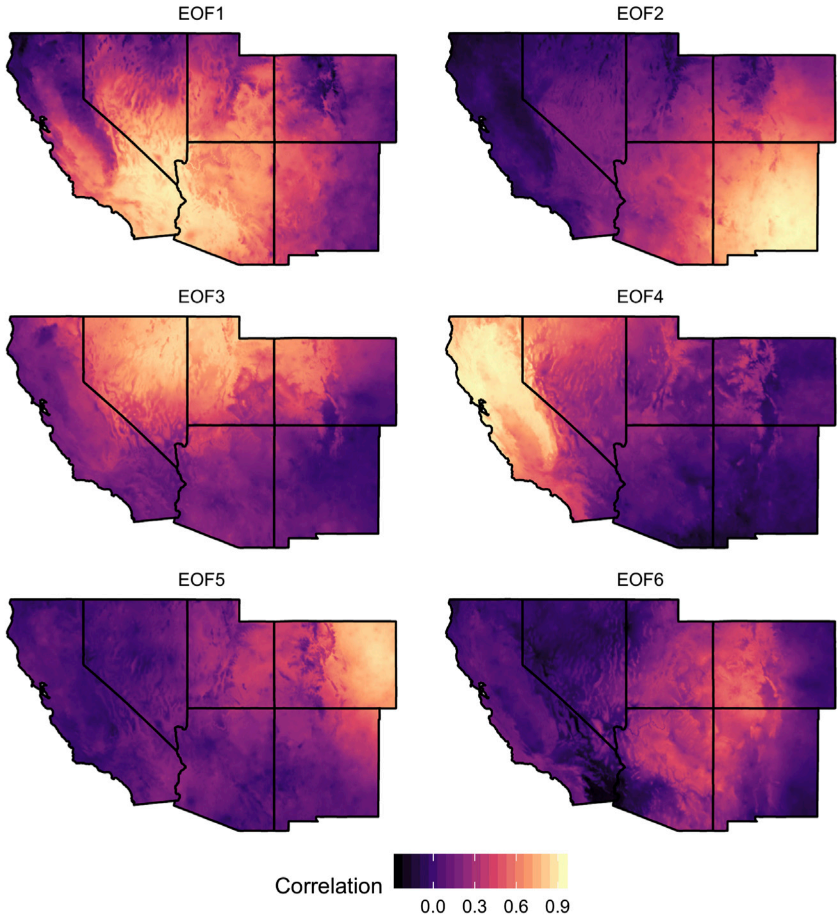

FIGURE 3 | Leading six rotated empirical orthogonal functions (EOFs) associated with the respective PC time series in **Figure 2**, derived from gridded PRISM climate data (Daly et al., 2008; Abatzoglou et al., 2017). These regions represent different oceanic and atmospheric influences; people living in the same EOF will often experience dry and wet years at the same time as one another.

3.4 Hydroclimate Variability Explains a Moderate But Clear Proportion of the Intensity of Social Interaction

A model predicting information flow using distance and climatic dissimilarity, measured as the absolute difference between the EOF loadings of a pair of sites, explains 42.5% of the variance in the ceramic similarity data. The increase over the distance-only null model is moderate but statistically significant, and the EOF model is superior in all measures of parsimony and goodness-of-fit. This difference changes over time, and refitting each model on data from each time step individually reveals that the improvement in the explanatory power of the EOF model over the distance-only null is most pronounced at and after 1300 CE (see SI). The improvement in explanatory power over the null model is quite small in the 1200 and 1250 CE time steps. This pattern suggests that ties shaped in part by the EOF patterns are more common during and after the period of regional relocation around 1300 CE.

The smooth functions estimated in the EOF model are all close to piecewise linear on the scale of the linear predictor, but the intensity of these functional relationships varies smoothly over time and across EOFs (**Figure 5**). Increasing distance along a particular EOF sometimes increases the intensity of social interaction, as was expected ahead of time, but some EOFs (3, 6) appear to slightly reduce social interaction at larger differences. The smoothness penalty also selects some EOFs out of the model entirely by estimating functions close to a horizontal line, and almost all the functions are flat when the climate differences are less than 0.2. Surprisingly, the fluctuations in the effect size of a particular EOF have no clear association with the sign of the associated PC amplitude time series reconstructed for each period (**Supplementary Figure S14**). This suggests that additional dynamic processes, such as cultural memory or institutional growth and decay, are in effect on time scales longer than a single generation. These processes may explain why different sets of EOF patterns appear to influence social interaction before and after the period of drought and interregional migration ca. 1275–1300 CE.

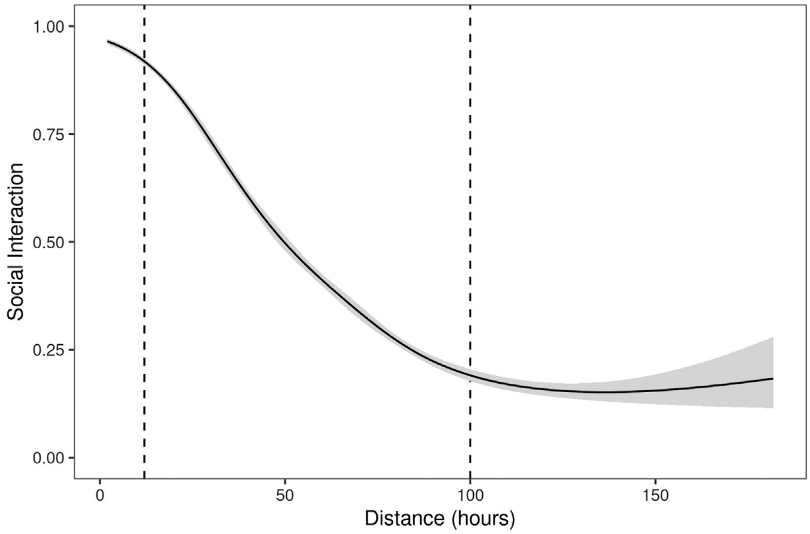

FIGURE 4 | Empirical distance deterrence function estimated with a generalized additive model, describing how the intensity of social interaction, defined as the information flow between two settlements and measured by the similarity in their decorated ceramic assemblages, decreases as a function of distance. Shaded area indicates the 95% confidence interval for the smooth function. Dashed lines indicate key thresholds in the function at 10 and 100 hours.

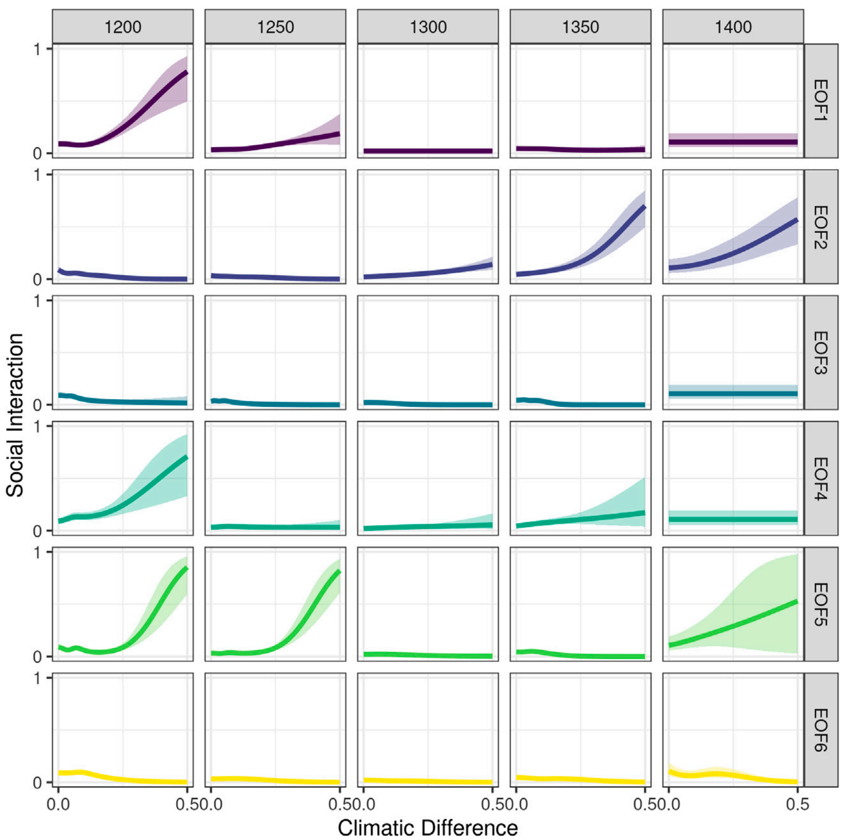

FIGURE 5 | Estimated smooth functions describing how the intensity of social interaction increases or decreases with increasing distance along each of six spatial drought patterns from **Figure 3**, compared over five time steps. As above, information flow is inferred from the similarity of the decorated ceramic assemblages at each pair of sites. Climatic difference is defined as the absolute difference between the EOF loadings of each pair of sites. Shaded regions correspond to the 95% confidence intervals for the smooth functions.

4 DISCUSSION AND CONCLUSION

The six spatial patterns of hydroclimate variability isolated here are consistent with the general mechanistic understanding of hydroclimate variability in the American Southwest. These patterns represent different zones of moisture transport, reflecting the influence of topography and marine or continental moisture sources (Liu et al., 2010; Hu et al., 2011). These spatial and temporal drought patterns, and their hypothesized drivers in the global climate system, are largely consistent with those from other studies using varied observational data and time windows (Comrie and Glenn, 1999; Cook et al., 1999; McCabe and Dettinger, 1999; McCabe et al., 2004; Ryu et al., 2010; Seager and Hoerling, 2014; Herrmann et al., 2016). These patterns from the observational period also appear in drought reconstructions spanning the past millennium, emphasizing the fact that these are robust, time invariant spatial modes.

Objective measures of hydroclimate variability, as opposed to point-to-point sample correlations, help isolate the most important drivers of that variability. Droughts and pluvials associated with tropical Pacific and Atlantic influences seem to have been most important for structuring social interaction, with ties connecting these regions greater than expected by chance and distance alone. Tropical Pacific sea surface temperatures are known to be the primary driver of variability in Southwest, with additional influences from moisture sources in the North Pacific and Atlantic (McCabe et al., 2004). A disruption in these patterns is thought to be one reason why droughts in this period led to such social transformation, as the networks of social infrastructure that had developed over previous centuries were unable to adapt fast enough to unusual conditions (Cordell et al., 2007).

In spite of the robustness of these spatial patterns, there remains considerable diversity in the functional responses of human social networks to these drought patterns. One possible explanation is that large-scale climate regimes influence the formation of ethnolinguistic groups. Quotidian interaction may have been biased toward groups of shared ethnolinguistic affiliation, as kinship and ethnicity both influence social exchanges (Nolin, 2010). At larger, regional scales, goods and information might also flow on sociopolitical hierarchies (Crumley, 1979). Populations in the late pre-Hispanic Southwest were also out of equilibrium (Hill et al., 2004). Strong social networks take time to form and effort to maintain and monitor. Free-riders who avoid that effort can damage this critical social infrastructure when it is most needed (Kohler and West, 1996). A simulation approach could better capture these processes and more clearly resolve social responses to interannual climate variability. Dynamic, as opposed to statistical, spatial interaction models can explicitly trace the coevolution of social and physical infrastructure networks (Bevan and Wilson, 2013). Simulations can also explore the biases that static archaeological data introduce in representing dynamic social processes (Crema et al., 2014, 2016).

The residuals of the statistical network models retain unexplained structure. These structures appear to represent cultural clusters, a common feature in social networks that is not accounted for by either distance or drought variability. One source of this error may be irrigation-dependent groups who relied on streamflow driven by remote precipitation and evapotranspiration and may thus have had more complex, indirect dependencies on the large-scale climate patterns isolated here (Nelson et al., 2010). At finer scales, the model residuals also display evidence of transitivity and triad closure, with more closed triangle structures than would be expected by chance. Although this feature is common in human social networks, it is also to be expected because the measure of cultural similarity is a metric subject to the triangle inequality. Statistical methods specifically designed for such structures will be useful in future work (Stillman et al., 2017). In addition, the archaeological data are not spatially extensive enough to sample the full range of hydroclimate variability. Given the relative spatial scales of the environmental and cultural data, there is a risk that many different correlated climate patterns will be indistinguishable at the scale of the cultural data. Correlations between competing hypotheses are a source of error in model selection using information criteria (Shirk et al., 2018). In spite of these concerns, these results highlight two key points: the need to use objective and physically meaningful measures of hydroclimate to assess the social impacts of climate variability in the past and the need to capture social dynamics out of equilibrium with the biophysical environment.

These results refine our understanding of the geography of human adaptation to climate and climate change, and emphasize the role of social interaction in increasing the robustness of human populations to environmental variability. Much of the world's food is still grown on small farms, and these farmers rely on complex spatial networks of formal and informal arrangements in much the same way as their predecessors have for thousands of years. Prehistoric exchange infrastructure evolved in part in response to robust, time-invariant spatial climate patterns. But social adaptions to one mode of variability are fragile to changes in the nature of that variability (Janssen et al., 2007). Large-scale patterns of hydroclimate variability act as a dynamic selective environment in which societies evolve new norms and institutions for regulating social interaction. Tracing the flows of information and energy within these complex social-ecological systems is essential for understanding their long-term behavior, and leveraging our archaeological understanding of why such systems succeed or fail will be critical to anticipating the impact of impending climate changes on farming communities in the developing world.

DATA AVAILABILITY STATEMENT

All original contributions presented in the study are included in the article or Supplementary Material in a reproducible R Markdown document. A preprocessed version of the SWSN v1.0 data, aggregated to 10 km grid cells to mask individual site locations, is available in the **Supplementary Material** with links to additional input climate and topographic raster data. Further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2020.620856/full#supplementary-material.

REFERENCES

Abatzoglou, J. T., McEvoy, D. J., and Redmond, K. T. (2017). The west wide drought tracker: drought monitoring at fine spatial scales. *Bull. Am. Meteorol. Soc.* 98 (9), 1815–1820. doi:10.1175/bams-d-16-0193.1

Anderies, J. M., and Hegmon, M. (2011). Robustness and resilience across scales: migration and resource degradation in the prehistoric US southwest. *Ecol. Soc.* 16 (2), 22. doi:10.5751/es-03825-160222

Anderies, J. M. (2015). Understanding the dynamics of sustainable social-ecological systems: human behavior, institutions, and regulatory feedback networks. *Bull. Math. Biol.* 77 (2), 259–280. doi:10.1007/s11538-014-0030-z

Ault, T. R., George, S. S., Smerdon, J. E., Coats, S., Mankin, J. S., Carrillo, C. M., et al. (2018). A robust null hypothesis for the potential causes of megadrought in Western North America. *J. Clim.* 31 (1), 3–24. doi:10.1175/jcli-d-17-0154.1

Bavaud, F. (2008). The endogenous analysis of flows, with applications to migrations, social mobility and opinion shifts. *J. Math. Sociol.* 32 (4), 239–266. doi:10.1080/00222500802352493

Benson, L. V., Stein, J. R., and Taylor, H. E. (2009). Possible sources of archaeological maize found in Chaco Canyon and aztec ruin, New Mexico. *J. Archaeol. Sci*. 36 (2), 387–407. doi:10.1016/j.jas.2008.09.023

Benson, L. V. (2010). Who provided maize to Chaco Canyon after the mid-12th-century drought?. *J. Archaeol. Sci*. 37 (3), 621–629. doi:10.1016/j.jas.2009.10.027

Bevan, A., and Wilson, A. (2013). Models of settlement hierarchy based on partial evidence. *J. Archaeol. Sci.* 40 (5), 2415–2427. doi:10.1016/j.jas.2012.12.025

Bloch, F., Genicot, G., and Ray, D. (2008). Informal insurance in social networks. *J. Econ. Theor.* 143 (1), 36–58. doi:10.1016/j.jet.2008.01.008

Bocinsky, R. K., and Kohler, T. A. (2014). A 2,000-year reconstruction of the rain-fed maize agricultural niche in the US Southwest. *Nat. Commun.* 5, 5618. doi:10.1038/ncomms6618

Borck, L., Mills, B. J., Peeples, M. A., and Clark, J. J. (2015). Are social networks survival networks? An example from the late pre-hispanic US southwest. *J. Archaeol. Method Theor*. 22 (1), 33–57. doi:10.31235/osf.io/ubvxy

Clarke, R. T., Rothery, P., and Raybould, A. F. (2002). Confidence limits for regression relationships between distance matrices : estimating gene flow with distance. *J. Agric. Biol. Environ. Stat.* 7 (3), 361–372. doi:10.1198/108571102320

Coats, S., Smerdon, J. E., Cook, B. I., and Seager, R. (2015). Are simulated megadroughts in the North American southwest forced?. *J. Clim*. 28 (1), 124–142. doi:10.1175/jcli-d-14-00071.1

Comrie, A. C., and Glenn, E. C. (1999). Principal components-based regionalization of precipitation regimes across the southwest United States and northern Mexico, with an application to monsoon precipitation variability. *Clim. Res*. 10 (3), 201–215. doi:10.3354/cr010201

Cook, E. R., Meko, D. M., Stahle, D. W., and Cleaveland, M. K. (1999). Drought reconstructions for the continental United States. *J. Clim*. 12 (4), 1145–1163. doi:10.1175/1520-0442(1999)012

Cook, B. I., Cook, E. R., Anchukaitis, K. J., Seager, R., and Miller, R. L. (2011). Forced and unforced variability of twentieth century North American droughts and pluvials. *Clim. Dynam*. 37 (5), 1097–1110. doi:10.1007/s00382-010-0897-9

Cordell, L. S., Van West, C. R., Dean, J. S., and Muenchrath, D. A. (2007). Mesa Verde settlement history and relocation: climate change, social networks, and Ancenstral Pueblo migration. *KIVA* 72 (4), 379–405. doi:10.1179/kiv.2007.72.4.001

Crema, E. R., Kerig, T., and Shennan, S. (2014). Culture, space, and metapopulation: a simulation-based study for evaluating signals of blending and branching. *J. Archaeol. Sci*. 43, 289–298. doi:10.1016/j.jas.2014.01.002

Crema, E. R., Kandler, A., and Shennan, S. (2016). Revealing patterns of cultural transmission from frequency data: equilibrium and non-equilibrium assumptions. *Sci. Rep*. 6, 39122. doi:10.1038/srep39122

Crumley, C. L. (1979). Three Locational Models: An Epistemological Assessment for Anthropology and Archaeology. *Adv. Archaeol. Meth. Theory* 2, 141–173.

Daly, C., Halbleib, M., Smith, J. I., Gibson, W. P., Doggett, M. K., Taylor, G. H., et al. (2008). Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. *Int. J. Climatol.* 28, 2031–2064. doi:10.1002/joc.1688

Daly, C., Taylor, G., and Gibson, W. (1997). The prism approach to mapping precipitation and temperature. *AMS Conf. Appl. Climatol.* 1, 1–4

Davies, T., Fry, H., Wilson, A., Palmisano, A., Altaweel, M., and Radner, K. (2014). Application of an entropy maximizing and dynamics model for understanding settlement structure: the Khabur Triangle in the Middle Bronze and Iron Ages. *J. Archaeol. Sci*. 43 (1), 141–154. doi:10.1016/j.jas.2013.12.014

Drennan, R. D. (1984). Long-distance transport costs in pre-Hispanic Mesoamerica. *Am. Anthropol.* 86 (1), 105–112. doi:10.1525/aa.1984.86.1.02a00100

Durante, R. (2009). *Risk, cooperation and the economic origins of social trust: an empirical investigation*., 1–45. Available at: http://papers.ssrn.com/abstract=1576774

Evans, T., Rivers, R., and Knappett, C. (2011). Interactions in space for archaeological models. *Adv. Complex Syst*. 15, 1150009. doi:10.1142/s021952591100327x

Fafchamps, M., and Gubert, F. (2007). The formation of risk sharing networks. *J. Dev. Econ*. 83 (2), 326–350. doi:10.1016/j.jdeveco.2006.05.005

Fotheringham, S. A., and O'Kelly, M. E. (1989). *Spatial interaction models: formulations and applications*. Dordrecht: Kluwer Academic Publishers.

Freeman, J., Anderies, J. M., Torvinen, A., and Nelson, B. A. (2014). Crop specialization, exchange and robustness in a semi-arid environment. *Hum. Ecol.* 42 (2), 297–310. doi:10.1007/s10745-013-9638-0

Gauthier, N. E. (2019). Archaeological approaches to population growth and social interaction in semiarid environments: pattern, process, and feedbacks. PhD thesis. Tempe: Arizona State University.

Halstead, P., and O'Shea, J. (1989). "Bad year economics: cultural responses to risk and uncertainty." in: Introduction: cultural responses to risk and uncertainty. Editors P. Halstead and J. O'Shea. Cambridge: Cambridge University Press.

Hannachi, A., Jolliffe, I. T., and Stephenson, D. B. (2007). Empirical orthogonal functions and related techniques in atmospheric science: a review. *Int. J. Climatol.* 27, 1119–1152. doi:10.1002/joc.1499

Hao, Y., Armbruster, D., Cronk, L., and Athena Aktipis, C. (2015). Food sharing networks in lowland Nicaragua An application of the social relations model to count data. *Evol. Hum. Behav.* 36, 265–273. doi:10.1016/j.evolhumbehav.2014.12.003

Head, K., and Mayer, T. (2015). Gravity equations: workhorse, toolkit, and cookbook. Elsevier, 4.

Herrmann, S. M., Didan, K., Barreto-Munoz, A., and Crimmins, M. A. (2016). Divergent responses of vegetation cover in Southwestern US ecosystems to dry and wet years at different elevations. *Environ. Res. Lett.* 11 (12), 124005. doi:10.1088/1748-9326/11/12/124005

Herweijer, C., Seager, R., Cook, E. R., and Emile-Geay, J. (2007). North American droughts of the last millennium from a gridded network of tree-ring data. *J. Clim.* 20, 1353–1376. doi:10.1175/JCLI4042.1

Hill, J. B., Clark, J. J., Doelle, W. H., and Lyons, P. D. (2004). Prehistoric demography in the southwest: migration, coalescence, and hohokam population decline. *Am. Antiq.* 69, 689–716. doi:10.2307/4128444

Hill, J. B., Peeples, M. A., Huntley, D. L., and Carmack, H. J. (2015). Spatializing social network analysis in the late precontact U.S. southwest. *Adv. Archaeol. Pract.* 3, 63–77. doi:10.7183/2326-3768.3.1.63

Hodder, I. (1974). Regression analysis of some trade and marketing patterns. *World Archaeol.* 6 (2), 172–189. doi:10.1080/00438243.1974.9979600

Hu, Q., Feng, S., and Oglesby, R. J. (2011). Variations in North American summer precipitation driven by the Atlantic multidecadal oscillation. *J. J. Clim.* 24 (21), 5555–5570. doi:10.1175/2011JCLI4060.1

Janssen, M. A., Anderies, J. M., and Ostrom, E. (2007). Robustness of social-ecological systems to spatial and temporal variability. *Soc. Nat. Res.* 20, 307–322. doi:10.1080/08941920601161320

Johnson, J. R. (1990). Chumash social geography: a quantitative analysis. Proceedings of the Society of California Archaeology. 3, 149–173.

Kohler, T. A., and West, C. R. (1996). "The calculus of self-interest in the development of cooperation: sociopolitical development and risk among the Northern Anasazi," in: Evolving complexity and environmental risk in the Prehistoric Southwest. Editors J. Tainter and B. B. Tainter. Reading, MA: Addison-Wesley.

Koster, J. M., and Leckie, G. (2014). Food sharing networks in lowland Nicaragua An application of the social relations model to count data. *Social Networks.* 38, 100–110. doi:10.1016/j.socnet.2014.02.002

Liu, Z., Bowen, G. J, and Welker, J. M. (2010). Atmospheric circulation is reflected in precipitation isotope gradients over the conterminous United States. *J. Geophys. Res. Atmos.* 115, 1–14. doi:10.1029/2010JD014175

Lebacher, M., Thurner, P. W., and Kauermann, G. (2018). International arms trade: a dynamic separable network model with heterogeneity components. arXiv preprint.

Lorenz, E. N. (1956). Empirical orthogonal functions and statistical weather prediction. Cambridge, MA: Statistical Forecast Project Report 1 Department of Meteorology MIT 49.

Malville, N. J. (2001). Long-distance transport of bulk goods in the pre-hispanic American southwest. *J. Anthropol. Archaeol.* 20 (2), 230–243. doi:10.1006/jaar.2000.0373

Masucci, A. P., Kalampokis, A., Eguíluz, V. M., and Hernández-García, E. (2011). Wikipedia information flow analysis reveals the scale-free architecture of the semantic space. *PLoS One* 6 (2), e17333. doi:10.1371/journal.pone.0017333

McCabe, G. J., Palecki, M. A., and Betancourt, J. L. (2004). Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States. *Proc. Natl. Acad. Sci. U.S.A.* 101 (12), 4136–4141. doi:10.1073/pnas.0306738101

McCabe, G. J., and Dettinger, M. D. (1999). Decadal variations in the strength of ENSO teleconnections with precipitation in the western United States. *Int. J. Climatol.* 19 (13), 1399–1410.

Mesoudi, A. (2018). Migration, acculturation, and the maintenance of between-group cultural variation. *PLoS One* 13 (10), 1–23. doi:10.1371/journal.pone.0205573

Mills, B. J., Clark, J. J., Peeples, M. A., Haas, W. R., Roberts, J. M., Hill, J. B., et al. (2013a). Transformation of social networks in the late pre-Hispanic US Southwest. *Proc. Natl. Acad. Sci. U.S.A.* 110 (15), 5785–5790. doi:10.1073/pnas.1219966110

Mills, B. J., Roberts, J. M., Jr, Clark, J. J., Haas, W. R., Jr, Huntley, D., Peeples, M. A., et al. (2013b). "The dynamics of social networks in the late prehispanic US southwest," in *Network analysis in archaeology: new approaches to regional interaction*. (Oxford : Oxford University Press), Chap. 8, 181–202.

Mills, B. J., Peeples, M. A., Haas, W. R., Jr., Borck, L., Clark, J. J., and Roberts, J. M., Jr. (2015). Multiscalar perspectives on social networks in the late prehispanic southwest. *Am. Antiq.* 80 (1), 3–24. doi:10.7183/0002-7316.79.4.3

Murphy, M. A., Dezzani, R., Pilliod, D. S., and Storfer, A. (2010). Landscape genetics of high mountain frog metapopulations. *Mol. Ecol.* 19 (17), 3634–3649. doi:10.1111/j.1365-294X.2010.04723.x

Nelson, M. C., Kintigh, K., Abbott, D. R., and Anderies, J. M. (2010). The cross-scale interplay between social and biophysical context and the vulnerability of irrigation-dependent societies: archaeology's longterm perspective. *Ecol. Soc.* 15 (3). doi:10.5751/es-03389-150331

Nolin, D. A. (2010). Food-Sharing networks in lamalera, Indonesia: reciprocity, kinship, and distance. *Hum. Nat.* 21 (3), 243–268. doi:10.1007/s12110-010-9091-3

North, G. R., Bell, T. L., and Cahalan, R. F. (1982). Sampling errors in the estimation of empirical orthogonal funtions. *Mon. Weather Rev.* 110 (7), 699–706.

Paliou, E., and Bevan, A. (2016). Evolving settlement patterns, spatial interaction and the socio-political organisation of late Prepalatial south-central Crete. *J. Anthropol. Archaeol.* 42, 184–197. doi:10.1016/j.jaa.2016.04.006

Peeples, M. A., and Haas, W. R. (2013). Brokerage and social capital in the prehispanic U.S. Southwest. *Am. Anthropol.* 115 (2), 232–247. doi:10.1111/aman.12006

Pingel, T. J. (2010). Modeling slope as a contributor to route selection in mountainous areas. *Cartogr. Geogr. Inf. Sci.* 37 (2), 137–148. doi:10.1559/152304010791232163

Rautman, A. E. (1993). Resource variability, risk, and the structure of social networks: an example from the prehistoric southwest. *Am. Antiq.* 58 (3), 403–424. doi:10.2307/282104

Richman, M. B. (1986). Review article: rotation of principal components. *J. Climatol.* 6, 293–335. doi:10.1002/joc.3370060305

Routson, C. C., Woodhouse, C. A., Overpeck, J. T., Betancourt, J. L., and McKay, N. P. (2016). Teleconnected ocean forcing of Western North American droughts and pluvials during the last millennium. *Quat. Sci. Rev.* 146, 238–250. doi:10.1016/j.quascirev.2016.06.017

Ryu, J. H., Svoboda, M. D., Lenters, J. D., Tadesse, T., and Knutson, C. L. (2010). Potential extents for ENSO-driven hydrologic drought forecasts in the United States. *Climatic Change* 101 (3), 575–597. doi:10.1007/s10584-009-9705-0

Schnegg, M. (2015). Reciprocity on demand : sharing and exchanging food in northwestern Namibia. *Hum. Nat.* 26 (3), 313–330. doi:10.1007/s12110-015-9236-5

Seager, R., and Hoerling, M. (2014). Atmosphere and ocean origins of North American droughts. *J. Clim.* 27 (12), 4581–4606. doi:10.1175/jcli-d-13-00329.1

Sen, A., and Smith, T. E. (1995). *Gravity models of spatial interaction behavior*. Oxford: Springer-Verlag.

Sheppard, P. R., Comrie, A. C., Packin, G. D., Angersbach, K., and Hughes, M. K. (2002). The climate of the US southwest. *Clim. Res.* 21, 219–238. doi:10.3354/cr021219

Shirk, A. J., Landguth, E. L., and Cushman, S. A. (2018). A comparison of regression methods for model selection in individual-based landscape genetic analysis. *Mol. Ecol. Resour.* 18 (1), 55–67. doi:10.1111/1755-0998.12709

Steiger, N. J., Smerdon, J. E., Cook, E. R., and Cook, B. I. (2018). A reconstruction of global hydroclimate and dynamical variables over the Common Era. *Sci. Data* 5, 1–15. doi:10.1038/sdata.2018.86

Stillman, P. E., Wilson, J. D., Denny, M. J., Desmarais, B. A., Bhamidi, S., Cranmer, S. J., et al. (2017). Statistical modeling of the default mode brain network reveals a segregated highway structure. *Sci. Rep.* 7 (1), 11694–11714. doi:10.1038/s41598-017-09896-6

Strawhacker, C., Snitker, G., Peeples, M. A., Kinzig, A. P., Kintigh, K. W., Bocinsky, K., et al. (2020). A landscape perspective on climate-driven risks to food security: exploring the relationship between climate and social transformation in the prehispanic U.S. Southwest. *Am. Antiq.* 85 (3), 427–451. doi:10.1017/aaq.2020.35

Strawhacker, C., Snitker, G., Spielmann, K. A., Wasiolek, M., Sandor, J., Kinzig, A., et al. (2017). "Risk landscapes and domesticated landscapes: food Security in the Salinas province," in *Landscapes of social transformation in the salinas province and the eastern pueblo world*. Editor K. A. Spielmann. (Tucson: University of Arizona Press), 103–118.

Taliaferro, M. S., Schriever, B. A., and Shackley, M. S. (2010). Obsidian procurement, least cost path analysis, and social interaction in the Mimbres area of southwestern New Mexico. *J. Archaeol. Sci.* 37 (3), 536–548. doi:10.1016/j.jas.2009.10.018

Tobler, W., and Wineburg, S. (1971). A cappadocian speculation. *Nature* 231 (5297), 39–41. doi:10.1038/231039a0

van Etten, J. (2017). R package gdistance: distances and routes on geographical grids. *J. Stat. Software* 76 (13), 1–21. doi:10.18637/jss.v076.i13

Varien, M. (1999). *Sedentism and mobility in a social landscape: mesa Verde and beyond*. Tucson: University of Arizona Press.

Verdery, A. M., Entwisle, B., Faust, K., and Rindfuss, R. R. (2012). Social and spatial networks: kinship distance and dwelling unit proximity in rural Thailand. *Soc. Networks* 34 (1), 112–127. doi:10.1016/j.socnet.2011.04.003

Vicente-Serrano, S. M., Beguería, S., López-Moreno, J. I., Angulo, M., and El Kenawy, A. (2010). A new global 0.5 gridded dataset (19012006) of a multiscalar drought index: comparison with current drought index datasets based on the palmer drought severity index. *J. Hydrometeorol.* 11 (4), 1033–1043. doi:10.1175/2010jhm1224.1

Weiss, B. (1982). The decline of Late Bronze Age civilization as a possible response to climatic change. *Climatic Change* 4 (2), 173–198.

Wilson, A. (2008). Boltzmann, Lotka and Volterra and spatial structural evolution: an integrated methodology for some dynamical systems. *J. R. Soc. Interface*. 5 (25), 865–871. doi:10.1098/rsif.2007.1288

Wilson, A. (1971). Family of spatial interaction models, and associated developments. *Environ. Plann*. 3 (1), 1–32. doi:10.1068/a030001

Wood, S. N. (2006). *Generalized additive models: an introduction with R*. Boca Raton: Chapman and Hall/CRC press.

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Different Human–Dog Interactions in Early Agricultural Societies of China, Revealed by Coprolite

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Dogs served in a variety of capacities in prehistory. After their domestication in Paleolithic hunter-gatherer societies, the emergence of agriculture shifted their partnerships with people. However, the associations between dogs and early farmers are not readily visible in the archaeological record. In the present study, dog coprolites, uncovered from two groups of early agricultural societies in China during the Neolithic Age, the early rice agricultural site of Tianluoshan in the lower Yangtze River, and three early millet-rice mixed agricultural sites of Shuangdun, Yuhuicun, and Houtieying along the middle Huai River, were examined based on the comparisons of lipid and palynological results to reveal different relationships of dogs and humans. The Tianluoshan dogs showed a plant-dominated diet with higher contents of plant sterols and fatty alcohols with longer chain lengths. Dogs may have lived on foraging or been provisioned with refuse for the cleanness purpose. On the contrary, dogs from the sites of Shuangdun, Yuhuicun, and Houtieying showed a meat-dominated diet with higher proportions of animal sterols and short-chain fatty alcohols. It most probably referred to their assistance in hunting and thus being provisioned with meat. Furthermore, activity areas of the dogs also reflect different deployment strategies and agricultural systems, evidenced by pollen spectra from the coprolites. Dogs at Tianluoshan mostly appeared in the rice field area, in correspondence with the labor-consuming rice cultivation as the main targeted resource, showing their participation in daily agricultural activities. On the other hand, high concentrations of pollen from forest and grassland revealed that hunting dogs played a regular role in the early millet-rice mixed farming societies, probably related to the importance of hunting activities in the daily subsistence.

Keywords: coprolite, human–dog interaction, China, Lower Yangtze Region, Huai River Region, subsistence

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INTRODUCTION

As the first domestic animal, current archaeological and genetic evidence suggest that dogs emerged during the Late Pleistocene (Germonpré et al., 2009, Germonpre et al., 2012; Ovodov et al., 2011; Larson et al., 2012). Historical records revealed that dogs participated in every aspect of human societies, helping in hunting, waste disposal, protection of people and belongings, guarding, entertainment, sacrifice, and offering (Vigne and Guilaine, 2004; Digard, 2006; Méniel, 2006; Horard-Herbin et al., 2014). However, in spite of the various capacities of dogs, few are perceivable in archaeological evidence, thus often remaining ambiguous (Lupo, 2011). With regard to Paleolithic Age when dogs joined hunting-gathering people, most research heavily relied on ethnographic records and emphasized their role of assistance for hunting in Late Pleistocene times, which greatly enhanced hunting productivity and catalyzed human population growth and spread (Lupo, 2017; Morey and Jeger, 2017). When agriculture emerged in the Neolithic Age, human–dog relationships may have changed, but it has rarely been discussed due to the lack of direct evidence. It has been assumed that the different functions of dogs in societies are correlated with variations in human subsistence and the reliance on resource categories (Lupo, 2019). It thus raises the questions of whether dogs continued helping with hunting among agricultural people living in permanent villages, when hunting success was not a crucial part for subsistence, and whether dogs were treated variably in different agricultural systems.

Dog coprolites have been uncovered in many prehistoric dwellings (e.g., Toker et al., 2005; Tolar and Galik, 2019; Borry et al., 2020), which indicated that they shared the same habitats with humans. Compared with traditional isotope analysis providing a rough dietary measurement and a broad signal of the average lifetime diet (e.g., Guiry, 2012), coprolites have the potentials to contribute to reconstructing the detailed diet of dogs and provide multiple lines of supporting evidence. Their high temporal resolution enables us to explore patterns of yearly, monthly, or even daily variability in diets. Lipids that normally appear in feces such as sterols and bile acids have been used as species indicators, but together with other molecules, they have the potentials to be applied as dietary indicators (Shillito et al., 2020).

In agricultural societies, different farming systems and subsistence strategies may leave traces in the diets of dogs. Dog coprolites uncovered from the early rice agricultural site of Tianluoshan in the Lower Yangtze Region, and three early millet-rice mixed agricultural sites of Shuangdun, Yuhuicun, and Houtieying along the middle Huai River, have been analyzed in the previous studies (Zhang et al., 2019; Zhang et al., 2020). All of the four sites were dated back to Middle-Late Neolithic Age (ca. 7000–5000 B.P.), an important time frame with transformation from hunter-gatherers to early farmers in prehistoric China. Our preliminary results showed that distinct lipid and palynological signals from the dog coprolites at two groups of sites indicate different diets of dogs and their living environments. By summarizing and comparing the above data, in the present study we intend to integrate lipid and palynological data to reveal different human–dog interactions. The results may further provide evidence of their associated agricultural systems and subsistence strategies.

ARCHAEOLOGICAL BACKGROUND AND THE STUDY SITE

Rice Agriculture in the Lower Yangtze Region and the Tianluoshan Site

Lower Yangtze Region has been widely recognized as one of the subcenters of rice domestication (Fuller et al., 2009; Nakamura, 2010; Gross and Zhao, 2014), and the domestication began as early as 10,000 B.P. or so at Shangshan (Zheng et al., 2016; Zuo et al., 2017). During the Middle Neolithic Age, rice remains including a minority of domesticated forms were found at Kuahuqiao (8,200–7000 B.P.), although the hunting-gathering subsistence still dominated (Zong et al., 2007). At a later stage, Hemudu (7000–5000 B.P.) is the representative culture of the Late Neolithic Age. A huge number of plant remains have been recovered in 1970s due to waterlogged condition of the site, among which the most noticeable were rice.

During the same period, dog remains of domesticated type have been uncovered in the Lower Yangtze Region. Morphometric data of dog remains from Kuahuqiao showed shortened dentition lengths, suggesting the domestication process has begun (Yuan and Yang, 2004). The sizes of the Hemudu dogs were similar to the modern domestic dog specimens and significantly smaller than wolves (Zhang, 2015).

Tianluoshan, a typical site of the Hemudu Culture, has been thoroughly excavated and studied in multidiscipline since 2004. Artifacts and radiocarbon dating analysis indicated that the lowest layers (8th and 7th layers) were dated back to ca. 7000–6,500 cal. B.P., representing the early phase of the Hemudu Culture. The 6-5th and 4-3rd layers of the Tianluoshan site were dated ca. 6,500–6,000 cal. B.P. and ca. 6,000–5,500 cal. B.P., comparable to the Middle and Late Hemudu Culture (Zhejiang Provincial Institute of Cultural Relics and Archaeology, 2007; Zhang, 2015).

An increased proportion of domesticated rice relative to wild gathered foods (Fuller et al., 2009) indicated the significance of rice domestication at Tianluoshan. Based on pollen, diatom, seed, and phytolith analysis, paddy fields reclaimed from wetlands provided suitable habitats for rice cultivation (Li et al., 2012; Zheng et al., 2012). Large amounts of acorns were uncovered from storage pits, indicating gathering activities in the mountain areas (Qin et al., 2010). It has also been speculated that forest edge was under human management through the analysis of wild fruits and seeds (Pan, 2011).

The analysis of the faunal remains pointed to the hunting of sika deer (*Cervus nippon*), sambar (*Cervus unicolor*), and muntjac (*Muntiacus reevesi*). Other mammal species including pig (*Sus* sp.), water buffalo (*Bubalus mephistopheles*), and a huge amount of freshwater fish (e.g., *Carassius auratus*, *Channa argus*) also provided meat income (Zhang, 2015). Dog is the only assured domestic animal at Tianluoshan, although it only accounted for 0.1%–0.2% of the identified specimens (Zhang, 2015).

Millet-Rice Mixed Farming Along the Huai River and the Shuangdun, Yuhuicun, and Houtieying Sites

The Huai River Valley, situated between the Yangtze and Yellow Rivers, is a core area for cultural exchange between northern and southern China. The interplay of rice and millet farming is the characteristic agricultural system in the Huai River Valley (Yang et al., 2016).

In the upper Huai River Valley, Jiahu (9,000–7800 B.P.) and Peiligang (9,000–7000 B.P.) are two representative cultures of the

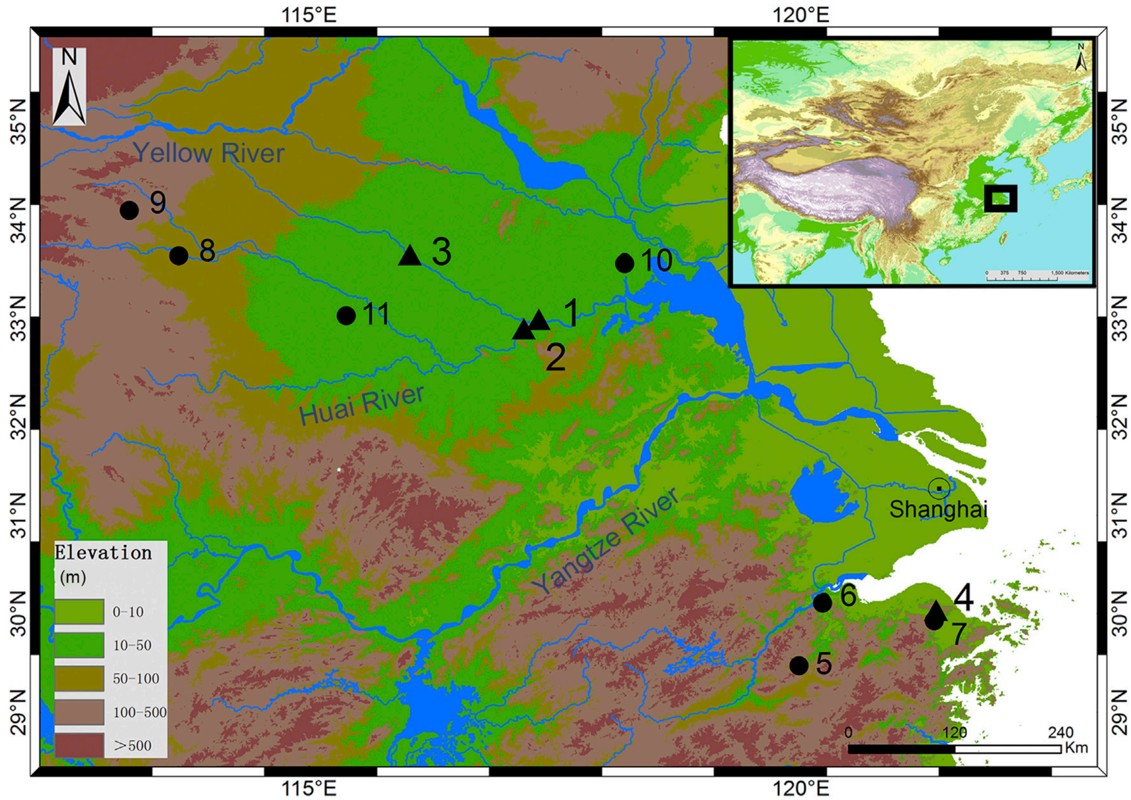

FIGURE 1 | Locations of the sites for study and other sites mentioned in the text (1. Shuangdun; 2. Yuhuicun; 3. Houtieying; 4. Tianluoshan; 5. Shangshan; 6. Kuahuqiao; 7. Hemudu; 8. Jiahu; 9. Tanghu; 10. Shunshanji; 11. Gongzhuang; black triangles indicate the sites for coprolite analysis in this study and black dots indicate the sites mentioned in the text).

Middle Neolithic Age. The analyses of the plant and animal remains indicated that rice was the only crop that appeared in large quantity at Jiahu and that a hunter-gatherer subsistence still formed the major part of the Jiahu economy (Zhang and Hung, 2013). Intentionally buried dogs were uncovered at Jiahu in cemeteries and beside houses (Henan Province Institute of Relics and Archaeology, 1999), indicating a strong relationship between human and dogs. The shortened dentition length of dogs showed that domestication progressed (Yuan, 2001). Phytolith analysis showed a broomcorn millet and rice mixed farming in the Peiligang Culture from 7800 B.P. at Tanghu (Zhang et al., 2012).

In the middle and lower Huai River Valley, Shuangdun (7300–6800 B.P.) and Shunshanji (8,500–7000 B.P.) are two representative Middle-Late Neolithic cultures, respectively. In the Shuangdun cultural sites, the analyses of seeds and starch grains emphasized the gathering of wild tuberous plants and rice was cultivated on a small scale (Dong et al., 2014; Cheng et al., 2016). As no millet remains were found, Shunshanji is supposed to have relied on rice farming, although a wide range of plant resources was detected by starch grain analysis including, e.g., *Coix lacryma-jobi*, Triticeae, *Oryza sativa*, and *Trichosanthes kirilowii*, indicating that gathering was still the main strategy (Yang et al., 2016; Luo et al., 2020).

At a later stage, Dawenkou Culture Period was an important stage for subsistence transformation from low-level food production to prehistoric agriculture (Luan, 2013). During early Dawenkou Period, although few sites have been studied, phytoliths from Gongzhuang showed a rice-dominated agriculture (Luo et al., 2018). During late Dawenkou Period, the cultivation of millet and broomcorn millet developed along the Huai River, integrated with the rice farming tradition (Cheng, 2020).

The three study sites, Shuangdun, Yuhuicun, and Houtieying, are situated in Anhui Province, along the mainstream and tributary of the Huai River (**Figure 1**). Shuangdun is the representative site of the Shuangdun Culture. Radiocarbon dating and stratigraphy showed that the Shuangdun site was dated back to 7300–6800 B.P. (Anhui Provincial Institute of Cultural Relics and Archaeology and the Museum of Bengbu, 2008). Sherds with special symbols, stone tools, clay sculptures, and abundant animal bones were discovered during the excavation in 1991–1992 and 2014 (Institute of Archaeology of Chinese Academy of Social Sciences and Museum of Bengbu, 2016). Phytoliths extracted from the sediments revealed that rice was the most common crop, while broomcorn millet appeared occasionally (Luo et al., 2019). At Yuhuicun, cultural remains recognized as the Shuangdun Culture (ca. 7000 B.P.) were uncovered during the excavation in 2017. More than 90 pits filled with sherds, bones and burnt soil, 160 column holes, and large wall base and living floor were discovered, exposing the planning of settlement and large constructions during the Shuangdun Period. Based on pottery morphology, Houtieying was identified as a typical site of Early-Middle Dawenkou Culture Period (ca. 6,500–6000 B.P.). During 2015 and 2016, systematic excavations revealed houses and pits, verifying the location of the settlement. Zoological analysis showed that deer and wild boar hunting provided the meat income, accompanied with a small number of Lamellibranchia. Domestic pigs also appeared at the site, indicating an early stage of pig husbandry (Dai and Zhang, 2018). At the three study sites, more than 100 coprolites have been uncovered at Shuangdun; however, only very few suspicious dog bones have been found at Shuangdun and Houtieying.

MATERIALS AND METHODS

103 dog coprolites were uncovered at Tianluoshan, in the 8th and 7th layers of trenches 205, 206, 301, 304, 305, 306, 403, 404, 405, and 406, within the main residential area of the early occupation period (ca. 7000 and 6,500 cal B.P.) (Zhejiang Provincial Institute of Cultural Relics and Archaeology, 2007). The coprolites were coded based on trench, layer, and sequential numbers (**Supplementary Material**). The palynological results have been published in Zhang et al. (2019) and in the present study all the lipid data were supplemented for comparative analysis.

The Yuhuicun and Houtieying coprolites originating from human and dogs were found in pits and excavated layers, usually accompanied with animal bones and dating back to the Shuangdun Cultural Period (ca. 7300–6800 B.P., Anhui Provincial Institute of Cultural Relics and Archaeology and the Museum of Bengbu, 2008) and the Early-Middle Dawenkou Culture Period (ca. 6,500–6000 B.P.), separately. All the pollen and lipid data from Yuhuicun and Houtieying have been published in Zhang et al. (2020). Here the results of dog coprolites from Yuhuicun and Houtieying were selected for comparison, including eight from Yuhuicun and four from Houtieying. Samples were named based on abbreviation of the site (Yuhuicun-YHC, Houtieying-HTY) and sequential numbers (**Supplementary Material**).

At Shuangdun, more than 100 coprolites were uncovered during the excavation. Most of them contain large bones with burnt inclusions. Based on morphology and contents, they have been identified as dog origin. However, probably because most coprolites have been burnt with animal bones and other objects, few pollen grains and lipid residues have been preserved. Therefore, in this paper only seven coprolites from Shuangdun were included to provide a general view and they were named based on abbreviation of the site (Shuangdun-SD) and sequential numbers (**Supplementary Material**).

To summarize the results and make the comparison, all the lipid and pollen data from the above sites were recalculated using new ratios to display the general pattern. All the new data from two groups of sites were compared and linked to their archaeological background for further interpretations in order to draw new conclusions.

Lipids

Fecal sterols in feces form from the gut through bacterial reduction of dietary sterols and have been widely used to distinguish the origins of the fecal materials. There are also potentials to assess the fecal lipids and other organic molecules as indicative of dietary preferences (Leeming et al., 1996; 1997). Through comparing the proportions of animal- and plant-derived sterols in the feces, it can give an indication of the relative inputs of meat and plants in the diets, which has been applied to the discussions of the diets of Neanderthals and nonhuman primates (Sistiaga et al., 2014; 2015). In dog feces, a special feature is the absence of 5β-stanols due to the lack of specific bifidobacteria inhibiting the production of 5β-stanols (Leeming et al., 1996). Therefore, fecal sterols in dog coprolites are less affected by biosynthesis processes during digestion and may directly represent the proportions of plant and animal intake from diets.

In the experimental procedures, all samples were ground with mortar and extracted with dichloromethane/methanol (DCM/MeOH) through Accelerated Solvent Extraction or ultrasonication. For the Tianluoshan coprolites, the extracts were gradient eluted using three separate solvents: hexane, hexane/DCM (4:1), and DCM/methanol (9:1). Alcohols and fatty acids were further fractionated with DCA/acetone (9:1) and 2% formic acid in DCM as elutions using an aminopropyl-coated stationary phase, and then the alcohol fraction was derivatized. To avoid loss, samples from Shuangdun, Yuhuicun, and Houtieying were directly derivatized by adding 50 μL of N,O-bis(trimethylsilyl)trifluoroacetamide (BSTFA) containing 1% trimethylchlorosilane (TMCS) and 50 μL hexane and heating at 70°C for 1 h. Gas chromatography mass spectrometry (GC/MS) analysis was conducted using an Agilent 7890A-5975C GC-MS equipped with HP-5MS column or a ThermoQuest TraceMS GC-MS equipped with DB5 column. *N*-alkanes, *n*-alcohols, and steroids were identified based on their mass spectra and the comparison of the retention times with standards.

Thirty-one coprolites from Tianluoshan and eight coprolites from Shuangdun, Yuhuicun, and Houtieying yielded detectable concentrations of lipids which were chosen for the comparison of lipid data. To summarize the proportions of plant- and animal-derived food in diets, the ratios of animal and plant sterols were calculated using the data from two groups of sites. The sum of animal sterols includes coprostanol, epicoprostanol, cholesterol, cholestanol, cholestan-3-one, and cholest-5-en-7-one. The sum of plant sterols includes 5β-stigmastanol, 5β-campestanol, sitosterol, and 5α-stigmastanol. As fatty alcohols were best preserved in the coprolites, average chain lengths of fatty alcohols were also calculated for each sample. *T* test was adopted to determine if there is significant difference in average chain lengths between two groups of sites. p value of 0.01 was used as criterion.

Pollen

Pollen contents of coprolites can provide valuable information on past vegetation and landscape (e.g., Yll et al., 2006; Wood et al., 2012; Taylor et al., 2020). It has been proposed that the dung pollen record may reflect the vegetation of the visiting areas of its producer or their prey (Carrión et al., 2001) and the range of habitats (Djamali et al., 2011). As an analogue, the palynological data from the coprolites of dogs in an archaeological context may also indicate the surrounding vegetations where they have visited.

In the experiments, extraction procedures for pollen grains followed Faegri et al. (1989), including KOH digestion, sieving (meshes 120 μm), bromoform-ethanol mixture (specific gravity 2) extraction, and acetolysis. To avoid any possible damage to the pollen grains, pretreatment procedures for the Shuangdun, Yuhuicun, and Houtieying coprolites only included digestion with 2 N HCl, sieving (meshes 355 μm), and zinc bromide (specific gravity 2) extraction. For each sample, a minimum of 300 pollen grains were identified and calculated as percentages. Considering the high frequencies of *Typha* pollen probably from local origin at Tianluoshan, *Typha* was excluded from the pollen sum for percentage calculations.

To compare the differences between two groups of sites, pollen data of eighty-two coprolites from Tianluoshan and ten coprolites from Yuhuicun and Houtieying that yielded enough pollen grains for counting were summarized into ecological groups based on the growth environment of the plants, i.e., wetland herbs, upland herbs, shrubs, and trees. In addition, large Poaceae (35–39 μm and >40 μm) pollen has been identified as criterion to represent the development of rice farming at Hemudu (Wang et al., 2010; Liu et al., 2016). Therefore, large Poaceae (35–39 μm and >40 μm) was selected to represent rice field vegetation and Poaceae (< 35 μm) was categorized into upland herbs.

RESULTS

Lipids

Within the thirty-one coprolites analyzed from Tianluoshan, twenty-six show higher proportions of plant sterol, ranging from 53.13% to 96.63% (average 72.26%), and less animal sterol, ranging from 3.37% to 46.85% (average 27.74%). Only five samples contain animal sterol of more than 50%, ranging from 53.69% to 94.53%. On the contrary, six coprolites from Yuhuicun and Houtieying contain 100% of animal sterol. The other two samples from Houtieying show equal contents of animal and plant sterols, with the plant sterol slightly higher. In addition, only trace amount of cholesterol was detected in one coprolite from Shuangdun.

Similarly, coprolites from Tianluoshan exhibit similar average chain lengths, ranging from 19.34 to 23.84 (average 21.35, stdev 0.81). The average chain length values of samples from Shuangdun, Yuhuicun, and Houtieying range from 12.41 to 26.56 (average 20.57, stdev 4.96), relatively lower than that of the Tianluoshan coprolites (**Figure 2**). The large variations between samples (stdev 4.96) from Yuhuicun and Houtieying are in correspondence with the sterol profiles such that they are either dominated by animal sterol or show a mix of plant and animal sterols. Probably because of this variation, the p value of 0.55 indicates that there is no significant difference in average chain lengths between two groups of sites.

Pollen

Large Poaceae pollen is the prevalent pollen species in most samples from Tianluoshan. Fourty-nine coprolites show large Poaceae pollen with highest proportions, ranging from 28.30% to 85.07%. They are either predominated by large Poaceae or accompanied with relatively higher percentages of arbor and upland herbs. Arboreal pollen reaches highest frequencies in eighteen samples (26.46%–77.74%). *Quercus* usually shows highest values, with other species including *Castanopsis*, *Liquidambar*, *Pinus*, and *Ulmus*, and upland herbs usually also reach higher values. The other fifteen samples are dominated by shrub pollen (43.81%–94.16%), with abundant species including Rosaceae, *Astragalus*, *Uncaria*, *Mallotus*, and arboreal and large Poaceae pollen to a lesser extent. Generally, upland herbs and wetland herbs occur less frequently in all samples.

On the other hand, five coprolites from Yuhuicun and one from Houtieying are dominated by arboreal pollen (90.00%–96.00%). *Quercus* is the most abundant pollen taxon, with percentages between 85.71% and 95.67%. Pollen from upland herbs is in lower percentages and wetland herbs occur more sporadically. Other samples mainly contain pollen from upland herbs (42.00%–95.36%). Poaceae is generally abundant and *Artemisia* reaches the highest frequency in YHC-9. In YHC-7, wetland herbs dominated by *Typha* are prevalent (**Figure 3**).

DISCUSSION

Implications of Dog Provisions and Their Role in Human Subsistence

Based on the sterol compounds, our results generally reflect a plant-dominated diet at Tianluoshan and a meat-dominated diet at Shuangdun, Yuhuicun, and Houtieying. Clusters of large undigested bone remains are present in the coprolites from the latter sites, also indicating the meat intake. At Tianluoshan, impressions of plant materials can be observed (**Figure 4**). The sterol profiles are in correspondence with the average chain lengths of fatty alcohols that the samples from Tianluoshan contain more fatty alcohols with long chain lengths from the input of leaf waxes. However, compared with the lipid data from Tianluoshan, results from Yuhuicun and Houtieying are more fluctuated, with samples either dominated by cholesterol and cholestanol or showing higher input of plant sterols and wider distributions of fatty alcohols.

It has been assumed that there will be dietary variations between wild canine populations that subsist on a diversity of resources (including human refuse) and domestic dogs that rely on domestic waste and human provisioning (Lupo, 2019). Barton et al. (2009) classified the above two types of dogs appearing at Dadiwan, a Middle Neolithic site in northern China: 1) "camp followers" wild-foraging dogs that benefited from a close association with humans and 2) camp-fed, behaviorally domestic dogs that lived and hunted with humans. The second type of dogs consumed more animal products and millets than did wild-foraging dogs, implying the intentional provisioning by humans.

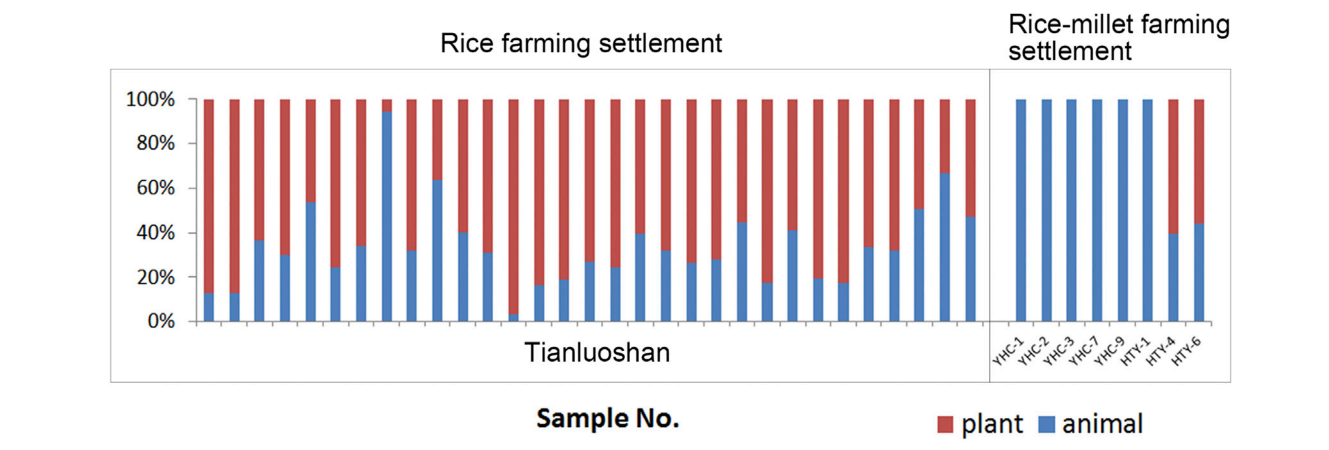

FIGURE 2 | Proportions of plant- and animal-derived sterols in coprolites recovered from rice farming settlement and mixed farming settlements.

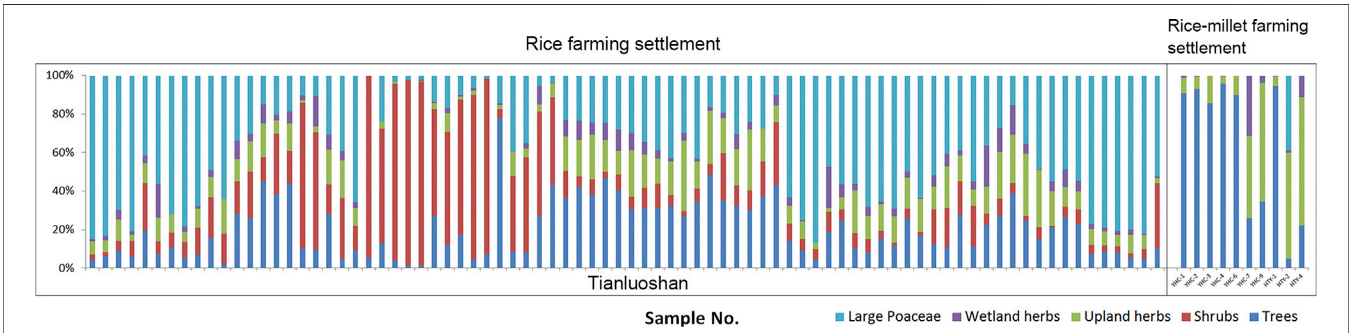

FIGURE 3 | Proportions of pollen groups in the spectrum of the coprolites for this study (note: twenty-one coprolites with extremely high contents of *Typha* pollen were excluded).

Using the above classifications, it can be distinguished that the dogs at Tianluoshan were more similar to the "camp followers" at Dadiwan that may have fed on domestic scraps. The sedentary and agricultural lifestyle at Tianluoshan may have supplied predictable and stable anthropogenic refuse for their diets to rely on scavenging discarded food waste. Caceotrophy, the consumption of feces commonly found in dogs, may have provided extra nutrients.

On the other hand, Shuangdun, Yuhuicun, and Houtieying dogs consumed higher proportions of meat, more similar to the camp-fed, behaviorally domestic dogs at Dadiwan. It is highly probable that they assisted with hunting because hunting dogs usually consume more meat, and the canine population used for hunting could only be sustained with intentional provisioning by humans. Otherwise, ethnographic records revealed that anthropogenic food refuse from small-sized villages could not establish or support an indigenous working dog population as canid scavengers (Lupo, 2019). The fluctuated diets may rely on the outcome of hunting and thus the feasibility of meat. At Houtieying, more plant input from dogs' diets may also relate to the less dependence on hunting at a later stage. However, as only the coprolites left in the site were examined, the results could only represent the diets when dogs were wandering around the site. We cannot rule out the possibility that the Tianluoshan dogs may have participated in hunting activities but left the feces in other temporary camps, where they also had a meat-dominated diet.

Furthermore, the food of dogs is also in correspondence with human diet. Lipid analysis of pottery residues at Tianluoshan has revealed that the pottery was largely used for processing starchy plant foods, yet the evidence for processing fish was very limited (Shoda et al., 2018), similar to the dominated plant intake of dogs. On the contrary, animal bones were uncovered in large quantities at Shuangdun, Yuhuicun, and Houtieying, depicting the subsistence relying on animals. A similar phenomenon was observed at the early Neolithic site of Jiahu, where large amounts of suspected dog coprolites were found. Hunting tools account for 49.2% of the Jiahu artifacts, above fishing tools (24.8%) and agricultural tools (26%), indicating a meat-dominated lifestyle (Lai et al., 2009).

Comparing the diets of humans and dogs, it can be concluded that dogs at all sites were permitted to roam freely and scavenge domestic refuse, thus their diets highly overlapped with that of humans. However, different human–dog relationships still

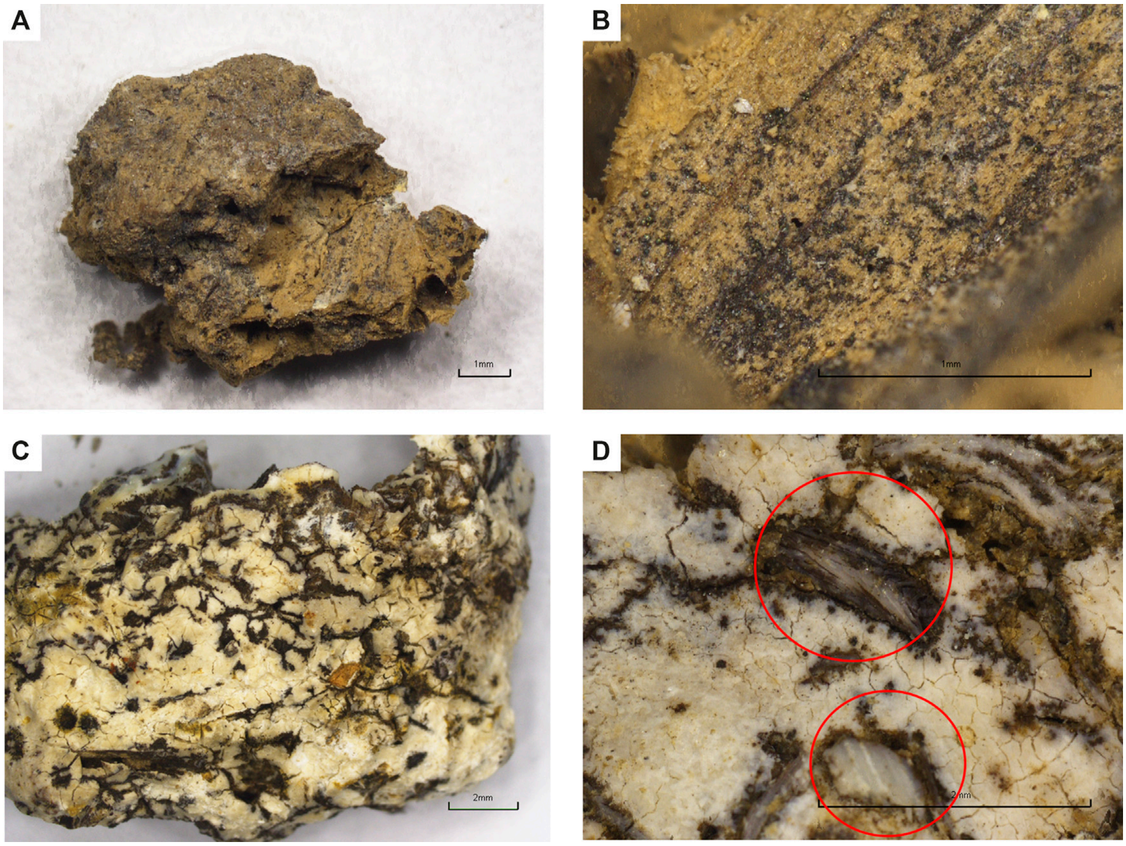

FIGURE 4 | Microscope photos of the cross sections of the coprolites. **(A)** Tianluoshan coprolite with incorporated plant materials. **(B)** Reticulate impressions of plant remains from the Tianluoshan coprolite. **(C)** Undigested bone fragments from the Yuhuicun coprolite. **(D)** Small bones (marked in red circle) incorporated in the Yuhuicun coprolite.

existed at two groups of sites. The Tianluoshan dogs may have relied on foraging of daily waste and used it for cleaning purpose, at least. Through consuming human waste, their existence in the food chain also accelerated the recycling of organic materials at the site. On the other hand, at Shuangdun, Yuhuicun, and Houtieying, hunting dogs may have been intentionally provided with meat, which maintained their role as the apex predator.

Activity Areas for Subsistence and Human–Dog Interactions Indicated by Pollen Data

Pollen spectra from dog coprolites are indicators of the places they have visited and also the frequencies. Comparing the pollen data from Tianluoshan and Shuangdun, Yuhuicun, and Houtieying, the results showed that the Tianluoshan dogs mostly appeared in the rice field area, and scarcely in shrub and forest areas, while the Yuhuicun and Houtieying dogs mainly visited the forest and upland grassland.

Considering the agricultural background at two groups of sites, the perennial wetland rice usually required more labor investment and intensive forms of management (Fuller and Qin, 2009). Therefore, wetland areas were heavily exploited at Tianluoshan, where dogs also spent most of their time. Moreover, the management of various wild plants has been recorded at Tianluoshan and shrub pollen also appeared in dog feces frequently, showing their similar activity area. Dogs may have accompanied humans for guarding or working in agricultural activities or even been raised for their products such as meat, skin, or bones.

On the contrary, at Yuhuicun and Houtieying, pollen data showed that forest and grassland were the main activity areas for dogs. Their appearance in the *Quercus* forest is in correspondence with the use of dogs as a hunting tool. At Yuhuicun, although rice and millets may have appeared, evidenced by the phytolith data at Shuangdun (Luo et al., 2019), our results show that hunting may still have been the main function of dogs. As fast-growing, warm-season crops, millets were grown as a low labor investment rain-fed summer crop (Miller et al., 2016). Therefore, compared with the single rice agricultural system at Tianluoshan, labors targeting at other resources in the forest were more available, and dogs may have continued their assistance in hunting. Stable isotope analysis at Dadiwan also suggested that broomcorn millet initially appeared in an economy that relied on hunting and dogs were likely the crucial tools in the hunting system of early millet-rice mixed farmers (Barton et al., 2009; Bettinger et al., 2010). At the later stage site of Houtieying, the high concentrations of miliacin and the presence of large Poaceae pollen all point to the existence of dogs in a more stable millet-rice mixed cultivation area, and their role may have transformed to the assistance in farming activities, similar to the domestic dogs at Tianluoshan.

CONCLUSION

Lipid and pollen data from dog coprolites uncovered from two groups of sites, i.e., Tianluoshan and Shuangdun, Yuhuicun, and Houtieying, were compared to reveal their different dietary components and associated human–dog relationships. The Tianluoshan dogs had more plant intake, indicating the foraging of domestic waste, while the Shuangdun, Yuhuicun, and Houtieying dogs consumed more meat, revealing human intentional provision. The results imply that the Shuangdun, Yuhuicun, and Houtieying dogs may have participated in hunting and the Tianluoshan dogs lived as "camp followers." Furthermore, the activity areas of the Tianluoshan dogs were highly centered at the rice fields, while the Yuhuicun and Houtieying dogs mostly appeared in the forest and grassland. The results show that dogs were mainly used in the wetland-based early rice farming system at Tianluoshan and in the hunting-dominated subsistence at Yuhuicun. At a later stage, millet agriculture with low labor investment developed at Houtieying, but hunting still made up part of the food income. Compared with archaeological evidence from Paleolithic sites, our results showed that dogs were used for multifunctions in early farming societies. Dogs in early rice-millet mixed farming settlements continued participating in hunting, while in early rice agricultural settlement, dogs may have played regular role in farming habitats.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: https://doi.org/10.1016/j.revpalbo.2019.104101, https://doi.org/10.1016/j.jasrep.2019.102135.

AUTHOR CONTRIBUTIONS

YZ and XW designed the research. YZ performed the experiments and wrote the manuscript. DZ and GS provided samples for this study. XY and XW revised the manuscript, with contributions from all authors.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2020.633724/full#supplementary-material.

REFERENCES

Anhui Provincial Institute of Cultural Relics and Archaeology, and the Museum of Bengbu (2008). *Bengbu Shuangdun: excavation report of neolithic sites*. Beijing, China: Science Press [in Chinese, with English summary].

Barton, L., Newsome, S. D., Chen, F. H., Wang, H., Guilderson, T. P., and Bettinger, R. L. (2009). Agricultural origins and the isotopic identity of domestication in northern China. *Proc. Natl. Acad. Sci. U.S.A.* 106 (14), 5523–5528. doi:10.1073/pnas.0809960106

Bettinger, R. L., Barton, L., and Morgan, C. (2010). The origins of food production in north China: a different kind of agricultural revolution. *Evol. Anthropol.* 19 (1), 9–21. doi:10.1002/evan.20236

Borry, M., Cordova, B., Perri, A., Wibowo, M., Prasad Honap, T., Ko, J., et al. (2020). CoproID predicts the source of coprolites and paleofeces using microbiome composition and host DNA content. *PeerJ* 8, e9001. doi:10.7717/peerj.9001

Carrión, J. S., Riquelme, J. A., Navarro, C., and Munuera, M. (2001). Pollen in hyaena coprolites reflects late glacial landscape in southern Spain. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 176 (1–4), 193–205. doi:10.1016/s0031-0182(01)00338-8

Cheng, Z. (2020). A preliminary study on prehistoric agriculture during Dawenkou culture period in Huaihe river basin of Anhui provi. *Nongye Kaogu* 1, 22–28. doi:10.06-2335(2020)01-0022-07[in Chinese, with English summary].

Cheng, Z., Yang, Y., Zhang, J., Fang, F., Yu, J., Chen, B., et al. (2016). Research on charred plant remains from the Xiaosungang site in Huainan city, Anhui Province. *Quat. Sci.* 36, 302–311. doi:10.11928/j.issn.1001-7410.2016.02.06[in Chinese, with English summary].

Dai, L., and Zhang, D. (2018). The study of animal bones uncovered from the Houtieying site, Bozhou, Anhui Province. *Cultural Relics Southern China* 2018 (01), 142–150 [in Chinese, with English summary].

Digard, J.-P. (2006). Essai d'ethno-archeologie du chien. *Ethnozootechnie* 78, 33–40.

Djamali, M., Biglari, F., Abdi, K., Andrieu-Ponel, V., de Beaulieu, J.-L., Mashkour, M., et al. (2011). Pollen analysis of coprolites from a late Pleistocene-Holocene cave deposit (Wezmeh Cave, west Iran): insights into the late Pleistocene and late Holocene vegetation and flora of the central Zagros Mountains. *J. Archaeol. Sci.* 38 (12), 3394–3401. doi:10.1016/j.jas.2011.08.001

Dong, Z., Zhang, J., Yang, Y., Yao, L., Li, W., and Jia, Q. (2014). Starch grain analysis reveals the utilization of plant food resources at Shishanzi site, Suixi County, Anhui Province. *Quat. Sci.* 34, 114–125. doi:10.3969/j.issn.1001-7410.2014.01.14[in Chinese, with English summary].

Faegri, K., Kaland, P. E., and Krzywinski, K. (1989). *Textbook of pollen analysis*. 4th Edn. New York, NY: Wiley and Sons.

Fuller, D. Q., Qin, L., Zheng, Y., Zhao, Z., Chen, X., Hosoya, L. A., et al. (2009). The domestication process and domestication rate in rice: spikelet bases from the lower Yangtze. *Science* 323 (5921), 1607–1610. doi:10.1126/science.1166605

Fuller, D. Q., and Qin, L. (2009). Water management and labour in the origins and dispersal of Asian rice. *World Archaeol.* 41 (1), 88–111. doi:10.1080/00438240802668321

Germonpré, M., Lázničková-Galetová, M., and Sablin, M. V. (2012). Palaeolithic dog skulls at the Gravettian Předmostí site, the Czech Republic. *J. Archaeol. Sci.* 39 (1), 184–202. doi:10.1016/j.jas.2011.09.022

Germonpré, M., Sablin, M. V., Stevens, R. E., Hedges, R. E. M., Hofreiter, M., Stiller, M., et al. (2009). Fossil dogs and wolves from palaeolithic sites in Belgium, the Ukraine and Russia: osteometry, ancient DNA and stable isotopes. *J. Archaeol. Sci.* 36 (2), 473–490. doi:10.1016/j.jas.2008.09.033

Gross, B. L., and Zhao, Z. (2014). Archaeological and genetic insights into the origins of domesticated rice. *Proc. Natl. Acad. Sci. U.S.A.* 111 (17), 6190–6197. doi:10.1073/pnas.1308942110

Guiry, E. J. (2012). Dogs as analogs in stable isotope-based human paleodietary reconstructions: a review and considerations for future use. *J. Archaeol. Method Theor* 19 (3), 351–376. doi:10.1007/s10816-011-9118-z

Henan Institute of Cultural Relics and Archaeology (1999). *Wuyang Jiahu*. Beijing, China: Science Press [in Chinese, with English summary].

Horard-Herbin, M.-P., Tresset, A., and Vigne, J.-D. (2014). Domestication and uses of the dog in western Europe from the paleolithic to the iron Age. *Anim. Front.* 4 (3), 23–31. doi:10.2527/af.2014-0018

Institute of Archeology of Chinese Academy of Social Sciences, and Museum of Bengbu (2016). “Achievements of excavation of Shuangdun site in Bengbu city, Anhui province during the 2014 and 2015,” in *Major archaeological discoveries in China*. Beijing, China: National Cultural Heritage Administration (Beijing, Heritage Press, , 20–24 [in Chinese, with English summary].

Lai, Y., Zhang, J., and Ying, R. (2009). The prehistoric economy of the site of Jiahu, information from the analysis of the unearthed artifacts. *Zhongyuan wenwu* 2, 22–28. doi:10.3969/j.issn.1003-1731.2009.02.005[in Chinese, with English summary].

Larson, G., Karlsson, E. K., Perri, A., Webster, M. T., Ho, S. Y., Peters, J., et al. (2012). Rethinking dog domestication by integrating genetics, archeology, and biogeography. *Proc. Natl. Acad. Sci. U.S.A.* 109 (23), 8878–8883. doi:10.1073/pnas.1203005109

Leeming, R., Latham, V., Rayner, M., and Nichols, P. (1997). “Detecting and distinguishing sources of sewage pollution in Australian inland and coastal waters and sediments,” in *Molecular markers in environmental geochemistry*. Editor R. P. Eganhouse (Washington, DC: American Chemical Society), 306–319.

Leeming, R., Ball, A., Ashbolt, N., and Nichols, P. (1996). Using faecal sterols from humans and animals to distinguish faecal pollution in receiving waters. *Water Res.* 30 (12), 2893–2900. doi:10.1016/s0043-1354(96)00011-5

Li, C., Zheng, Y., Yu, S., Li, Y., and Shen, H. (2012). Understanding the ecological background of rice agriculture on the Ningshao Plain during the Neolithic Age: pollen evidence from a buried paddy field at the Tianluoshan cultural site. *Quat. Sci. Rev.* 35, 131–138. doi:10.1016/j.quascirev.2012.01.007

Liu, Y., Sun, Q., Fan, D., Lai, X., Xu, L., Finlayson, B., et al. (2016). Pollen evidence to interpret the history of rice farming at the Hemudu site on the Ningshao coast, eastern China. *Quat. Int.* 426, 195–203. doi:10.1016/j.quaint.2016.05.016

Luan, F. S. (2013). “The Dawenkou culture in the lower Yellow River and Huai River basin areas” in *A companion to Chinese Archaeology*. Editor A. P. Underhill (Hoboken, NJ: Blackwell Publishing Ltd.), 411–434.

Luo, W., Gu, C., Yang, Y., Zhang, D., Liang, Z., Fang, F., et al. (2018). Phytolith evidence for the development of agriculture between early Dawenkou and Longshan cultures at the Gongzhuang site in Linquan county, Anhui province. *Acta Micropalaeontol. Sin.* 35 (4), 370–380 [in Chinese, with English summary].

Luo, W., Gu, C., Yang, Y., Zhang, D., Liang, Z., Li, J., et al. (2019). Phytoliths reveal the earliest interplay of rice and broomcorn millet at the site of Shuangdun (ca. 7.3-6.8 ka BP) in the middle Huai River valley, China. *J. Archaeol. Sci.* 102, 26–34. doi:10.1016/j.jas.2018.12.004

Luo, W., Yang, Y., Zhuang, L., Gan, H., Gu, C., Huang, C., et al. (2020). Phytolith evidence of water management for rice growing and processing between 8500 and 7500 cal years BP in the middle Huai river valley, China. *Veg. Hist. Archaeobotany*, 1–12. doi:10.1007/s00334-020-00782-2

Lupo, K. D. (2011). “A dog is for hunting” in *Ethnozooarchaeology: the present and past of human-animal relationships*. Editors U. Albarella and A. Trentacoste (London, United Kingdom: Oxbow Press), 4–12.

Lupo, K. D. (2019). Hounds follow those who feed them: what can the ethnographic record of hunter-gatherers reveal about early human-canid partnerships? *J. Anthropol. Archaeol.* 55, 101081. doi:10.1016/j.jaa.2019.101081

Lupo, K. D. (2017). When and where do dogs improve hunting productivity? The empirical record and some implications for early Upper Paleolithic prey acquisition. *J. Anthropol. Archaeol.* 47, 139–151. doi:10.1016/j.jaa.2017.05.003

Méniel, P. (2006). Le chien en Gaule, Animali tra uomini e dei, archeozoologia del mondo preromano. *Studi e Scavi* 14, 45–52.

Miller, N. F., Spengler, R. N., and Frachetti, M. (2016). Millet cultivation across Eurasia: origins, spread, and the influence of seasonal climate. *Holocene* 26 (10), 1566–1575. doi:10.1177/0959683616641742

Morey, D. F., and Jeger, R. (2017). From wolf to dog: late Pleistocene ecological dynamics, altered trophic strategies, and shifting human perceptions. *Hist. Biol.* 29 (7), 895–903. doi:10.1080/08912963.2016.1262854

Nakamura, S.-I. (2010). The origin of rice cultivation in the lower Yangtze region, China. *Archaeol. Anthropol. Sci.* 2, 107–113. doi:10.1007/s12520-010-0033-0

Ovodov, N. D., Crockford, S. J., Kuzmin, Y. V., Higham, T. F., Hodgins, G. W., van der Plicht, J., et al. (2011). A 33,000-year-old incipient dog from the Altai mountains of Siberia: evidence of the earliest domestication disrupted by the last glacial maximum. *PLoS One* 6, e22821. doi:10.1371/journal.pone.0022821

Pan, Y. (2011). Resource production of the Yangzi Delta and Qiantang drainage during 10000-6000 BP: paleoethnobotany and human ecology studies. PhD thesis. Fudan (China): Fudan University [in Chinese, with English summary].

Qin, L., Fuller, D., and Zhang, H. (2010). Modelling wild food resource catchments among early farmers: case study from the lower Yangtze and central China. *Quat. Sci.* 30, 245–261 [in Chinese, with English summary].

Shillito, L. M., Blong, J. C., Green, E. J., and Van Asperen, E. (2020). The what, how and why of archaeological coprolite analysis. *Earth Sci. Rev.* 207, 103196. doi:10.1016/j.earscirev.2020.103196

Shoda, S., Lucquin, A., Sou, C. I., Nishida, Y., Sun, G., Kitano, H., et al. (2018). Molecular and isotopic evidence for the processing of starchy plants in Early Neolithic pottery from China. *Sci. Rep.* 8 (1), 17044–17049. doi:10.1038/s41598-018-35227-4

Sistiaga, A., Mallol, C., Galván, B., and Summons, R. E. (2014). The Neanderthal meal: a new perspective using faecal biomarkers. *PLoS One* 9 (6), e101045. doi:10.1371/journal.pone.0101045

Sistiaga, A., Wrangham, R., Rothman, J. M., and Summons, R. E. (2015). New insights into the evolution of the human diet from faecal biomarker analysis in wild chimpanzee and gorilla faeces. *PLoS One* 10 (6), e0128931. doi:10.1371/journal.pone.0128931

Taylor, A., Hutson, J. M., Bryant, V. M., and Jenkins, D. L. (2020). Dietary items in early to late holocene human coprolites from paisley caves, Oregon, USA. *Palynology* 44 (1), 12–23. doi:10.1080/01916122.2018.1530699

Toker, N. Y., Onar, V., Belli, O., Ak, S., Alpak, H., and Konyar, E. (2005). Preliminary results of the analysis of coprolite material of a dog unearthed from the Van-Yoncatepe necropolis in eastern Anatolia. *Turk. J. Vet. Anim. Sci.* 29 (3), 759–765.

Tolar, T., and Galik, A. (2019). A study of dog coprolite from late neolithic pile-dwelling site in Slovenia. *Ad* 07 (01), 20. doi:10.4236/ad.2019.71002

Vigne, J. D., and Guilaine, J. (2004). Les premiers animaux de compagnie, 8500 ans avant notre ère? ou comment j'ai mangé Mon chat, Mon chien et Mon renard. *Anthropozoologica* 39 (1), 249–273.

Wang, W., Shu, J., Chen, W., and Ding, J. (2010). Holocene environmental changes and human impact in the Yangtze river delta area, east China. *Quat. Sci.* 30 (2), 233e244. doi:10.3969/j.issn.1001-7410.2010.02.01 [in Chinese, with English summary].

Wood, J. R., Wilmshurst, J. M., Wagstaff, S. J., Worthy, T. H., Rawlence, N. J., and Cooper, A. (2012). High-resolution coproecology: using coprolites to reconstruct the habits and habitats of New Zealand's extinct upland moa (Megalapteryx didinus). *PLoS One* 7 (6) e40025. doi:10.1371/journal.pone.0040025

Yang, Y., Cheng, Z., Li, W., Yao, L., Li, Z., Luo, W., et al. (2016). The emergence, development and regional differences of mixed farming of rice and millet in the upper and middle Huai River Valley, China. *Sci. China Earth Sci.* 59 (9), 1779–1790. doi:10.1007/s11430-015-5340-3

Yang, Y., Li, W., Yao, L., Cheng, Z., Luo, W., Zhang, J., et al. 2016). Plant food sources and stone tools' function at the site of Shunshanji based on starch grain analysis. *Sci. China Earth Sci.* 59 (8), 1574–1582. doi:10.1007/s11430-016-5321-9

Yll, R., Carrión, J. S., Marra, A. C., and Bonfiglio, L. (2006). Vegetation reconstruction on the basis of pollen in late pleistocene hyena coprolites from San Teodoro Cave (Sicily, Italy). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 237 (1), 32–39. doi:10.1016/j.palaeo.2005.11.027

Yuan, J. (2001). Issues on the origin of livestock in Neolithic China. *Wen Wu* 5, 51–58 [in Chinese, with English summary].

Yuan, J., and Yang, M. (2004). "Research on animal remains," in *Zhejiang provincial institute of relics and archaeology and museum of Xiaoshan*. Editor Kuhuqiao (Beijing, China: Cultural Relic Press), 241–270 [in Chinese, with English summary].

Zhang, C., and Hung, H. C. (2013). Jiahu 1: earliest farmers beyond the Yangtze river. *Antiquity* 87 (335), 46–63. doi:10.1017/S0003598X00048614

Zhang, J., Lu, H., Gu, W., Wu, N., Zhou, K., Hu, Y., et al. (2012). Early mixed farming of millet and rice 7800 years ago in the middle Yellow River region, China. *PLoS One* 7, e52146–e52148. doi:10.1371/journal.pone.0052146

Zhang, Y. (2015). Animal procurement in the late neolithic of the Yangtze River basin: integrating the fish remains into a case-study from tianluoshan. PhD thesis. London (United Kingdom): University College London.

Zhang, Y., van Geel, B., Gosling, W. D., McMichael, C. N. H., Jansen, B., Absalah, S., et al. (2019). Local vegetation patterns of a neolithic environment at the site of Tianluoshan, China, based on coprolite analysis. *Rev. Palaeobot. Palynol.* 271, 104101. doi:10.1016/j.revpalbo.2019.104101

Zhang, Y., Zhang, D., Yang, Y., and Wu, X. (2020). Pollen and lipid analysis of coprolites from Yuhuicun and Houtieying, China: implications for human habitats and diets. *J. Archaeol. Sci.: Report* 29, 102135. doi:10.1016/j.jasrep.2019.102135

Zhejiang Provincial Institute of Cultural Relics and Archaeology, Yuyao Municipal Council of Cultural Relics Conservation, Hemudu Site Museum (2007). Brief report of the excavation on a neolithic site at Tianluoshan hill in Yuyao city, Zhejiang. *Cultural Relics* 11, 4–24 [in Chinese, with English summary].

Zheng, Y., Crawford, G. W., Jiang, L., and Chen, X. (2016). Rice domestication revealed by reduced shattering of archaeological rice from the lower Yangtze valley. *Sci. Rep.* 6, 28136. doi:10.1038/srep28136

Zheng, Y., Sun, G., and Chen, X. (2012). Response of rice cultivation to fluctuating sea level during the Mid-Holocene. *Chin. Sci. Bull.* 57, 370–378. doi:10.1007/s11434-011-4786-3

Zong, Y., Chen, Z., Innes, J. B., Chen, C., Wang, Z., and Wang, H. (2007). Fire and flood management of coastal swamp enabled first rice paddy cultivation in east China. *Nature* 449 (7161), 459–462. doi:10.1038/nature06135

Zuo, X., Lu, H., Jiang, L., Zhang, J., Yang, X., Huan, X., et al. (2017). Dating rice remains through phytolith carbon-14 study reveals domestication at the beginning of the Holocene. *Proc. Natl. Acad. Sci. U.S.A.* 114 (25), 6486–6491. doi:10.1073/pnas.1704304114

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Impacts of the Wetland Environment on Demographic Development During the Neolithic in the Lower Yangtze Region—Based on Peat and Archaeological Dates

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Wetlands were important resources for the hunting–gathering and early farming communities in coastal areas in the Neolithic. However, the relationship between the development of the wetland environment and the human population remains unclear due to the lack of successive wetland environmental changes throughout the Holocene in coastal areas. Here, the summed probability distributions (SPD) of radiocarbon dates of peat were used as an indicator and combined with archaeological radiocarbon dates to reconstruct the wetland environmental and demographic changes during the Neolithic in the lower Yangtze region. The results showed that the shifts in demographic centers and population development were related to wetland environment with peat formation. The first shift of the demographic center was from the hilly regions to the coastal plain and occurred during ca. 8,300–8,000 cal yr BP, which might be caused by the attractiveness of survival resources offered by the coastal wetland environment and the 8.2 ka event. The second shift occurred from the Ningshao Plain to the Taihu region and might be attributed to the widespread waterlogged environment in the Ningshao Plain. The peak of demographic development coincided with the peak of peat formation during the middle Holocene in the lower Yangtze region, indicating that the wetland environment facilitated changes in human societies. The formation of peat might be related to the sea-level and El Niño-Southern Oscillation events; however, further studies are required for deep comprehension. The present study is an attempt at identifying the past impacts of the wetland environment on demographic development and can form the basis for a more comprehensive understanding of the interactions between the humans and their living environment.

Keywords: peat, archaeological radiocarbon dates, summed probability distributions, wetlands, demographic center shift, Holocene

INTRODUCTION

The lower Yangtze region is characterized as one of the flourish Neolithic cultural centers and early agricultural centers (Jiang and Liu, 2006; Liu et al., 2017; Zuo et al., 2017). Since ancient times, the region is strongly influenced by environmental changes such as climate changes, extreme climate events, and sea-level fluctuations (Innes et al., 2014; Patalano et al., 2015; He et al., 2018; Yang et al., 2020) as it is located in the boundary between the sea and the land. Studies on largescale environmental changes and human society developments aid the understanding of general rules about the evolution of human society through environmental changes. In addition, for specific sites, studying regional characteristic environmental changes and regional settlement shifts is also fundamental for comprehending human–climate–ecosystem interactions.

Wetlands are vital ecosystems in coastal areas, especially for prehistoric people, as they are valuable sources of food, and provide suitable conditions for farming (Ma et al., 2020; Zhang et al., 2020). Indeed, previous studies indicate that wetland environment attracted Neolithic people (Chen et al., 2008; Zong et al., 2011); however, the exact relationship between the evolution of the wetland environment and human activities remains unclear due to the lack of successive wetland environment reconstruction during the Holocene. In coastal areas, peat has been used as indicators of sea-level or floods in previous studies (Zhao et al., 1979; Törnqvist et al., 2004; Zhang et al., 2004; Zong, 2004; Zhang et al., 2005; Zhan and Wang, 2014; Brain et al., 2017; Hijma and Cohen, 2019). However, peat is one of wetlands products that is formed in flat terrain and relatively calm water environment (Chai, 1990; Lang et al., 1999; Mitsch and Gosselink, 2015). Furthermore, the exact time of peat formation can be directly dated as the primary organic element sources from *in situ* plant materials (Chai, 1990; Brain et al., 2017). The direct peat dating can refrain the anomalous radiocarbon dates caused by reworked sediments, which is a prevalent problem in the lower Yangtze region (Stanley and Chen, 2000; Li et al., 2014; Long et al., 2016).

In recent years, the summed probability distributions (SPD) of archaeological radiocarbon dates have been widely used to explore demographic changes (Shennan et al., 2013; Wang et al., 2014a; Goldberg et al., 2016; Bevan et al., 2017; Xu et al., 2019; Dong et al., 2020). In fact, not only the archaeological radiocarbon dates can reflect human population evolution, but also the temporal radiocarbon frequency distributions of environmental indicators are meaningful for environmental changes (Michczyńska et al., 2007; Wang et al., 2014b; Guo et al., 2018). Like the basis for SPD of archaeological radiocarbon dates to reflect the demographic changes, the high frequency of the environmental indicators always means good development and widespread of the corresponding environment. In previous studies, high probability distributions of radiocarbon dates of peat were used to indicate humid and moderate climate or the coaction of climate and sea-level changes (Michczyńska and Pazdur, 2004; Michczyńska et al., 2007; Dommain et al., 2011), whereas high SPD of peat directly indicates the large and contemporary formation of the corresponding wetland environment.

Here, we first attempt at using SPD of radiocarbon dates of peat to reconstruct successive wetland environmental changes and compare them with the demographic changes reflected by the SPD of archaeological radiocarbon dates to discuss the impacts of the regional wetland environmental changes on the development of the Neolithic human population in the lower Yangtze region. Further, we speculate the possible environmental backgrounds of peat formation to increase the predictability of coastal environment. The results provide a regional perspective on human-environment interactions that contribute to a deeper comprehension of human adaption to the environment, which may help generate sustainable human strategies pertaining to human development in the future.

NEOLITHIC ARCHEOLOGICAL BACKGROUND

The lower Yangtze region is one of the Chinese Neolithic cultural communities and an important origin center of Chinese civilization (Su and Yin, 1981; Yan, 1987). Shangshan Culture (11,000–8,500 years BP) is the earliest Neolithic culture in the lower Yangtze region, which is distributed primarily in the Jinqu Basin. Most sites of Shangshan Culture are in the center of the basin, close to the tributaries and before the hills, facilitating hunting and gathering in the region (Xu et al., 2016; Xu et al., 2020). Kuahuqiao Culture (8,300–7,200 years BP) is distributed primarily on the Qiantang River, which is the transition culture from mountain culture to river mouth culture (Jiang, 2014). The core area of Hemudu Culture (7,000–5,000 years BP) is the Ningshao Plain, a low-lying coastal plain. Research indicates that the Hemudu Culture is in the early period of rice cultivation, although the gathering and hunting economy still have their place (Fuller et al., 2009; Center for the Study of Chinese Archaeology, Peking University and Zhejiang Province Institute of Relics Archaeology, 2011). Majiabang Culture (7,000–5,800 years BP), Songze Culture (5,800–5,300 years BP), Liangzhu Culture (5,300–4,300 years BP), and Qianshanyang-Guangfulin Culture (4,300–3,900 years BP) are primarily distributed in the Taihu region, a coastal plain in the north of the Qiantang River (Institute of Archaeology, China Academy of Social Sciences, 2010; Cultural Relics and Archaeology Institute of Zhejiang Province, Huzhou Museum, 2014; Shanghai Museum, 2014; Zhejiang Provincial Institute of Cultural Relics and Archaeology, 2019) (**Figure 1**).

MATERIALS AND METHODS

We reviewed 647 published radiocarbon dates (including 68 archaeological sites) of the Neolithic archaeological culture in the lower Yangtze region, spanning ca. 10,000–2,000 years BP (**Supplementary Table S1**). Data selection and processing were performed according to Wang et al. (2014a) as follows: (1) Screening the uncalibrated ^{14}C dates: sixty archaeological dates were rejected according to the selection criteria. (2) Combining redundant dates: the R_Combine command within OxCal 4.4 was used for combining the dates (**Supplementary Table S2**). (3) SPD calculation: we calculated SPD with the CALIB 8.1 program (Stuiver and Reimer, 1993) and the IntCal20 calibration curve

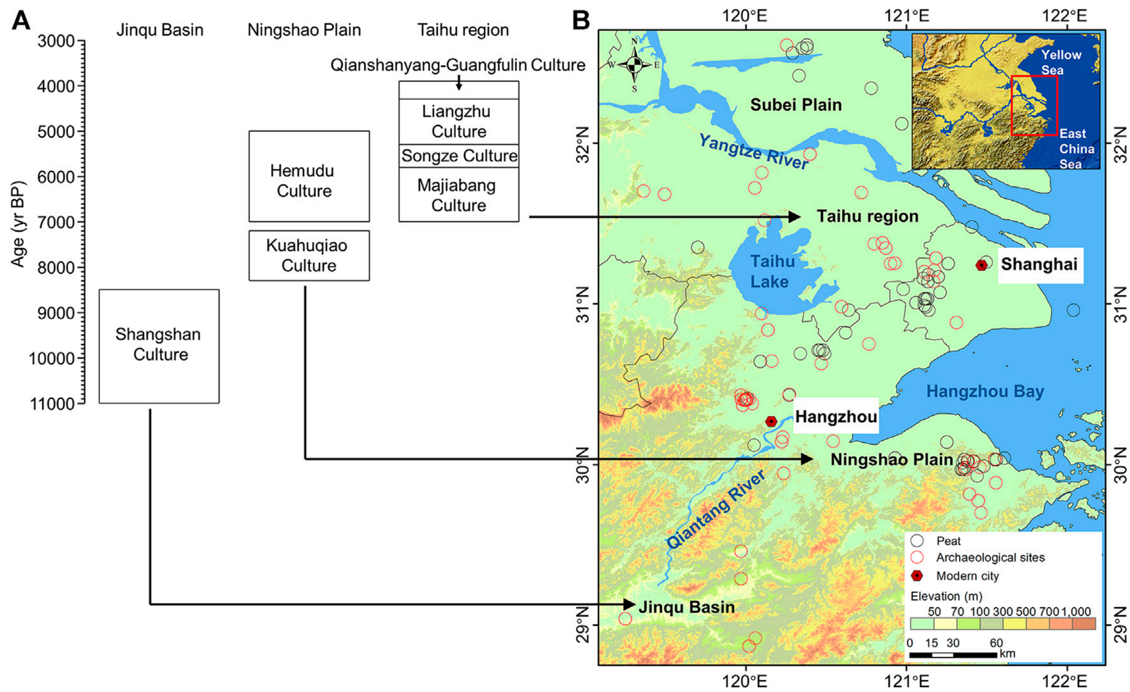

FIGURE 1 | Temporal and spatial distribution of Neolithic culture, archaeological sites, and peat in the lower Yangtze region. **(A)** Main cultures in the Jinqu Basin, Ningshao Plain, and Taihu region. **(B)** Distribution of radiocarbon dates of archaeological sites and peat. Black arrows indicate the locations of the regions on the map. Digital elevation model (DEM) data are provided by the Geospatial Data Cloud site, Computer Network Information Center, and Chinese Academy of Sciences (http://www.gscloud.cn).

(Reimer et al., 2020). (4) Taphonomic bias correction. (5) Data standardization. To investigate the temporal and spatial distribution of Neolithic demographic changes in the lower Yangtze region, we divided the lower Yangtze region into three subregions: Jinqu Basin, Ningshao Plain, and Taihu region (**Figure 1**). According to the distribution of the archaeological culture and sites, archaeological sites belonging to Shangshan Culture were placed into the Jinqu Basin category. The rest of the archaeological sites were categorized according to their relative position with respect to the Qiantang River; archaeological sites that were located south of the Qiantang River were placed into the Ningshao Plain category and those north of the Qiantang River were placed into the Taihu region category (including sites belonging to the Subei Plain). Thereafter, the SPD of each lower Yangtze region subdivision was calculated. The altitude of each archaeological site was extracted from 30 m Global Digital Elevation Model (GDEM) Version 2 (**Supplementary Table S2**) (http://www.gscloud.cn). The mean centers of archaeological dates per 1,000 years were calculated by the "Mean Center" tool in ArcGIS.

A total of 103 published radiocarbon dates of peat (including 60 peat sites) were reviewed for the lower Yangtze region, spanning the entire Holocene (**Supplementary Table S3**). Data selection and processing were as follows: 1) Screening the uncalibrated ^{14}C dates: we eliminated the dates with high error bars (1σ standard deviation > 400 ^{14}C yr) and reverse dates and reserved only one date if many dates were available from the same depth of the same core or profile. According to the selection criteria, eight peat dates were rejected. 2) SPD calculation: we calculated SPD with the CALIB 8.1 program (Stuiver and Reimer, 1993) and the IntCal20 calibration curve (Reimer et al., 2020). 3) Data standardization. We divided the peat radiocarbon data into the aforementioned geographical areas; however, we excluded the Jinqu Basin because only little data from the mountain area were reported (**Figure 1**). Thereafter, the SPD of each lower Yangtze region subdivision was calculated. The altitude of peat was collected from the published data (**Supplementary Table S3**). The mean centers of radiocarbon dates of peat per 1,000 years were calculated by the "Mean Center" tool in ArcGIS.

RESULTS

Temporal and Spatial Distribution of the Radiocarbon Dates of Archaeological Sites and Peat

During the Neolithic, the mean centers of the archeological radiocarbon dates shifted from the mountain area to the coastal plain area and from the middle of the Ningshao Plain and the Taihu region to the Taihu region. Overall, the mean centers of peat shifted southward during the Holocene, although they shifted back and forth between the Taihu region and the Ningshao Plain after 7,000 cal yr BP (**Figure 2**). From ca. 11,000 to 6,000 cal yr BP, the radiocarbon dates of archeological sites and peat tended to be distributed closely

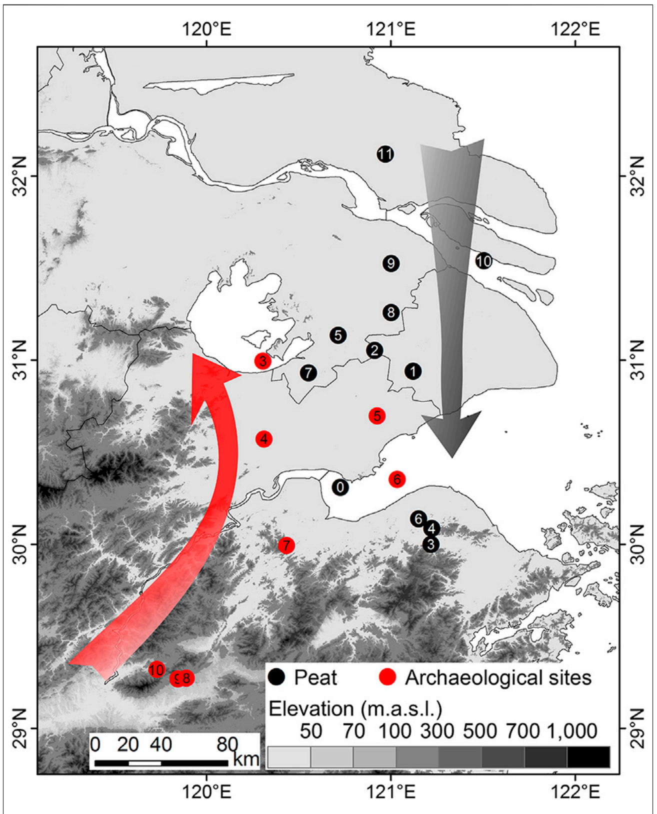

FIGURE 2 | Mean centers of radiocarbon dates of archaeological sites and peat per 1,000 years. Numbers in the circles indicate the upper time limits per 1,000 years of mean centers; e.g., 11 suggests 12,000–11,000 cal yr BP. Arrows indicate the shift directions of the mean centers. DEM data are provided by the Geospatial Data Cloud site, Computer Network Information Center, and Chinese Academy of Sciences (http://www.gscloud.cn).

and were observed to be further apart from ca. 6,000 to 3,000 cal yr BP according to distribution of sites and mean centers; meanwhile, their altitudes were gradually close to each other (**Figures 2**, **3**).

Summed Probability Distributions of the Archaeological Radiocarbon Dates

Figure 4 shows the SPD curves of archaeological radiocarbon dates for the lower Yangtze region. The overall curve gradually increased from ca. 11,000 to ca. 5,000 cal yr BP, although there were small fluctuations in this period. During ca. 5,000–4,700 cal yr BP, the curve sharply increased initially followed by a sharp decrease. After ca. 4,700 cal yr BP, the curve tended to decrease. For the SPD of the archaeological radiocarbon dates, the peak periods of the subregions in the lower Yangtze region differed. The peak periods of the Jinqu Basin, Ningshao Plain, and Taihu region were ca. 9,200–8,300 cal yr BP, ca. 7,900–5,000 cal yr BP, and ca. 5,000–4,400 cal yr BP, respectively. The core areas of the Neolithic population shifted from the Jinqu Basin to the Ningshao Plain and then to the Taihu region at ca. 8,300–8,000 cal yr BP and 5,200–4,900 cal yr BP, respectively.

Summed Probability Distributions of the Radiocarbon Dates of Peat

The SPD curves of peat through the Holocene in the lower Yangtze region were constructed, and these showed a fluctuating trend. The more developed periods of peat formation were ca. 9,100–8,000 cal yr BP, ca. 7,600–6,200 cal yr BP, ca. 5,700–5,300 cal yr BP, ca. 5,000–4,400 cal yr BP, ca. 3,500–2,700 cal yr BP, and ca. 1,700–800 cal yr BP (**Figure 5**).

DISCUSSION

What Do the Summed Probability Distributions of Peat Mean in This Study

Peat is one of several wetland products (Chai, 1990; Lang et al., 1999; Mitsch and Gosselink, 2015). Necessary conditions for peat formation include the presence of organic matter and a relatively long-term and calm waterlogged environment. This means that the high SPD of peat in the lower Yangtze region indicates a widespread wetland environment characterized by abundant plant growth and relatively stable and excess water table. This type of wetland environment can provide abundant resources and suitable conditions for farming around this area. Whereas the mean centers are different from SPD, as mean centers identify the geographic centers of archaeological or peat dates distribution, calculated as the average *x* and *y* geographical coordinates of dates per 1,000 years (Scott and Janikas, 2010).

Impacts of Wetland Environment on Demographic Development

As indicated by previous studies, the resources and environmental characteristics of wetland environment made it attractive for ancient people (Chen et al., 2008; Zong et al., 2011; Beach et al., 2019). In this

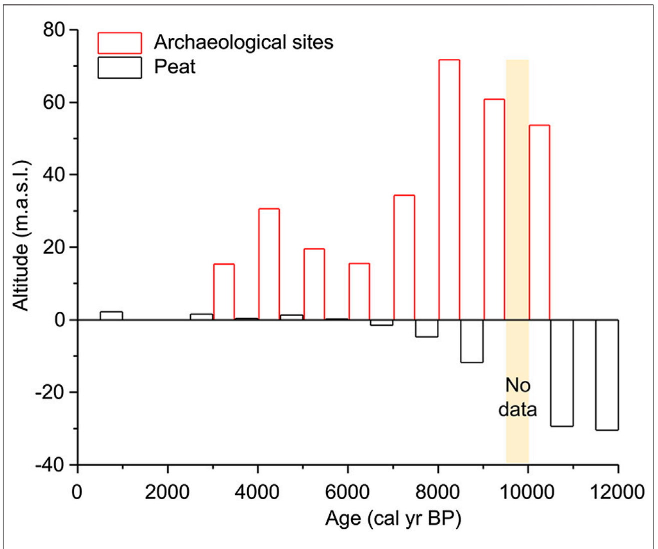

FIGURE 3 | Average altitude per 1,000 years of radiocarbon dates of the archaeological sites and peat.

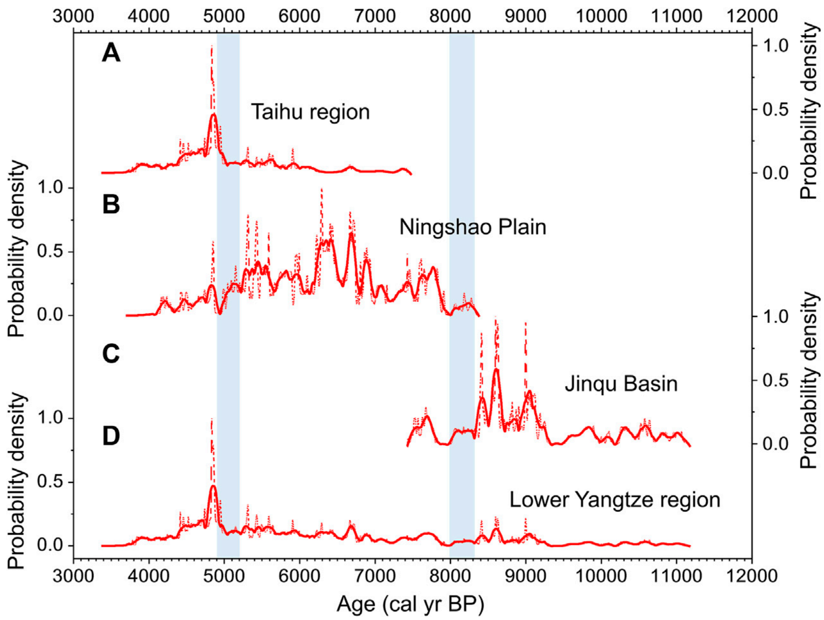

FIGURE 4 | Summed probability distributions (SPD) of the archaeological radiocarbon dates in the lower Yangtze region. **(A)** Taihu region. **(B)** Ningshao Plain. **(C)** Jinqu Basin. **(D)** Lower Yangtze region. Dotted curves show the SPD results and solid lines show the 200-point-smoothing of the SPD results. Blue bands show the shift periods of core areas of population.

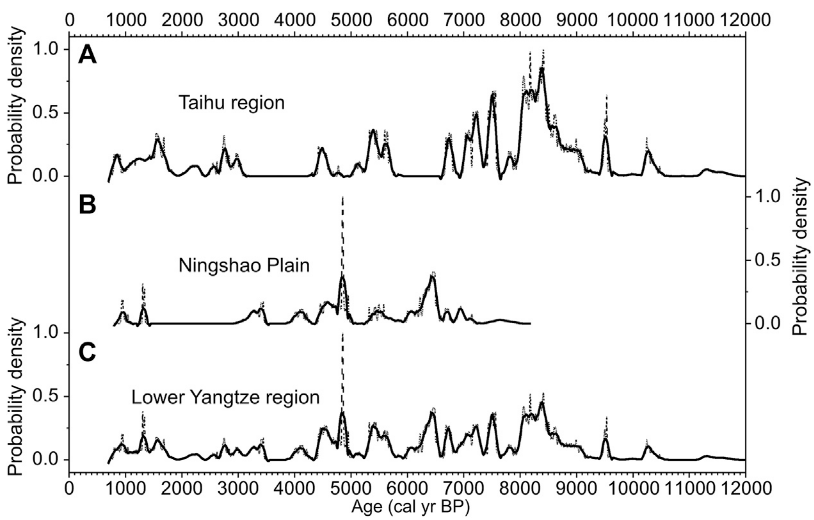

FIGURE 5 | Summed probability distributions (SPD) of radiocarbon dates of peat in the lower Yangtze region. **(A)** Taihu region. **(B)** Ningshao Plain. **(C)** Lower Yangtze region. Dotted curves show the SPD results and solid lines show the 200-point-smoothing of the SPD results.

study, the mean altitude of archaeological dates sharply decreased after 8,000 cal yr BP (**Figure 3**), and the SPD of archaeological dates also revealed that the first transition of core areas of demographic distribution, from the hilly regions to the coastal areas, occurred at ca. 8,300–8,000 cal yr BP, when peat was widespread in the coastal areas (**Figure 6**). This suggested that the wetland environment might be responsible for this transition. Meanwhile, the 8.2 ka event might be another reason for the transition. Previous investigations reported that the 8.2 ka cold event led to the migration or collapse of human population (González-Sampériz et al., 2009; Wicks and Mithen, 2014). In the lower Yangtze region, paleobotany evidences indicated the cold and dry conditions around 8.2 ka (Song et al., 2017; Zuo et al., 2020). Thus, the reduced resources caused by vegetation changes in the hilly regions and the attractive coastal marshes might have caused the transition of the core areas of population in the lower Yangtze region.

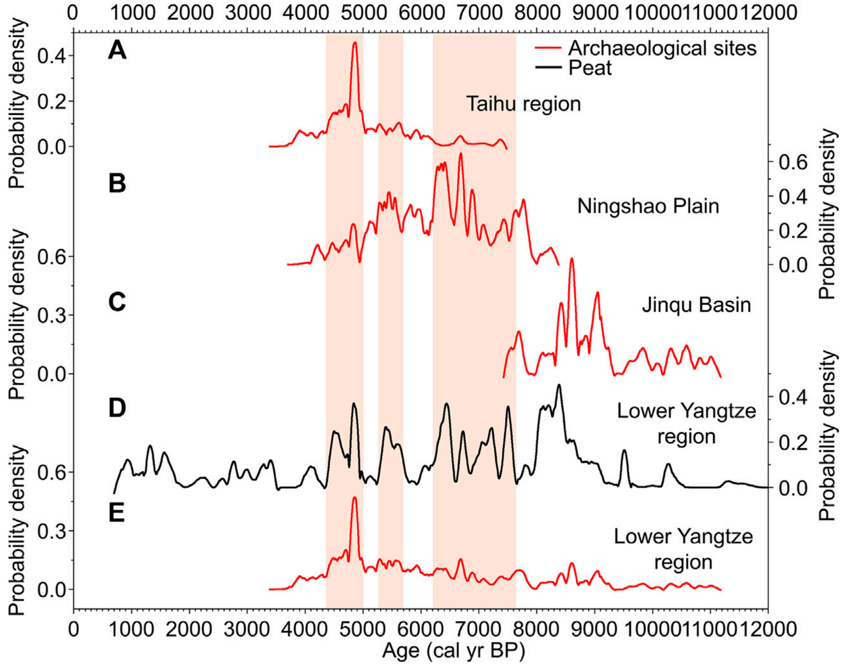

FIGURE 6 | Comparison between the SPD of radiocarbon dates of archaeological sites and peat. **(A)** SPD of archaeological radiocarbon dates in the Taihu region. **(B)** SPD of archaeological radiocarbon dates in the Ningshao Plain. **(C)** SPD of archaeological radiocarbon dates in the Jinqu Basin. **(D)** SPD of radiocarbon dates of peat in the lower Yangtze region. **(E)** SPD of archaeological radiocarbon dates in the lower Yangtze region. All these are 200-point-smoothing results. Orange bands show the peak periods of radiocarbon dates of archaeological sites and peat.

This type of wetland environment was not just attractive for ancient people, and it facilitated demographic development. Results of this study revealed that there were three periods of high SPD of peat dates during the middle Holocene, in the lower Yangtze region, ca. 7,600–6,200 cal yr BP, ca. 5,700–5,300 cal yr BP, and ca. 5,000–4,400 cal yr BP; these coincided with the flourishing of the Hemudu Culture and the Liangzhu Culture (**Figure 6**). Previous research in this area demonstrated that wetland food resources such as *Typha*, *Euryale*, and *Trapa* were a part of the diet of Kuahuqiao and Hemudu people (Zong et al., 2007; Fuller et al., 2009; Fuller and Qin, 2010; Zhang et al., 2020). The wetland environment was also suitable for rice farming (Chen et al., 2008; Zong et al., 2012; Ma et al., 2020). Hence, the formation and the reasonable resource utilization of the wetland environment might be the reason for the demographic development in the lower Yangtze region.

However, because of the long-term waterlogged conditions required for peat formation, such an area cannot be settled directly; this was reflected by the findings that the SPD peaks of human population and peat did not overlap in the same region and the mean centers of archaeological dates and peat dates finally kept apart in the lower Yangtze region (**Figures 2**, **7**). Furthermore, when the peat layer overlapped with or was overlying on the cultural layer, that indicated the collapse of the culture in the sites area (Zheng et al., 2012; He et al., 2018). Meanwhile, the sudden appearance of the extensive waterlogged environment was indicative of the previous extreme climate events, such as floods and storms. Thus, the widespread waterlogged environment and previous extreme climate events reflected by the peak of SPD of radiocarbon dates of peat in the Ningshao Plain at ca. 6,600–6,200 cal yr BP might be the reason for the ubiquitous cultural interruption of Hemudu culture (He et al., 2018; Tang et al., 2019), and the high SPD of peat at ca. 5,000–4,400 cal yr BP may explain the decreasing population in this area (**Figure 7**).

Possible Environmental Backgrounds for Peat Formation in the Lower Yangtze Region

The reasons for peat formation were complex and included climatological, geological, and hydrological factors (Chai, 1990; Lang et al., 1999; Mitsch and Gosselink, 2015). In the lower Yangtze region, peat was used to reconstruct Holocene sea-level changes or floods (Zhao et al., 1979; Zhang et al., 2004; Zong, 2004; Zhang et al., 2005; Zhan and Wang, 2014). The altitudes of peat nearly fit the curve of sea-level changes in this study (**Figure 8A**). Additionally, through the comparison with El Niño-Southern Oscillation (ENSO) frequency (Moy et al., 2002), the results showed that the widening of the spread of peat coincided with the high frequency of ENSO events during the period of relatively stable sea-level (**Figures 8B**,C). A previous study by Jiang et al. (2006) indicated that high frequency of ENSO events was correlated with abundant precipitation in the middle and lower Yangtze region. The rising sea-level or the abundant precipitation contributed to saltwater intrusion or an increase in the relative water level in the low-lying plain, which raised the groundwater level and led to inundation (Alizadeh et al., 2015; Becker et al., 2020). Thus, the abundance of water might promote peat formation in the lower Yangtze region.

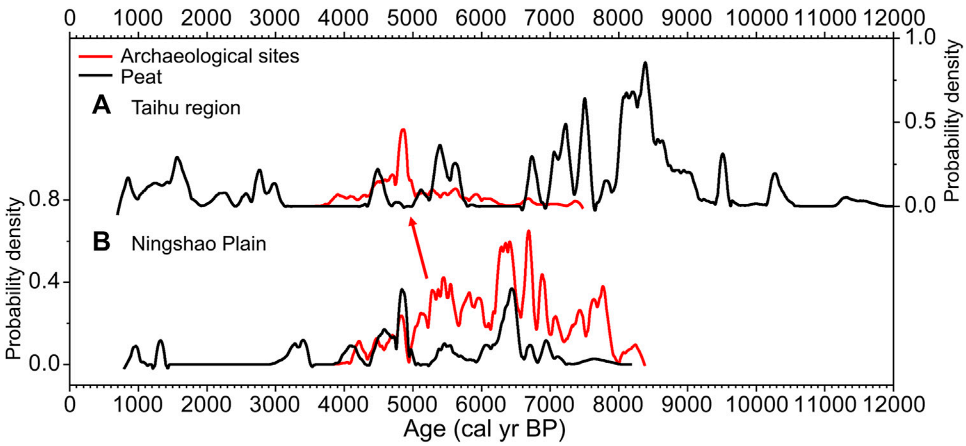

FIGURE 7 | Comparison between the SPD of radiocarbon dates of archaeological sites and peat in the Ningshao Plain and the Taihu region. **(A)** Taihu region. **(B)** Ningshao Plain. All these are 200-point-smoothing results. Red arrow indicates the shift of demographic centers.

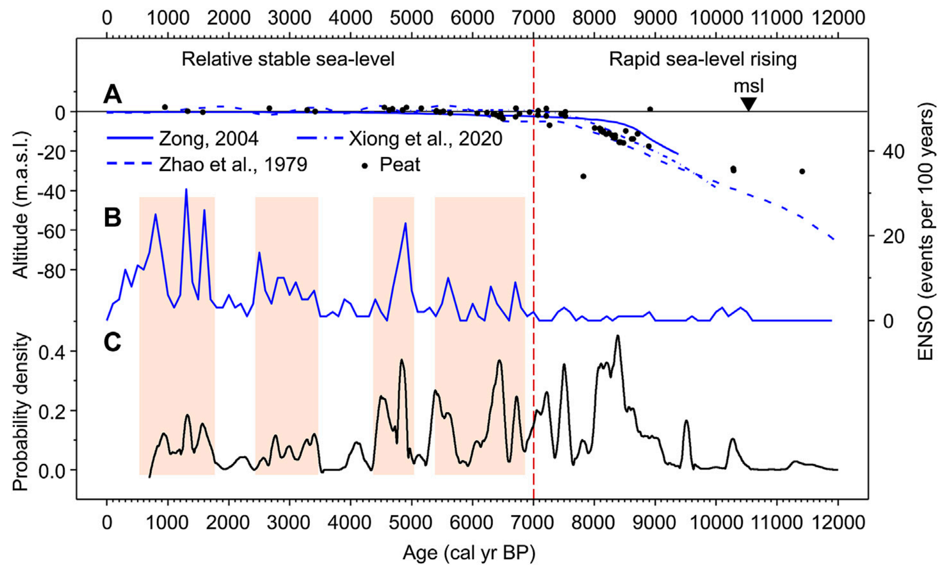

FIGURE 8 | Environment backgrounds of peat formation. **(A)** Sea-level curves of east China (Zhao et al., 1979; Zong, 2004; Xiong et al., 2020) and altitude of peat in this study. **(B)** El Niño-Southern Oscillation (ENSO) events per 100 years (Moy et al., 2002). **(C)** SPD of radiocarbon dates of peat in the lower Yangtze region (200-point-smoothing result).

Higher precipitation caused by frequent ENSO events or rising sea-level were viewed as disasters for prehistoric coastal people. However, studies indicated ancient people could also benefit from El Niño floodwaters by converting them into productive water for agriculture (Caramanica et al., 2020). In addition, the increased sediment supply during the period of high sea-level resulted in the acceleration of coastal progradation and formation of livable flatlands (Ma et al., 2020). As in the lower Yangtze region, ENSO events or sea-level rising might facilitate human societies by promoting the formation of wetlands. As the data in this study are limited, more studies are required for a better understanding of coastal wetland environment and its relationship with human societies and climate changes.

CONCLUSION

This study was the first attempt to use peat as an indicator of the wetland environment in the lower Yangtze region, with the reconstruction of demographic development via archaeological radiocarbon dates. The data were used to investigate the impacts of wetland environment on Neolithic demographic evolution. The demographic centers of the lower Yangtze region transitioned from the hilly regions to the coastal plain at ca. 8,300–8,000 cal yr BP, which was likely influenced by the 8.2 ka event and the attraction of the wetland environment. Peat formation coincided with the development of the population during the middle Holocene in the lower Yangtze region, indicating that the wetland environment facilitated Neolithic demographic development. However, due to the long-term waterlogged environment requirement for peat formation, the region with widespread peat formation could not be settled directly. The widespread peat in the Ningshao Plain during ca. 5,000–4,400 cal yr BP might be the reason for the transition of the core area of the population.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

KS and JZ designed research. KH and KS collected data. KS analyzed data. KS, JZ, CW, and HL wrote the article. All authors read and approved the final manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2021.635640/full#supplementary-material.

REFERENCES

Alizadeh, K., Cohen, M., and Behling, H. (2015). Origin and dynamics of the northern South American coastal savanna belt during the Holocene – the role of climate, sea-level, fire and humans. *Quat. Sci. Rev.* 122, 51–62. doi:10.1016/j.quascirev.2015.05.009

Beach, T., Luzzadder-Beach, S., Krause, S., Guderjan, T., Valdez, F., Fernandez-Diaz, J. C., et al. (2019). Ancient Maya wetland fields revealed under tropical forest canopy from laser scanning and multiproxy evidence. *Proc. Natl. Acad. Sci. U. S. A.* 116, 21469–21477. doi:10.1073/pnas.1910553116

Becker, M., Papa, F., Karpytchev, M., Delebecque, C., Krien, Y., Khan, J. U., et al. (2020). Water level changes, subsidence, and sea level rise in the Ganges-Brahmaputra-Meghna delta. *Proc. Natl. Acad. Sci. U. S. A.* 117, 1867–1876. doi:10.1073/pnas.1912921117

Bevan, A., Colledge, S., Fuller, D., Fyfe, R., Shennan, S., and Stevens, C. (2017). Holocene fluctuations in human population demonstrate repeated links to food production and climate. *Proc. Natl. Acad. Sci. U. S. A.* 114, E10524–E10531. doi:10.1073/pnas.1709190114

Brain, M. J., Kemp, A. C., Hawkes, A. D., Engelhart, S. E., Vane, C. H., Cahill, N., et al. (2017). Exploring mechanisms of compaction in salt-marsh sediments using Common Era relative sea-level reconstructions. *Quat. Sci. Rev.* 167, 96–111. doi:10.1016/j.quascirev.2017.04.027

Caramanica, A., Huaman Mesia, L., Morales, C. R., Huckleberry, G., Castillo B, L. J., and Quilter, J. (2020). El Niño resilience farming on the north coast of Peru. *Proc. Natl. Acad. Sci. U. S. A.* 117, 24127–24137. doi:10.1073/pnas.2006519117

Center for the Study of Chinese Archaeology, Peking University, Zhejiang Province Institute of Cultural Relics Archaeology (2011). *Integrated studies on the natural remains from Tianluoshan Site*. Beijing: Cultural Relics Press. [in Chinese].

Chai, X. (1990). *Peatland*. Beijing, China: Geology Press. [in Chinese].

Chen, Z., Zong, Y., Wang, Z., Wang, H., and Chen, J. (2008). Migration patterns of neolithic settlements on the abandoned yellow and Yangtze river deltas of China. *Quat. Res.* 70, 301–314. doi:10.1016/j.yqres.2008.03.011

Cultural Relics and Archaeology Institute of Zhejiang Province, Huzhou Museum (2014). *Qiangshanyang A report on the third and fourth excavations of the site*. Beijing, China: Cultural Relics Press. [in Chinese].

Dommain, R., Couwenberg, J., and Joosten, H. (2011). Development and carbon sequestration of tropical peat domes in south-east Asia: links to post-glacial sea-level changes and Holocene climate variability. *Quat. Sci. Rev.* 30, 999–1010. doi:10.1016/j.quascirev.2011.01.018

Dong, G., Li, R., Lu, M., Zhang, D., and James, N. (2020). Evolution of human–environmental interactions in China from the late paleolithic to the bronze age. *Prog. Phys. Geogr.* 44, 233–250. doi:10.1177/0309133319876802

Fuller, D. Q., Qin, L., Zheng, Y., Zhao, Z., Chen, X., Hosoya, L. A., et al. (2009). The domestication process and domestication rate in rice: spikelet bases from the lower Yangtze. *Science* 323, 1607–1610. doi:10.1126/science.1166605

Fuller, D. Q., and Qin, L. (2010). Declining oaks, increasing artistry, and cultivating rice: the environmental and social context of the emergence of farming in the Lower Yangtze Region. *Environ. Archaeol.* 15, 139–159. doi:10.1179/146141010X12640787648531

Goldberg, A., Mychajliw, A. M., and Hadly, E. A. (2016). Post-invasion demography of prehistoric humans in South America. *Nature* 532, 232–235. doi:10.1038/nature17176a

González-Sampériz, P., Utrilla, P., Mazo, C., Valero-Garcés, B., Sopena, M. C., Morellón, M., et al. (2009). Patterns of human occupation during the early Holocene in the Central Ebro Basin (NE Spain) in response to the 8.2 ka climatic event. *Quat. Res.* 71, 121–132. doi:10.1016/j.yqres.2008.10.006

Guo, L., Xiong, S., Ding, Z., Jin, G., Wu, J., and Ye, W. (2018). Role of the mid-Holocene environmental transition in the decline of late Neolithic cultures in the deserts of NE China. *Quat. Sci. Rev.* 190, 98–113. doi:10.1016/j.quascirev.2018.04.017

He, K., Lu, H., Zheng, Y., Zhang, J., Xu, D., Huan, X., et al. (2018). Middle-Holocene sea-level fluctuations interrupted the developing Hemudu culture in the lower Yangtze River, China. *Quat. Sci. Rev.* 188, 90–103. doi:10.1016/j.quascirev.2018.03.034

Hijma, M. P., and Cohen, K. M. (2019). Holocene sea-level database for the Rhine-Meuse Delta, The Netherlands: implications for the pre-8.2 ka sea-level jump. *Quat. Sci. Rev.* 214, 68–86. doi:10.1016/j.quascirev.2019.05.001

Innes, J. B., Zong, Y., Wang, Z., and Chen, Z. (2014). Climatic and palaeoecological changes during the mid- to Late Holocene transition in eastern China: high-resolution pollen and non-pollen palynomorph analysis at Pingwang, Yangtze coastal lowlands. *Quat. Sci. Rev.* 99, 164–175. doi:10.1016/j.quascirev.2014.06.013

Institute of Archaeology, China Academy of Social Sciences (2010). *Chinese Archaeology Neolithic*. Beijing, China: China Social Sciences Press. [in Chinese].

Jiang, L., and Liu, L. (2006). New evidence for the origins of sedentism and rice domestication in the Lower Yangzi River, China. *Antiquity* 80, 355–361. doi:10.1017/S0003598X00093674

Jiang, L. (2014). *Study on Kuahuqiao culture*. Beijing, China: Science Press. [in Chinese].

Jiang, T., Zhang, Q., Zhu, D., and Wu, Y. (2006). Yangtze floods and droughts (China) and teleconnections with ENSO activities (1470–2003). *Quat. Int.* 144, 29–37. doi:10.1016/j.quaint.2005.05.010

Lang, H., Zhao, K., and Chen, K. (1999). *Wetland vegetation in China*. Beijing, China: Science Press. [in Chinese].

Li, C., Li, Y., and Burr, G. S. (2014). Testing the accuracy of ^{14}C age data from pollen concentrates in the Yangtze Delta, China. *Radiocarbon* 56, 181–187. doi:10.2458/56.16920

Liu, B., Wang, N., Chen, M., Wu, X., Mo, D., Liu, J., et al. (2017). Earliest hydraulic enterprise in China, 5,100 years ago. *Proc. Natl. Acad. Sci. U. S. A.* 114, 13637–13642. doi:10.1073/pnas.1710516114

Long, T., Hunt, C. O., and Taylor, D. (2016). Radiocarbon anomalies suggest late onset of agricultural intensification in the catchment of the southern part of the Yangtze Delta, China. *CATENA* 147, 586–594. doi:10.1016/j.catena.2016.08.017

Ma, T., Rolett, B. V., Zheng, Z., and Zong, Y. (2020). Holocene coastal evolution preceded the expansion of paddy field rice farming. *Proc. Natl. Acad. Sci. U. S. A.* 117, 24138–24143. doi:10.1073/pnas.1919217117

Michczyńska, D. J., Michczyński, A., and Pazdur, A. (2007). Frequency distribution of radiocarbon dates as a tool for reconstructing environmental changes. *Radiocarbon* 49, 799–806. doi:10.1017/S0033822200042673

Michczyńska, D. J., and Pazdur, A. (2004). Shape analysis of cumulative probability density function of radiocarbon dates set in the study of climate change in the Late Glacial and Holocene. *Radiocarbon* 46, 733–744. doi:10.1017/S0033822200035773

Mitsch, W. J., and Gosselink, J. G. (2015). *Wetlands*. 5th Edn. New York, NY: Wiley.

Moy, C. M., Seltzer, G. O., Rodbell, D. T., and Anderson, D. M. (2002). Variability of El niño/southern oscillation activity at millennial timescales during the Holocene epoch. *Nature* 420, 162–165. doi:10.1038/nature01194

Patalano, R., Wang, Z., Leng, Q., Liu, W., Zheng, Y., Sun, G., et al. (2015). Hydrological changes facilitated early rice farming in the lower Yangtze River Valley in China: a molecular isotope analysis. *Geology* 43, 639–642. doi:10.1130/G36783.1

Reimer, P. J., Austin, W. E. N., Bard, E., Bayliss, A., Blackwell, P. G., Bronk Ramsey, C., et al. (2020). The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon* 62, 725–727. doi:10.1017/RDC.2020.41

Scott, L. M., and Janikas, M. V. (2010). "Spatial statistics in ArcGIS," in *Handbook of applied spatial analysis*. Editors M. Fischer and A. Getis (Berlin, Germany: Springer). doi:10.1007/978-3-642-03647-7_2

Shanghai Museum (2014). *Proceedings on the excavation at guang fu lin*. Shanghai, China: Shanghai Classics Publishing House. [in Chinese].

Shennan, S., Downey, S. S., Timpson, A., Edinborough, K., Colledge, S., Kerig, T., et al. (2013). Regional population collapse followed initial agriculture booms in mid-Holocene Europe. *Nat. Commun.* 4, 2486. doi:10.1038/ncomms3486

Song, B., Li, Z., Lu, H., Mao, L., Saito, Y., Yi, S., et al. (2017). Pollen record of the centennial climate changes during 9–7 cal ka BP in the Changjiang (Yangtze) River Delta plain, China. *Quat. Res.* 87, 275–287. doi:10.1017/qua.2017.1

Stanley, D. J., and Chen, Z. (2000). Radiocarbon dates in China's Holocene Yangtze delta: record of sediment storage and reworking, not timing of deposition. *J. Coast. Res.* 16, 1126–1132.

Stuiver, M., and Reimer, P. J. (1993). Extended ^{14}C data base and revised Calib 3.0 ^{14}C age calibration program. *Radiocarbon* 35, 215–230. doi:10.1017/S0033822200013904

Su, B., and Yin, W. (1981). Regional distribution, evolutionary lines and types of archaeological cultures. *Cult. Relics* 5, 10–17. [in Chinese].

Tang, L., Lv, Y., Nian, X., Lei, S., and Wang, Z. (2019). Middle Holocene seawater intrusion and human's rapid response in the Yaojiang-Ningbo coastal plain, China. *Quat. Sci.* 39, 1116–1132. [in Chinese]. doi:10.11928/j.issn.1001-7410.2019.05.05

Törnqvist, T. E., Bick, S. J., González, J. L., van der Borg, K., and de Jong, A. F. M. (2004). Tracking the sea-level signature of the 8.2 ka cooling event: new constraints from the Mississippi Delta. *Geophys. Res. Lett.* 31, L23309. doi:10.1029/2004GL021429

Wang, C., Lu, H., Zhang, J., Gu, Z., and He, K. (2014a). Prehistoric demographic fluctuations in China inferred from radiocarbon data and their linkage with climate change over the past 50,000 years. *Quat. Sci. Rev.* 98, 45–59. doi:10.1016/j.quascirev.2014.05.015

Wang, H., Chen, J., Zhang, X., and Chen, F. (2014b). Palaeosol development in the Chinese Loess Plateau as an indicator of the strength of the East Asian summer monsoon: evidence for a mid-Holocene maximum. *Quat. Int.* 334–335, 155–164. doi:10.1016/j.quaint.2014.03.013

Wicks, K., and Mithen, S. (2014). The impact of the abrupt 8.2 ka cold event on the Mesolithic population of western Scotland: a Bayesian chronological analysis using "activity events" as a population proxy. *J. Archaeol. Sci.* 45, 240–269. doi:10.1016/j.jas.2014.02.003

Xiong, H., Zong, Y., Li, T., Long, T., Huang, G., and Fu, S. (2020). Coastal GIA processes revealed by the early to middle Holocene sea-level history of east China. *Quat. Sci. Rev.* 233, 106249. doi:10.1016/j.quascirev.2020.106249

Xu, D., Lu, H., Chu, G., Liu, L., Shen, C., Li, F., et al. (2019). Synchronous 500-year oscillations of monsoon climate and human activity in Northeast Asia. *Nat. Commun.* 10, 4105. doi:10.1038/s41467-019-12138-0

Xu, Y., Lin, Z., and Jiang, L. (2020). The correlation between landscape characteristics in Qu River and the site selection of Shangshan Culture. *Adv. Geosci.* 10, 778–791. [in Chinese]. doi:10.12677/ag.2020.108078

Xu, Y., Lin, Z., and Jiang, L. (2016). The relationship between the distribution of archaeological sites of Shangshan Culture and environment. *Cult. Relics South. China* 3, 131–138. [in Chinese].

Yan, W. (1987). The unification and diversity of prehistorical culture of China. *Cult. Relics* 3, 38–50. [in Chinese].

Yang, Q., Zheng, H., Taylor, D. M., Hu, Z., Zhou, B., Ma, C., et al. (2020). Catastrophic tidal bores associated with sea level rise: a lesson from the collapse of Kuahuqiao Neolithic Culture, East Coastal China. *Earth Space Sci. Open Arch.* doi:10.1002/essoar.10504129.1

Zhan, Q., and Wang, Z. (2014). Mid-Holocene sea-level of northern Yangtze River delta reconstructed by salt marsh peat. *J. Palaeogeogr. Chin. ed.* 16, 548–556. [in Chinese].

Zhang, Q., Jiang, T., Shi, Y., Lorenz, K., Liu, C., and Martin, M. (2004). Paleo-environmental changes in the Yangtze Delta during past 8000 years. *J. Geogr. Sci.* 14, 105–112. doi:10.1007/BF02873097

Zhang, Q., Zhu, C., Liu, C., and Jiang, T. (2005). Environmental change and its impacts on human settlement in the Yangtze Delta, P.R. China. *CATENA* 60, 267–277. doi:10.1016/j.catena.2004.12.001

Zhang, Y., van Geel, B., Gosling, W. D., Sun, G., Qin, L., and Wu, X. (2020). *Typha* as a wetland food resource: evidence from the Tianluoshan site, Lower Yangtze Region, China. *Veg. Hist. Archaeobot.* 29, 51–60. doi:10.1007/s00334-019-00735-4

Zhao, X., Geng, X., and Zhang, J. (1979). Sea level changes of the eastern China during the past 20000 years. *Acta Oceanologia. Sinica.* 1, 269–281. [in Chinese].

Zhejiang Provincial Institute of Cultural Relics and Archaeology (2019). *A comprehensive study of Liangzhu ancient city*. Beijing, China: Cultural Relics Press. [in Chinese].

Zheng, Y., Sun, G., and Chen, X. (2012). Response of rice cultivation to fluctuating sea level during the Mid-Holocene. *Chin. Sci. Bull.* 57, 370–378. doi:10.1007/s11434-011-4786-3

Zong, Y., Chen, Z., Innes, J. B., Chen, C., Wang, Z., and Wang, H. (2007). Fire and flood management of coastal swamp enabled first rice paddy cultivation in east China. *Nature* 449, 459–462. doi:10.1038/nature06135

Zong, Y., Innes, J. B., Wang, Z., and Chen, Z. (2012). Environmental change and Neolithic settlement movement in the lower Yangtze wetlands of China. *Holocene* 22, 659–673. doi:10.1177/0959683611414933

Zong, Y., Innes, J. B., Wang, Z., and Chen, Z. (2011). Mid-Holocene coastal hydrology and salinity changes in the east Taihu area of the lower Yangtze wetlands, China. *Quat. Res.* 76, 69–82. doi:10.1016/j.yqres.2011.03.005

Zong, Y. (2004). Mid-Holocene sea-level highstand along the southeast coast of China. *Quat. Int.* 117, 55–67. doi:10.1016/S1040-6182(03)00116-2

Zuo, X., Lu, H., Jiang, L., Zhang, J., Yang, X., Huan, X., et al. (2017). Dating rice remains through phytolith carbon-14 study reveals domestication at the beginning of the Holocene. *Proc. Natl. Acad. Sci. U. S. A.* 114, 6486–6491. doi:10.1073/pnas.1704304114

Zuo, X., Lu, H., Li, Z., Song, B., Xu, D., and Dai, J. (2020). Phytolith records of flourishing early Holocene Pooideae linked to an 8.2 ka cold event in subtropical China. *Elem. Sci. Anth.* 8, 077. doi:10.1525/elementa.077

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Human Subsistence Strategies and Adaptations in the Lower Yangtze River Region During the Prehistoric Era

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Understanding the human subsistence strategies and adaptations in the Lower Yangtze River Region during the prehistoric period is vital to reveal the human-environment interactions, the origin and development of rice agriculture, cultural development, and social complexity. No systematic analysis of isotopic data of human bones in the region has been undertaken within the environmental (sea level), spatiotemporal (site distribution), and economic (animal and plant resources) contexts yet, in order to provide the direct evidence of human diets and trajectory of human subsistence strategies and adaptations. In this paper, I collected the isotopic data in the region as many as possible and incorporated within the environmental, spatiotemporal, and economic information. The results show that humans rarely made use of marine resources when facing the situation of rising sea levels and having good accesses to marine environment during the eastward movement. Alternatively, humans consumed large amount of terrestrial resources and supplementary freshwater or wetland resources. Rice agriculture was still of low-level production and contributed less to human diets. The unique human subsistence strategies enhanced human adaptations to the fluctuation of sea level in the Holocene in eastern China and facilitated the increases of archaeological cultures and human population, challenging the traditional opinion that the developed agriculture is the necessary pathway to develop cultures and grow human population.

Keywords: the lower Yangtze River region, human-environment interaction, stable isotope analysis, subsistence strategy, adaptation

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INTRODUCTION

In recent years, more and more archaeological evidence has shown that the Lower Yangtze River Region (LYRR), including the Ningshao Plain, the Hangjiahu Plain and areas around Taihu Lake, is not only the birthplace of rice agriculture but also one of the important places for the occurrence of Chinese civilization, paralleling to that in the Yellow River Valley (e.g., Renfrew and Liu, 2018). Different from those in the Yellow River Valley, human activities in the LYRR are quite sensitive to and highly influenced by the fluctuation of sea levels in the Holocene as the region is located in the east of China and close to the coastline. Understanding human subsistence strategies and adaptations in prehistoric periods is critical to reveal the human-environment interaction, the origin and development of rice agriculture, cultural developments, and the formation of social complexity.

TABLE 1 | The chronology of cultures in the LYRR (revised from Pan and Yuan, 2018).

Culture	Dates (~BC)
Shangshan	9400-6500
Kuahuqiao	6200-5000
Hemudu (ningshao plain)	5000-3800
Majiabang (area around taihu)	5000-4000
Songze	4000-3300
Liangzhu	3300-2300
Qianshanyang	2300-2000
Guangfulin	2300-2000
Maqiao	1900-1200

So far, several methods have been applied to investigating human diets in the LYRR, such as paleobotanical analysis, archaeozoological analysis, residue analysis and stable isotope analysis. Among them, the analyses of animal and plant remains (carbonized plants and microfossils such as phytolith, pollen and starch grains) have been widely used to reveal the origin and development of rice agriculture and exploitation of animal resources (wild and domesticated animals) (e.g., Pan and Yuan, 2018; Pan and Yuan, 2019). The residues preserved in the prehistoric pottery have been preliminarily analyzed to identify the animal or plant resources (Shoda et al., 2018), providing another effective way to reveal human diets in short periods. In contrast, the stable isotope ($\delta^{13}C$, $\delta^{15}N$) analysis of human bones can offer the direct evidence of human diets during long-term periods before the individual's death and has been increasingly used to reveal human subsistence strategies in China (e.g., Hu, 2018). Given the fact that human bones in the LYRR are generally not preserved well, the isotopic studies are not as popular as those in the Yellow River Valley. However, the accumulation of isotopic data in recent years makes it possible for us to trace back human diets and their diachronic shifts in the prehistoric periods. To our knowledge, no systematic analysis of isotopic data has been undertaken within the environmental (sea level), spatiotemporal (site distribution), economic (animal and plant resources) contexts yet.

In this paper, I collected the isotopic data of human bones in the LYRR as many as possible and focused on interpreting human diets and activities on the basis of reviewing the chronology of prehistoric cultures, the fluctuation of sea level, the distribution of sites, and the utilization of plant and animal resources. My aim was to reveal the interactions among sea levels, archaeological cultures, and human subsistence strategies in the LYRR and discuss the impacts of the fluctuation of sea levels on human activities and human adaptations to the unstable environment.

CONTEXTS

Chronological Context: Chronology of Prehistoric Cultures in the LYRR

Continuous archaeological excavations and studies have established the chronological framework of archaeological cultures in the LYRR. Here, I cited the chronology of prehistoric cultures outlined by Pan and Yuan (2018) and listed it in **Table 1**.

Environmental Context: The Fluctuation of Sea Levels in the LYRR

The LYRR is near the coastline in east China. Different from that in the Yellow River Valley, the most important climatic factor to influence cultural development and human activities in the LYRR during the Holocene is the fluctuation of sea levels after the Last Glacial Maximum and extreme environmental events such as sea transgression, sea flooding and storms (Wang et al., 2018). Thus, understanding of the fluctuation of sea levels and coastline is the prerequisite to understand the distribution of archaeological sites, human living environment and subsistence strategies.

The model of global sea level curve constructed by Lambeck et al. (2014), is regarded as one of the best and most reliable curves as it synthesized more than a thousand points data of sediment cores worldwide and incorporated global ice volume modeling (Zheng et al., 2018). It suggests that: 1) sea level rose rapidly since the Last Deglaciation by 10–15 m from 21 to 18 ka, and kept constant during the next 1.5 ka (18–16.5 ka); 2) during the period of 16.5–7.0 ka, sea level rose by about 120 m and reached to −5 to −3 m at 7.0 ka; 3) after 7 ka, the rise of sea level decelerated significantly and remained relatively stable (Lambeck et al., 2014).

There are several differences of sea level curve models on millennial scale reconstructed from various sediment cores along Chinese east coastline from the above model. Yang and Xie (1984) and Zhao et al. (1994) suggest that sea level was higher than today around 6 ka and fell to the present level gradually while Liu et al. (2004) propose that the sea level during 6.5–7.0 ka was higher than today. Song et al. (2013) claim that the high sea level was present around 5 ka and kept constant since then. Recent study indicates the sea level close to the present might occur c. 8.0–7.5 cal. ka BP and decline c. 7.6–7.5 cal. ka BP (Yan et al., 2020). Whereas, Xiong et al. (2020) think that the rise of sea level from *c.* −38.3 ± 1.6 m to the present height happened from *c.* 10000 cal. a BP to 7000 cal. a BP with the uneven average rate of sea-level rise and that the rise and fall of sea level also took place between 7000 and 4000 cal. a BP.

In summary, sea level in the east China coastline rose around 20000 BP and approached to the present height c. 7000 BP and might have fluctuated differently in varied areas of the LYRR along the coastline.

Spatiotemporal Context: The Spatial and Temporal Distribution of Archaeological Sites

The fluctuation of sea level in the Holocene has strong impact on humans to settle down in the prehistoric periods. The investigation of over 2000 sites dated to the prehistory and Shang and Zhou Dynasties using DEM and GIS methods (Zheng et al., 2018) provides the good opportunity for us to look at the spatial and temporal distribution of archaeological sites in the LYRR. During the period of 1000-8500 BP, the sites were sparsely in the basins and far from the sea (Zheng et al., 2018). During the period of

TABLE 2 | The animal and plant species mainly used in different periods (modified from Pan and Yuan, 2019).

Period (BP) Food category	11000-8400	8200-6000	6000-5300	5300-4300	4300-2300
Rice	+	+	++	+++	++
Foxnut	+	+++	+	+	+
Water chestnut		++++	+	+	+
Fagaceae nut		+++			
Millets					+
Dog		+	+	+	+
Pig		+	+	+++	+
Deer		+++	++	+	++
Bird		+	+	+	+
Fish		+	+	+	+

Note: The number of "+" indicates the increase of the percentage among foods.

9000-7000 BP, the sea transgression occurred. About 7000 BP, the rise of sea level slowed down and sea level was close to the present height (Zheng et al., 2018). The decrease of sea level rise made the land exposed, which resulted in the lower Yangtze River delta (Zheng et al., 2018). The regression of coastline and expansion of lands eastwards offered a wide space for the development of Neolithic cultures. In this period, the number and size of sites increased dramatically and the distribution of sites went eastwards (Zheng et al., 2018). Around 4000 BP, the number of sites decreased greatly and only the sites belonging to the Guangfulin and Qianshanyang cultures existed.

In the meantime, the sea transgression or extreme environmental events had great influence on the disruption of the archaeological sites and cultures, which can also be uncovered in the sediment cores. The Kuahuqiao site might be inundated by the rise of sea level around 7400 cal. BP (Pan, 2020). The sea transgression at the Yaojiang-Ningbo Plain during the periods of 6300-6000 BP, 5400-5300 BP and 4500-3400 BP caused the lacking of continuous deposits of archaeological cultures (Tang et al., 2019). This phenomenon was also observed at sites dating to the Hemudu Culture (Ouyang et al., 2019; He et al., 2020). In particular, the coastal flooding occurring 4.5 cal. ka BP could have been a major reason accounting for the diminishment and abandonment of the Liangzhu Culture around 4.4 cal. ka BP (Wang et al., 2020). Besides, Ling et al. (2021) note that overbank flooding or storm surge events happened at the Liangzhu Ancient City area during the middle to late Holocene (after c. 7600 cal. BP).

In brief, human settlements and archaeological cultures in the LYRR were highly influenced by the fluctuation of sea level. The sea regression and transgression as well as extreme environmental events (flood, storm, typhoon, *etc.*) can be regarded as one of the important factors to influence the flourishment and abandonment of archaeological sites and cultures.

Economic Context: The Animal and Plant Resources Used by Humans in the LYRR

The fauna and flora assemblages collected at the archaeological sites in the LYRR create a good opportunity for us to understand the animal and plant resources used by humans. Here, I follow the summary proposed by Pan and Yuan (2018); Pan and Yuan (2019) to reveal the shift of animal and plant resources through time.

Pan and Yuan (2018); Pan and Yuan (2019) systematically summed up the main animal and plant remains from 57 archaeological sites and suggested the following trajectory of animal and plant resources utilized by humans (**Table 2**). During the period of 11000-8400 BP, representative of the Shangshan culture, humans greatly relied on the hunting, fishing and gathering and cultivated rice as supplement. During the period of 8200-5300 BP, represented by the Kuahuqiao, Hemudu, Majiabang, Songze cultures, humans relied mainly on hunting, fishing, and gathering (shells). The cultivation of rice, the animal husbandry (pigs and dogs) developed further and many kinds of freshwater plant resources were also utilized. During the period of 5300-4300 BP, typical of Liangzhu Culture, the rice agriculture was intensified and raising pigs became more popular with other plant resources (fruits) exploited. There might have been subsistence distinction between the central and suburb settlements. During the period of 4300-2300 BP, representative of the Guangfulin, Qianjiayang, Maqiao Cultures, the rice agriculture and animal husbandry decreased and millets came into this region in the Shang-Zhou dynasties.

In **Table 2** can infer that the marine resources had never been one of main food components in human menu in the LYRR even though they were found sparsely at several sites (Pan and Yuan, 2018; Pan and Yuan, 2019). In contrast, the terrestrial and freshwater resources were continuously made use of by humans in the prehistoric periods. The Jingtoushan site (**Figure 1**), the newly found earliest site (c. 8000 BP) near the coastline, could have been of an exception, where large quantity of marine foodstuff (shells) was found (He and Lv, 2017; http://kaogu.cssn.cn/zwb/kgyd/kgsb/202006/t20200609_5140596.shtml). Even though, terrestrial resources, such as rice and acorn, were also abundant at the site (He and Lv, 2017, suggesting that terrestrial resources were of necessary components in human foodways.

In addition, the events of sea transgression in the Holocene hamper the successive development of rice domestication. Rice phytolith analysis from more than 10 archaeological sites dating to 10000-2000 BP indicated that the ratio of bulliform phytolith with the numbers of fish-scale decoration higher or equal to 9 (domesticated rice) to that with the numbers of fish-scale decoration less than 9 (wild rice) did not always increase through time (Lv, 2017). This suggests that rice domestication was not straightforward and fluctuated at times. The fall of rice domestication during the periods of 7900-7400 BP and 6500-5600 BP might have been caused by the marine transgression (He et al., 2020). Apparently, the marine transgression decreased the continuous rice domestication during the mid-Holocene in the LYRR (He et al., 2020; He et al., 2020; Liu et al., 2020; Ma et al., 2020) and humans had to rely on diverse terrestrial and freshwater resources before the Liangzhu Culture.

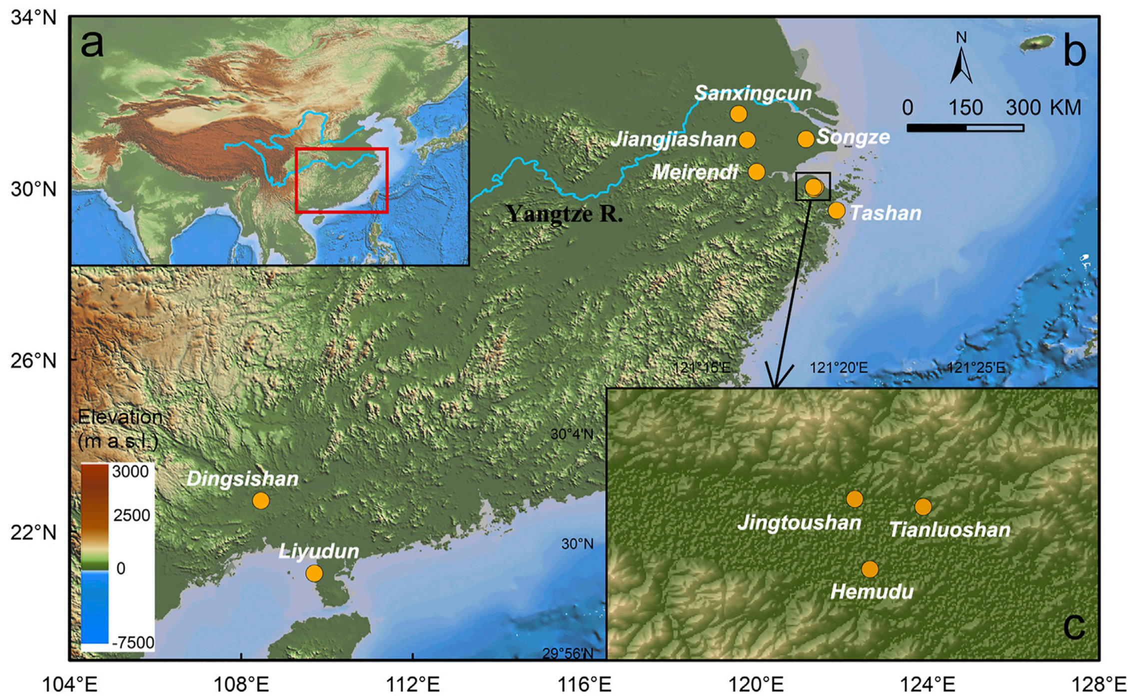

FIGURE 1 | The geographic location of archaeological sites edited by Bing Yi. **(A)** The study area; **(B)** Locations of archaeological sites mentioned in the text. **(C)** Enlarged locations of archaeological sites in the Ningshao Plain.

TABLE 3 | Collections of isotopic data of human bones in the LYRR.

Site name	Dates (BP)	Mean $\delta^{13}C$ (‰)	Mean $\delta^{15}N$ (‰)	$\delta^{13}C$(SD) (‰)	$\delta^{15}N$(SD) (‰)	Sample number	References
Songze	6000-5300	−19.9	10.9	0.5	1.7	2	Zhang et al. (2003)
Hemudu	7000-6000	−16.7	11.4	2.3	0.3	2	Zhang et al. (2003)
Sanxincun	6500-5500	−20.1	9.7	0.21	0.3	19	Hu et al. (2007)
Liyudun	7000-6000	−17	13.8	1.3	1.4	2	Hu et al. (2010)
Tianluoshan[1]	7000-6000	−20.7	8.7	0.5	0.9	10	Minagawa et al. (2011)
Tashan	5900-5600	−18.4	9.2	0.5	0.7	3	Zhang et al. (2015)
Tianluoshan[2,*]	7000-6000	−20.6	9.0	0.5	0.9	10	Dong (2016)
Jiangjiashan*	6900-5800	−20.5	10.2			1	Yu (2016)
Meirendi#	5300-4300	−19.8	10.5			9	Yoneda (2017)
Dingshishan	9000-7000	−21.1	12.3	0.7	1.8	38	Zhu et al. (2020)

[1]*One abnormal isotopic data were deleted for discussion at both sites marked by "*".*
[2]*No isotopic data in detail were reported in the paper marked with "#". The average isotopic data were estimated from the scatter plot by the author.*

Isotopic ($\delta^{13}C$, $\delta^{15}N$) Analysis of Human Bones in the LYRR

The stable isotope analysis of human bones in China initiated in 1980s and only until the 21st century is it not paid attention to by Chinese scholars (Hu, 2018). Zhang et al. (2003) reported the first isotopic data ($\delta^{13}C$, $\delta^{15}N$) of human bones in the LYRR. Subsequently, Hu et al. (2007) carried on the stable isotope analysis of human bones at the Sanxincun site, Jiangsu. Since 2010, the isotopic studies in the LYRR have increased and relatively rich isotopic data from human and animals have been accumulated. Compared to the summary of isotopic data (Chen, 2017; Qin and Fuller, 2019; Liu et al., 2021), we collected more isotopic data (**Table 3**) including the previously published and unpublished data as well as two reference groups from South China, in order to better understand human subsistence strategies and adaptation within the environmental, spatiotemporal, economic contexts in the region. The information on the site name, site location (**Figure 1**), date, the isotopic data and references is listed in **Table 3** and the error bar plot is shown in **Figure 2**.

According to **Table 3** and **Figure 2**, we can draw the following inferences:

1. Hardly humans consumed marine resources except those at Hemudu consuming a few marine resources, and relied heavily on terrestrial and/or freshwater foods. The LYRR is located

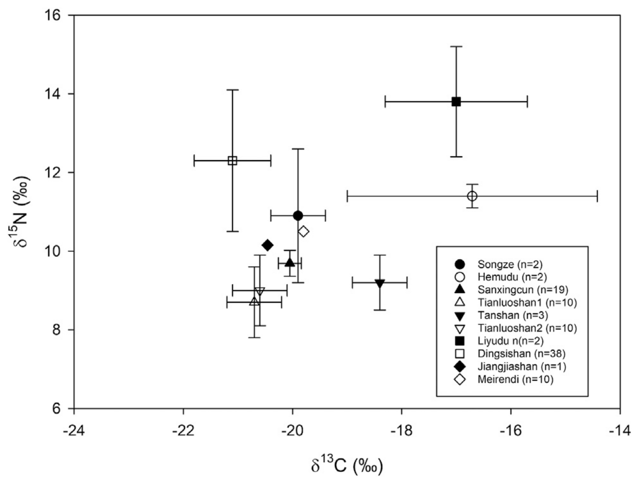

FIGURE 2 | The error bar plot of human bones in LYRR and South China.

near the China east coast. After 7000 BP, with the regression of sea levels and the expansion of lands, humans moved eastwards and occupied large lands exposed and might have had great accesses to marine foods. In general, humans consuming large quantity of marine resources should have much positive $\delta^{13}C$ values and high $\delta^{15}N$ values such as those at Liyudun in Figure 4. It is so surprising for us to see that humans dating to 7000-5000 BP except those at Hemudu did not mainly consume marine foods during the process of population movements eastwards. In particular, humans at Tashan, closest to the coastline (**Figure 1**), did not consume any marine foods and mainly relied on terrestrial foods (**Table 3**; **Figure 2**). This unique dietary pattern of humans reflects that humans had conservative preference on terrestrial and/or freshwater resources even though they had great opportunity to obtain the seafoods. Our inference here is consistent with the opinion (Qin and Fuller, 2019) suggesting that the prehistoric humans in the LYRR were lack of the motives of exploiting marine resources.

2. Humans did not be mainly engaged in the hunting/fishing activities and consumed large quantity of terrestrial resources with some freshwater resources supplemented. In general, humans consuming a lot of freshwater fish have low $\delta^{13}C$ and high $\delta^{15}N$ values such as those at Dingsishan in South China (**Figure 2**). Compared to those at Dingsishan, humans in the LYRR in **Figure 2** have higher $\delta^{13}C$ and lower $\delta^{15}N$ values, strongly indicating that their foods were deprived more from terrestrial surroundings and less from freshwater fish. This is in line with the archaeozoological finding (**Table 2**), indicating that fish was not one of important components in human diets even though they were present all the time. Instead, terrestrial animals (deer, pigs) or wetland plants with possible lower $\delta^{15}N$ values (rice including domesticated rice or wild rice, gorgon fruit, water chestnut, *etc.*) could have been the necessary compositions in human diets.
3. Human diets were diverse and shifted diachronically. Humans at Hemudu might consume some marine foods while those at Tianluoshan ate many plant resources. They could be deprived from several types of wetland plants, like rice, gorgon fruit, water chestnut (Pan and Yuan, 2018; Pan and Yuan, 2019) and typha (Zhang et al., 2020). The consumption of starchy plants was also confirmed by the residue analysis (Shoda et al., 2018). Different from those at Tianluoshan, humans at Jiangjiashan consumed more freshwater resources such as fish; humans at Songze mainly inhabited on the terrestrial and freshwater environment; humans at Tashan obtained their foods mainly from terrestrial environment and seldom from freshwater resources; humans at Sanxincun intensified the utilization of freshwater resources such as shells. It seems that humans at Meirendi escaped from the wetland environment and consumed more animal protein from freshwater resources or domestic animals. Given the popularity of pig husbandry during the Liangzhu Culture (**Table 2**), domestic pigs could have contributed more to animal resources at the site.
4. The cultivation of rice and its contribution to human diets vary in the different areas and periods. As indicated in **Table 2**, the domestication of rice has developed quickly around 7000-6000BP and matured around 5000 BP. In principle, if rice would be more and more incorporated in human diets, the decrease of $\delta^{15}N$ values from humans should have been expected as rice belongs to starchy plants with low nitrogen contents and has low $\delta^{15}N$ values in general (Suzuki et al., 2008). However, large isotopic difference among human populations can be seen in **Figure 2**, even though the domesticated rice is present in different periods and areas. This could be caused by the consumption of diverse terrestrial or freshwater resources. Therefore, no matter what rice is wild or domesticated, rice production by humans should have been of low-level. Humans at Meirendi in the core area of Liangzhu Culture have a little higher $\delta^{13}C$ and $\delta^{15}N$ values than those in Tianluoshan (**Figure 2**) and the isotopic data don't show decreasing pattern as expected if rice agriculture was intensified during the period. Nevertheless, we should caution that given the limited isotopic data available here the current discussion on the contribution of rice agriculture to human subsistence strategy is still preliminary. More isotopic data are needed to prove or refute it in the near future.

DISCUSSION

It is traditionally supposed that the occurrence and development of agriculture is the key to increase the food production and satisfy with the population growth and the rise of social complexity (e.g., Gignoux et al., 2011). However, recent study (Lewis, et al., 2020) challenges the above standpoint.

The global increase of sea levels in the Holocene has great impact on human activities worldwide (Dong et al., 2020) and makes humans easily approach the marine resources. A number of isotopic studies show that humans close to the coastline have intensively consumed marine foods in Europe (Richards and Hedges, 1999; Montgomery, et al., 2013; Schulting, 2018), Japan (Kusaka et al., 2010), and South Korea (Choy et al., 2012) before the transition to agriculture. The adaptation of sea level increase by humans greatly expands food choices in human menu and stimulates the cultural developments and population increase in Southern Scandinavia before the arrival of agriculture (Lewis et al., 2020).

Compared to humans in Southern Scandinavia, the humans in the LYRR, however, adopted a quite different strategy when facing the rise of sea level in the Holocene as well. The economic (**Table 2**) and isotopic (**Table 3**; **Figure 2**) evidence strongly suggests that humans rarely relied on marine resources and consumed large quantity of terrestrial and/or freshwater resources (plants) instead, even though they had good accesses to marine environment. Before the Liangzhu Culture, the rice had been in low-level food production and contributed less to human diets for a long time. On the other hand, humans subsisted mainly on the terrestrial and freshwater or wetland resources. This unique subsistence strategy could possibly have made humans well adapt to unstable environment and sea transgression at times, which expanded the settlements and population subsequently and resulted in the social complexity. Therefore, our comprehensive study here illustrates a novel pattern of human subsistence strategy and adaption to increasing human population in the condition of low-level agricultural production, challenging the traditional view that only developed agriculture can make human population grow and advance human society.

CONCLUSION

Based on the introduction to environmental, spatiotemporal and economic contexts, this paper summarized the isotopic data of human bones in the LYRR and drew several inferences on human subsistence strategies. The most striking finding is that humans hardly consumed marine resources even though they faced the coastline directly. Instead, they subsisted mainly on terrestrial and/or freshwater (wetland) resources and less on rice production. The specific subsistence strategies, long-term insistence, and adaptations to the unstable environment and frequent sea transgression make it possible for humans in the prehistoric period to meet the demands of settlement expansion and population increase. The uniqueness of human subsistence strategies in the LYRR expands our understanding of the means of increasing human population and social complexity.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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REFERENCES

Chen, X. (2017). Stable isotope (C, N) analysis and the advances of agricultural archaeology. *Agric. Archaeology* 6, 13–25. (in Chinese).

Choy, K., An, D., and Richards, M. P. (2012). Stable isotopic analysis of human and faunal remains from the Incipient Chulmun (Neolithic) shell midden site of Ando Island, Korea. *J. Archaeological Sci.* 39 (7), 2091–2097. doi:10.1016/j.jas.2012.03.005

Dong, G., Li, R., Lu, M., Zhang, D., and James, N. (2020). Evolution of human-environmental interactions in China from the late paleolithic to the bronze age. *Prog. Phys. Geogr. Earth Environ.* 44 (2), 233–250. doi:10.1177/0309133319876802

Dong, Y. (2016). *Preliminary exploration of prehistoric human subsistence in Zhejiang coastline*. Master's thesis. Hangzhou: Zhejiang University. (in Chinese).

Gignoux, C. R., Henn, B. M., and Mountain, J. L. (2011). Rapid, global demographic expansions after the origins of agriculture. *Proc. Natl. Acad. Sci. USA* 108 (15), 6044–6049. doi:10.1073/pnas.0914274108

He, K., Lu, H., Zheng, H., Yang, Q., Sun, G., Zheng, Y., et al. (2020). Role of dynamic environmental change in sustaining the protracted process of rice domestication in the lower Yangtze River. *Quat. Sci. Rev.* 242, 106456. doi:10.1016/j.quascirev.2020.106456

He, K., and Lv, H. (2017). "The origin of marine culture: the temperature increase during the early Holocene in the Lower Yangtze River Region and rice utilization and human activities on the basis of the rise of sea level," in *The collection of abstracts for No. 10 symposium of palynology branch of Chinese* (Chifeng: Palaeontology Society).

He, K. Y., Lu, H. Y., Li, Y. N., Ding, F. Y., Zhang, J., and Wang, C. (2020). Cultural response to Middle Holocene sea-level fluctuations in eastern China: a multi-proxy approach. *Boreas* 49 (1), 71–88. doi:10.1111/bor.12421

Hu, Y., Li, F., Wang, C., and Richards, M. P. (2010). Stable isotope (C, N) analysis of human bones at Liyudun site, Zhanjiang, Guangdong: preliminary exploration of human lifestyles during the Neolithic in South China. *Acta Anthropologia Sinica* 29 (3), 264–269. (in Chinese).

Hu, Y. (2018). Thirty-four years of stable isotopic analyses of ancient skeletons in China: an overview, progress and prospects. *Archaeometry* 60 (1), 144–156. doi:10.1111/arcm.12367

Hu, Y., Wang, G., Cui, Y., Dong, Y., Guan, L., and Wang, C. (2007). Paleodietary study on humans at the Sanxincun site, jintan, jiangsu. *Chin. Sci. Bull.* 52 (1), 85–88. doi:10.1007/s11434-007-0085-4 (in Chinese).

Kusaka, S., Hyodo, F., Yumoto, T., and Nakatsukasa, M. (2010). Carbon and nitrogen stable isotope analysis on the diet of Jomon populations from two coastal regions of Japan. *J. Archaeological Sci.* 37 (8), 1968–1977. doi:10.1016/j.jas.2010.03.002

Lambeck, K., Rouby, H., Purcell, A., Sun, Y., and Sambridge, M. (2014). sea level and global ice volumes from the last glacial Maximum to the Holocene. *Proc. Natl. Acad. Sci. USA* 111 (43), 15296–15303. doi:10.1073/pnas.1411762111

Lewis, J. P., Ryves, D. B., Rasmussen, P., Olsen, J., van der Sluis, L. G., Reimer, P. J., et al. (2020). Marine resource abundance drove pre-agricultural population increase in Stone Age Scandinavia. *Nat. Commun.* 11 (1), 2006–2010. doi:10.1038/s41467-020-15621-1

Ling, G., Ma, C., Yang, Q., Hu, Z., Zheng, H., Liu, B., et al. (2021). Landscape evolution in the Liangzhu area since the early Holocene: a comprehensive sedimentological approach. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 562, 110141. doi:10.1016/j.palaeo.2020.110141

Liu, J., Milliman, J., Gao, S., and Cheng, P. (2004). Holocene development of the Yellow River's subaqueous delta, north Yellow sea. *Mar. Geology.* 209, 45–67. doi:10.1016/j.margeo.2004.06.009

Liu, R., Pollard, M., Schulting, R., Rawson, J., and Liu, C. (2021). Synthesis of stable isotopic data for human bone collagen: a study of the broad dietary patterns across ancient China. *The Holocene*, doi:10.1177/0959683620941168

Liu, Y., Deng, L., He, J., Jiang, R., Fan, D., Jiang, X., et al. (2020). Early to middle Holocene rice cultivation in response to coastal environmental transitions along the South Hangzhou Bay of eastern China. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 555, 109872. doi:10.1016/j.palaeo.2020.109872

Lv, H. (2017). New methods and advances on the study of the origin and evolution of Chinese prehistoric agriculture. *Scientia Sinica Terrae* 47 (2), 181–199. (in Chinese).

Ma, T., Rolett, B. V., Zheng, Z., and Zong, Y. (2020). Holocene coastal evolution preceded the expansion of paddy field rice farming. *Proc. Natl. Acad. Sci. USA* 117 (39), 24138–24143. doi:10.1073/pnas.1919217117

Minagawa, M., Matsui, A., Nakamura, S., and Sun, G. (2011). "Carbon and nitrogen stable isotope analysis of human and animal remains from Tianluoshan site: to understand food resource management of Hemudu culture,". Integrated Studies on the Natural Remains from Tianluoshan in *Center for the study of Chinese archaeology, peking university and zhejiang province institute of archaeology and cultural heritage* (Beijing: Cultural Relics Press), 262–269. (in Chinese).

Montgomery, J., Beaumont, J., Jay, M., Keefe, K., Gledhill, A. R., Cook, G. T., et al. (2013). Strategic and sporadic marine consumption at the onset of the Neolithic: increasing temporal resolution in the isotope evidence. *Antiquity* 87 (338), 1060–1072. doi:10.1017/s0003598x00049863

Ouyang, X., Hao, X., Zheng, L., Zhuo, B., and Liu, Y. (2019). Early to mid-Holocene vegetation history, regional climate variability and human activity of the Ningshao Coastal Plain, eastern China: new evidence from pollen, freshwater algae and dinoflagellate cysts. *Quat. Int.* 528, 88–99. doi:10.1016/j.quaint.2019.05.027

Pan, H. (2020). *Vegetation changes and human activities during the Neolithic period in the Kuahuqiao area of Zhejiang: comparison of pollen records between natural cores and archaeological profiles*. Master thesis. Hefei: University of Science and Technology of China.

Pan, Y., and Yuan, J. (2018). Subsistence in the lower Yangtze River region from the neolithic to pre-qin period (part one). *Relics in South* 4, 111–125. (in Chinese).

Pan, Y., and Yuan, J. (2019). Subsistence in the lower Yangtze River region from the neolithic to pre-qin period (part two). *Relics in South* 1, 122–135. (in Chinese).

Qin, L., and Fuller, D. Q. (2019). "Why rice farmers don't sail: coastal subsistence traditions and maritime trends in early China," in *Prehistoric maritime cultures and seafaring in east asia* (Singapore: Springer), 159–191.

Renfrew, C., and Liu, B. (2018). The emergence of complex society in China: the case of Liangzhu. *Antiquity* 92 (364), 975–990. doi:10.15184/aqy.2018.60

Richards, M. P., and Hedges, R. E. M. (1999). Stable isotope evidence for similarities in the types of marine foods used by Late Mesolithic humans at sites along the Atlantic coast of Europe. *J. Archaeological Sci.* 26 (6), 717–722. doi:10.1006/jasc.1998.0387

Schulting, R. (2018). "Dietary shifts at the Mesolithic–Neolithic transition in Europe: an overview of the stable isotope data," in *The Oxford handbook of the archaeology of diet* (Oxford: Oxford University Press), 1–32.

Shoda, S., Lucquin, A., Sou, C. I., Nishida, Y., Sun, G., Kitano, H., et al. (2018). Molecular and isotopic evidence for the processing of starchy plants in Early Neolithic pottery from China. *Sci. Rep.* 8 (1), 17044–17049. doi:10.1038/s41598-018-35227-4

Song, B., Li, Z., Saito, Y., Okuno, J., Li, Z., Lu, A., et al. (2013). Initiation of the Changjiang (Yangtze) delta and its response to the mid-Holocene sea level change. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 388, 81–97. doi:10.1016/j.palaeo.2013.07.026

Suzuki, Y., Chikaraishi, Y., Ogawa, N. O., Ohkouchi, N., and Korenaga, T. (2008). Geographical origin of polished rice based on multiple element and stable isotope analyses. *Food Chem.* 109 (2), 470–475. doi:10.1016/j.foodchem.2007.12.063

Tang, L., Lv, Y., Nian, X., Lei, S., and Wang, Z. (2019). Middle Holocene seawater intrusion and human rapid response in the Yaojiang-Ningbocoastal plain, China. *Quat. Sci.* 39 (5), 1116–1132. (in Chinese).

Wang, S., Ge, J., Kilbourne, K. H., and Wang, Z. (2020). Numerical simulation of mid-Holocene tidal regime and storm-tide inundation in the south Yangtze coastal plain, East China. *Mar. Geology.* 423, 106134. doi:10.1016/j.margeo.2020.106134

Wang, Z., Saito, Y., Zhan, Q., Nian, X., Pan, D., Wang, L., et al. (2018). Three-dimensional evolution of the Yangtze River mouth, China during the Holocene: impacts of sea level, climate and human activity. *Earth-Science Rev.* 185, 938–955. doi:10.1016/j.earscirev.2018.08.012

Xiong, H., Zong, Y., Li, T., Long, T., Huang, G., and Fu, S. (2020). Coastal GIA processes revealed by the early to middle Holocene sea-level history of east China. *Quat. Sci. Rev.* 233, 106249. doi:10.1016/j.quascirev.2020.106249

Yan, D., Wünnemann, B., Gao, S., and Zhang, Y. (2020). Early Holocene tidal flat evolution in a western embayment of East China Sea, in response to sea level rise episodes. *Quat. Sci. Rev.* 250, 106642. doi:10.1016/j.quascirev.2020.106642

Yang, H., and Xie, Z. (1984). Sea-level changes along the east coast of China over the last 20000 years. *Oceanologia Limnologia Sinica* 15, 1–13. (in Chinese).

Yoneda, M. (2017). Perspectives on methodology of isotope ecology: reconstruction of lives and society of early farmers in the Lower Yangtze River Region. *Relics in South* (3), 10–15. (in Chinese).

Yu, B. (2016). *Preliminary exploration of pathways to pig domestication in China*. Master's thesis. Hangzhou: Zhejiang University.

Zhang, G., Jiang, L., Hu, Y., Si, Y., Lv, P., Song, G., et al. (2015). Stable isotope (C, N) analysis of human and animal bones at the Tashan site, Zhejiang. *Huaxia Archaeology* (2), 138–146. (in Chinese).

Zhang, X., Wang, J., Xi, Z., and Qiu, S. (2003). Dietary research on ancient humans. *Archaeology* 2, 62–75. (in Chinese).

Zhang, Y., van Geel, B., Gosling, W. D., Sun, G., Qin, L., and Wu, X. (2020). Typha as a wetland food resource: evidence from the Tianluoshan site, Lower Yangtze Region, China. *Veget Hist. Archaeobot.* 29 (1), 51–60. doi:10.1007/s00334-019-00735-4

Zhao, X., Tang, L., Shen, C., and Wang, S. (1994). Holocene climate change and sea level change in Qingfeng section, Jianhu, Jiangsu. *Acta Oceanologia Sinica* 16, 78–88. (in Chinese).

Zheng, H., Zhou, Y., Yang, Q., Hu, Z., Ling, G., Zhang, J., et al. (2018). Spatial and temporal distribution of Neolithic sites in coastal China: sea level changes, geomorphic evolution and human adaption. *Sci. China Earth Sci.* 61 (2), 123–133. doi:10.1007/s11430-017-9121-y

Zhu, S., Li, F., Chen, X., Fu, X., and Hu, Y. (2020). *First direct evidence on human subsistence strategy and health during the middle Neolithic (9000-7000 BP) in southern China*. Mancester: Antiqnty. In press https://doi.org/10.15184/aqy.2020.214

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The Impact of Ancient Landscape Changes on the City Arrangement of the Early Shang Dynasty Capital Zhengzhou, Central China

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Buried underneath modern Zhengzhou city in Henan Province, China, lies the archeological remains of one of the ancient capital cities of the Shang dynasty (1766 – 1122 BCE). Although it is likely that people planned this Shang capital city according to the demands of the surrounding environment, there is no clear relationship between the current environment, such as the hydrology and topography, and the ancient city's layout. To better understand the relationship between planning principles used during the Shang dynasty and the nearby environment at Zhengzhou, we measured and sampled stratigraphic exposures at excavation locations throughout Zhengzhou. Through these excavations we obtained both absolute and relative chronological data from each culture layer, enabling us to use geospatial interpolation and analysis methods to reconstruct the ancient landscape. The results show that ancient city's different activity areas had a close relationship with their environmental context. For example, the Shang dynasty palace was located on high ground and workshops were located down below along the courses of ancient rivers. In conclusion, we argue that research that merges geomorphology and archeology is a necessary prerequisite for understanding the development of urban areas.

Keywords: Zhengzhou Shang City, landscape changes, ancient city arrangement, human-environmental interactions, geomorphic evolution

INTRODUCTION

Cities are the most complex form of human settlement and are usually a signal of increasing socio-political complexity. During the early Neolithic, societies shifted from a highly mobile, hunting and gathering, subsistence strategy to a lifeway more grounded in permanent settlement and agriculture. Based on evidence from archeological excavations, archeologists have uncovered a significant amount of evidence that the earliest settlements were not only small in size but also had limited functions and activity spaces (Trigger, 1989; Renfrew and Bahn, 1991; Liu, 2004; Lu et al., 2013). As population increased and settlements became more numerous, some of these settlements became "central places" as they developed into political, economic, and regional centers. Therefore, location and form of early cities is likely an outcome of a long term, regional, process of increasing socio-political complexity. The original layout of a city not only reflects the characteristics of the natural environment but also the cultural beliefs (Wheatley, 1971). The geographic position and spatial arrangement of early cities is a significant factor for understanding human-environment interactions.

A significant amount of research has examined the interconnection between the layout of early cities and their relationship to landscape evolution. For example, Assefa Getaneh et al. (2018) reconstructed the spatial distribution of some pre-Aksumite cultural structures like stone-based walls using magnetic reconnaissance survey in the Seglamen Site of northern Ethiopia. Schwerin et al. (2016) drew a more accurate archeological map in the Copan site of Honduras using LiDAR data. Gianna Ayala et al. (2017) reconstructed the alluvial landscape of Neolithic Çatalhoyük, central southern Turkey. Sun et al. (2017) reported the settlement structure of Neolithic Shimao which was believed as a regional political and ritual center on China's north Loess Plateau. Wu et al. (2019) and Storozum et al. (2020)'s work examines the "city on top of a city' phenomenon at Kaifeng from a geoarcheological perspective. Qian (2019) reconstructed the spatial pattern of North Wei (386-534 AD) Capital Luoyang City. Although this research has helped identify characteristics of the internal layout of several ancient cities, there is generally less discussion concerning human-environmental interaction from the perspective of landscape evolution. As a result, this research loses useful information concerning the development of early cities and the process of urbanization. Moreover, it is also difficult to identify the roles that the nearby environment plays in supporting a developing cityscape.

From 2011 to 2020, we conducted a multidisciplinary archeological research project at the early Shang dynasty capital of Zhengzhou, one of the oldest cities in the China in an attempt to recover the plan of the city's original layout and examine this layout's relationship to the contemporaneous geomorphological units. In general, our research at Zhengzhou attempts to use a geoarcheological investigation to answer several important questions:

- Why did the ancient Shang people build their capital there?
- How was its relationship with the regional terrain?
- What were the early landscape features like?
- How did the ancient landscape influence the city's layout?

EARLY SHANG DYNASTY CAPITAL ZHENGZHOU

Zhengzhou Shang City is an important early capital city of China. The capital belonged to the early stage of Shang dynasty (ca. 1,600 BC) (Ren and Liu, 2019). This archeological site is located directly underneath the modern Zhengzhou city in central Henan Province and covers over 25 km^2 (Chen, 1999). Here, archeologists have found remains of the ancient city, including massive city walls, a palace, and large bronze ritual vessels (Chen and Zeng, 1991; HICRA, 1993, 2001; HICRA and ZICRA, 1999; Yuan et al., 2004).

The area of the Shang dynasty city of Zhengzhou was located at the transitional zone between the Loess Plateau and the North China Plain. This makes the region high in the west and low in the east. Although the Yellow River is no more than 20 km to the north of the city, the city is actually located within the catchment of the Huai River (**Figure 1**). On the northern and southern edges of the Shang dynasty city is a small river called the Jinshui River. To the south of the Shang city is the Xiong'er River. Both rivers are tertiary tributaries of the Huai River. This region is located within a warm temperate continental monsoonal climate. The annual average temperature is 14°C and the annual precipitation is 600 mm (Shi, 1983).

Over the past 60 years, archeologists have conducted a wide range of excavations in Zhengzhou Shang City (An, 1954; Zhao et al., 1957). In general, archeologists now understand the layout of the ancient city (Yuan and Zeng, 2004; Liu et al., 2010; Yuan, 2018). Archeologists have divided the city into three areas, the outer city, the inner city, and the palace city (**Figure 1**). Each of these areas is divided by walls. The walls of outer city were round and archeologists have only found the remains of these walls in the western and southern parts of the city (Yuan and Zeng, 2004; Jiang et al., 2009; Liu et al., 2010; Yuan, 2018). The walls of the inner city are approximately rectangular and there was a beveled edge at the northeast corner. The palace city was located at the northeastern part of the inner city. Several Shang dynasty palaces have been found there (An and Yang, 1983; Zeng et al., 2000). Other activity areas, like workshops, hoards, and sacrificial zones, are scattered throughout the site (Pan, 2010; Chang, 2018; Hou, 2018; Zhang, 2018). The northern and southern sides of the outer city are flanked by rivers, the Jinshui River in the north and the Xionger River in the south. The Jinshui River's course still runs through the modern area where the inner city was located. To the east of the city was a large lake (Huang, 2011; Huang and Wang, 2014), but so far, no geological evidence demonstrate the lakes existence has been documented.

MATERIALS AND METHODS

Field Survey and Sampling

We conducted a detailed field survey around the Shang city and the surrounding areas. Before the survey, we drew a detailed geomorphic map of the region using the DEM, remote sensing images, as well as geological and topographic maps. We observed, measured, and analyzed exposed sections in different geomorphic settings around Zhengzhou. The color, depth, structure, sediment type, and the presence of absence of inclusions in every layer were recorded in detail. The stratigraphic profiles were drawn according to a fixed and standardized scale. From these field

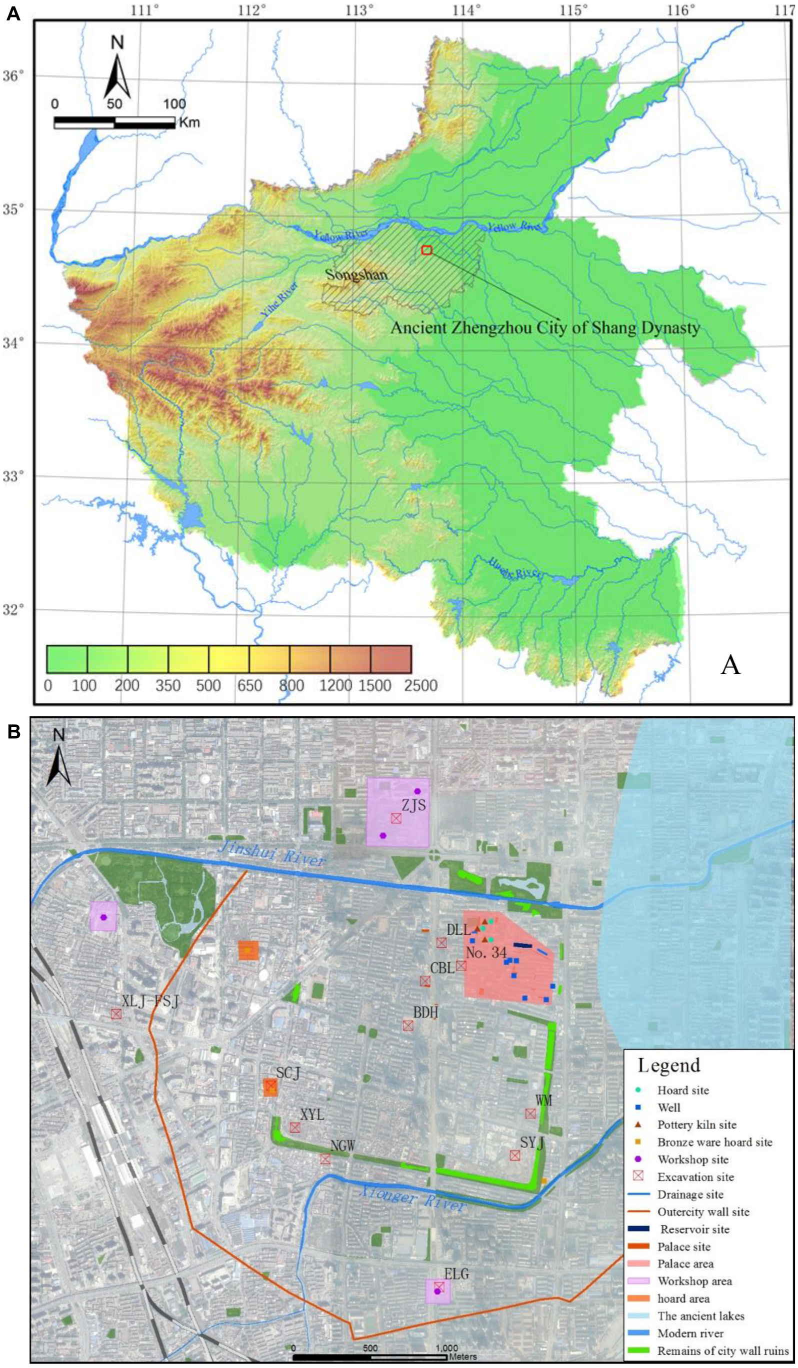

FIGURE 1 | Research area. **(A)** The location of Zhengzhou Shang city in Henan Province; **(B)** The layout of Zhengzhou Shang city. The excavation sites in **Figure 3** are labeled on this map.

observations, we interpreted the approximate time of deposition and depositional environment.

Some of the most important sections and layers were sampled. Sediment samples were collected at equal intervals of 5 cm. There are two ways to collect samples for dating purposes. The ^{14}C samples were collected from the carbon-rich strata. If the stratum did not contain much carbonized flecks, we collected OSL samples to date the layers. In total, we collected 583 sediment samples, 1 ^{14}C samples and 12 OSL samples.

Dating

Radiocarbon dating was done at Peking University. Radiocarbon samples were tested by the methods of Accelerator Mass Spectrometer (AMS). The half-life period of ^{14}C is 5,568 years.

BP is the radiocarbon years before present (Present = AD 1950). Tree rings enable the calibration of radiocarbon curves, known as IntCal13 (Reimer et al., 2013). We used OxCal to calibrate the radiocarbon dates.

The OSL samples were analyzed at the Institute of Geography, Henan Academy of Sciences, China. Samples pretreatment was carried out using fine particle methods. Calcium, carbonate and organic matter were removed from all samples using HCl and H_2O_2. The quartz particles in the 4-11 μm fraction were tested in the machine. Every sample was tested 8-12 sample slices. The method for measure is the Single Aliquot Regenerative-dose (SAR) protocol. The contents of U, TH, and K in the samples were determined by neutron activation method (NAA). We measured the measured moisture content and the absolute error was set at 5%. The aliquots num is the number of practical test pieces in the final calculation (Lai and Ou, 2013).

Particle Size Analysis

Particle size analysis was also carried out at the Institute of Geography, Henan Academy of Sciences. Organic matter and inorganic carbon were removed from the samples using diluted hydrochloric acid and hydrogen peroxide. Then 10 mL of 0.05 mol/L sodium hexametaphosphate was added to the sample. After the particles were well dispersed by heating the sample to a boil, each sample was analyzed using a laser particle size analyzer. The measuring range of particle diameter is 0.02-2000 μm.

Database and Terrain Simulation

Since 1984, there have been around 200 excavations at the Shang city underneath modern Zhengzhou. We collected all the stratigraphic information from each excavation report and used these data to build a GIS database. The data include geographic position, coordinates, altitude, depositional types, sediment characteristics and stratigraphic thickness. Using these data, we can precisely display the stratigraphic information on a map to conduct spatial analyses.

We used the Natural Neighbor method to simulation the landscape evolution for the area. First, this method creates a Voronoi polygon using the existing spatial data. The points waiting to be solved are also used to create a Voronoi polygon. The intersection of both polygons forms a pattern, from which, according to the area of each spot, we can determine the value of the unknown points. Using this method, we can obtain the stratigraphic thickness for a specific time period. Then, we calculated the DEM for each time period using the formula below:

$$DEM_i = DEM_p - T_i$$

Whereas, DEM_i is the DEM for a specific time period, DEM_p is the DEM of the present topography, T_i is the stratigraphic thickness for each specific simulated time period using the Natural Neighbor analysis. We then used the DEM for each specific period to analyze how the terrain changed overtime.

TABLE 1 | Dating results.

OSL

Lab.N	Sample N.	Depth (cm)	U/ppm	Th/ppm	K/%	Rb/ppm	Q-De (Gy)	aliqouts Num.	w.c (%)	Q-Dose rate	Q-Age (ka)
L461	ZSC8IIT537 OSL1	40	1.74 ± 0.58	9.40 ± 0.74	2.28 ± 0.36	89.8 ± 0.58	12.44 ± 0.24	10	1.23	4.178 ± 0.360	2.978 ± 0.263
L462	ZSC8IIT537 OSL2	140	2.15 ± 2.87	12.3 ± 0.69	1.80 ± 0.46	80.1 ± 1.47	111.08 ± 1.74	10	13.73	3.462 ± 0.638	32.082 ± 5.930
L463	ZSC8IIT537 OSL3	220	2.16 ± 1.11	12.9 ± 1.02	1.77 ± 0.26	78.2 ± 0.78	142.48 ± 1.05	10	15.85	3.395 ± 0.315	41.961 ± 3.901
L464	ZSC8IIT537 OSL4	280	2.23 ± 3.27	12.5 ± 1.37	1.79 ± 0.95	78.8 ± 1.51	143.38 ± 1.64	10	11.47	3.549 ± 0.943	40.397 ± 10.740
L465	ZSC8IIT537 OSL5	360	1.91 ± 0.85	10.1 ± 0.66	1.86 ± 0.59	80.3 ± 1.27	124.02 ± 1.06	10	11.95	3.277 ± 0.481	37.844 ± 5.568
L167	ZSC8IIT501②B	260	1.19 ± 0.0476	10.9 ± 0.3052	1.87 ± 0.05797	95.5 ± 7.9265	10.62 ± 0.09	10	20 ± 5	2.909 ± 0.153	3.650 ± 0.194
L170	ZSC8IIT500-6②	500	2.67 ± 0.1068	12.9 ± 0.3483	1.42 ± 0.0426	102 ± 6.528	4.38 ± 0.04	10	20 ± 5	3.070 ± 0.188	1.426 ± 0.088
L176	DLLC8II T499-13[illegible]	720	2.05 ± 0.0861	11 ± 0.308	1.74 ± 0.05568	78.7 ± 5.3516	86.67 ± 3.95	10	20 ± 5	2.991 ± 0.166	28.976 ± 2.081
L429	ZSC8IIT518 OSL1	30	1.9 ± 1.59	11.7 ± 1.58	1.64 ± 0.46	104 ± 0.59	7.88 ± 0.11	10	3.39	3.709 ± 0.541	2.125 ± 0.312
L627	ZZBDH-1	110	2.43 ± 2.0	13 ± 2.2	2.35 ± 0.38	89.3 ± 2.5	3.87 ± 0.11	7	7.23	4.410 ± 0.536	0.877 ± 0.109
L628	ZZBDH-2	150	2.37 ± 1.3	14.2 ± 1.2	2.45 ± 0.81	91.3 ± 0.5	5.89 ± 0.09	10	6.15	4.644 ± 0.714	1.268 ± 0.196
L629	ZZBDH-3	170	2.14 ± 1.4	12.3 ± 1.2	2.47 ± 0.1	99.2 ± 3	7.43 ± 0.15	10	6.02	4.417 ± 0.340	1.682 ± 0.134

AMS ^{14}C

Lab.N	Sample N.	Sample	Location	^{14}C age (BP)	1σ (68.2%)	2σ (95.4%)
BA192642	WMD005	carbon	Zhengzhou Shang City	1240 ± 20	693AD (54.5%) 747AD	687AD (72.4%) 779AD
					763AD (13.7%) 776AD	790AD (23.0%) 870AD

RESULTS

The Geomorphic Location of Zhengzhou Shang City

There are many different kinds of geomorphic landforms located at the transition zone between the Loess Plateau and the North China Plain (Lu et al., 2014). According to the altitude, topographic relief, accumulation rates and sedimentary characteristics of different deposits in the area, Lu et al. (2021) divided the regional topography into several types of landforms, which include mountains, hills, tablelands and plains. At present, Zhengzhou is located in the plains. However, our field survey

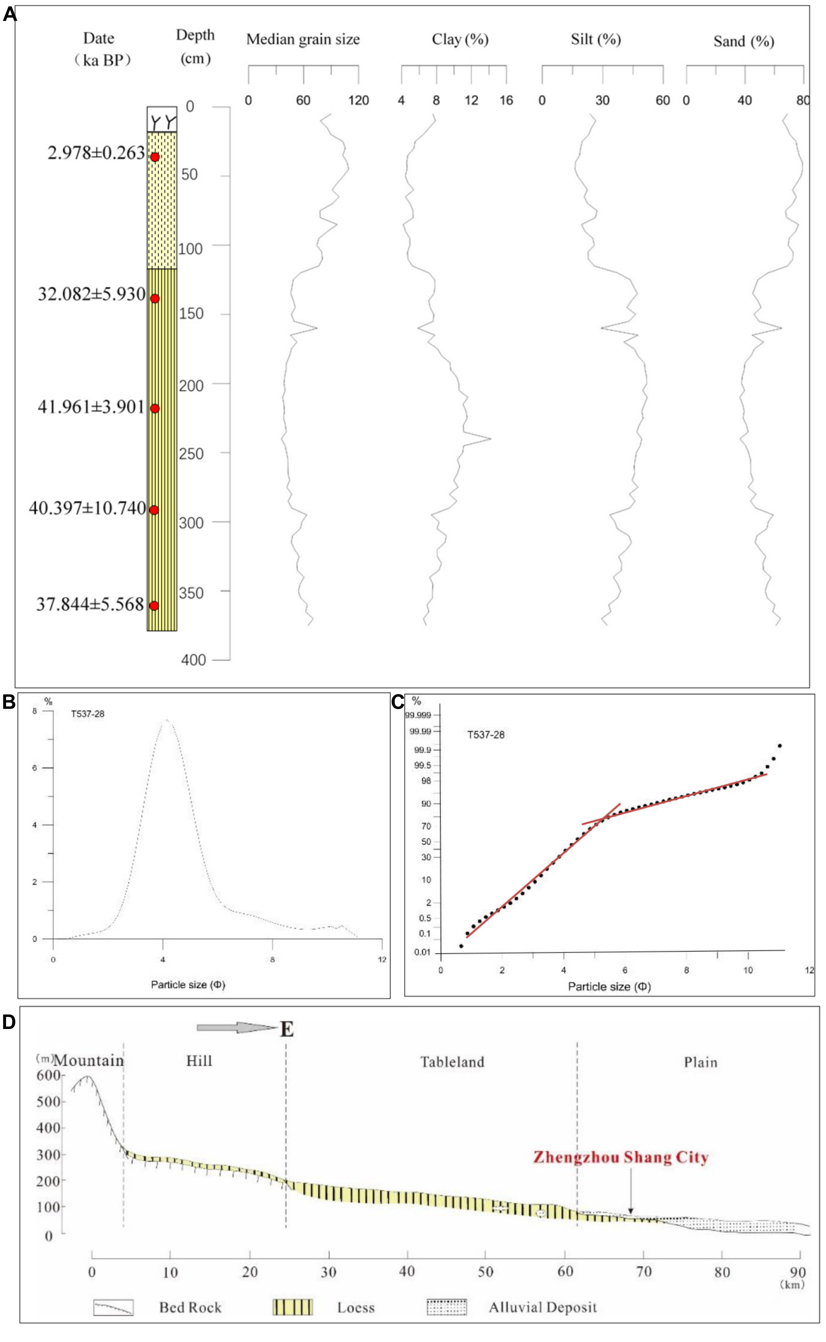

FIGURE 2 | Particle size analysis **(A)** The particle size component of T537 profile in No.34 courtyard. The OSL ages are marked on the stratigraphic section according to the depth. Although the three ages are inverted in the bottom, all of them fall into the Late Pleistocene, and their errors are also within the appropriate range. **(B)** The frequency distribution curve of sample 28 (140 cm) of T537. **(C)** The probability cumulative curve of sample 28 of T537. **(D)** The geomorphic position of Zhengzhou Shang City.

indicates that Zhengzhou was not always located on an alluvial plain. Under the cultural layers found in the excavations at Zhengzhou, there is a layer of loess, which OSL ages from T537, indicate were deposited during the late Pleistocene (**Table 1**). The result of particle size analysis showed this sediment is primarily silty sand (**Figure 2**). The probability accumulation curve of sample 28 (140 cm) showed the particle was thinner. The particle diameter is smaller than 4Φ, which is less than 10% of the saltation load. At 70%, particle diameters greater than 4Φ are part of the suspended load. The samples are poorly sorted as shown in the frequency distribution curve of sample 28 (**Figure 2**). These data indicate that the accumulation curves closely resemble those of aeolian loess deposits formed during the late Pleistocene (STCCG, 1978). This demonstrated that the loess tableland in the west extended into the area of Zhengzhou Shang city during the late Pleistocene.

Although the area of Zhengzhou Shang city was part of the loessic tablelands during the late Pleistocene, the distribution of loess does not continue much farther to the east. Liu (1992) found a thick alluvial stratum at the Zhacheng Site, around 10 km east of Zhengzhou. These deposits date to the late Pleistocene (Liu, 1992). At the Dahecun site, the alluvial strata date back to 12,000 BP (Yu, 2016). The date of these alluvial sediments east of Zhengzhou extend back into the middle-late Holocene (Liu, 1992; Yu, 2016). This corresponded to a famous ancient lake, Putianze, which is recorded in Chinese historical documents (Huang and Wang, 2014).

From the above analysis, we argue that Zhengzhou Shang city was located at the transitional zone between the loess tablelands and alluvial plain. According to the recovered sediments, the site area should be at the front of the loess tableland, which extended into the alluvial plain (**Figure 2**). During the Shang dynasty, people decided to locate their early capital in this area because of it had high ground, flat terrain, and was nearby to fresh water.

The Depositional Characteristics of Site Area

Unlike archeological sites in the countryside, most of Zhengzhou Shang city is covered by modern Zhengzhou. This complicates archeological and geoarchaeological work and required that our field work visit each point in the city. The field survey

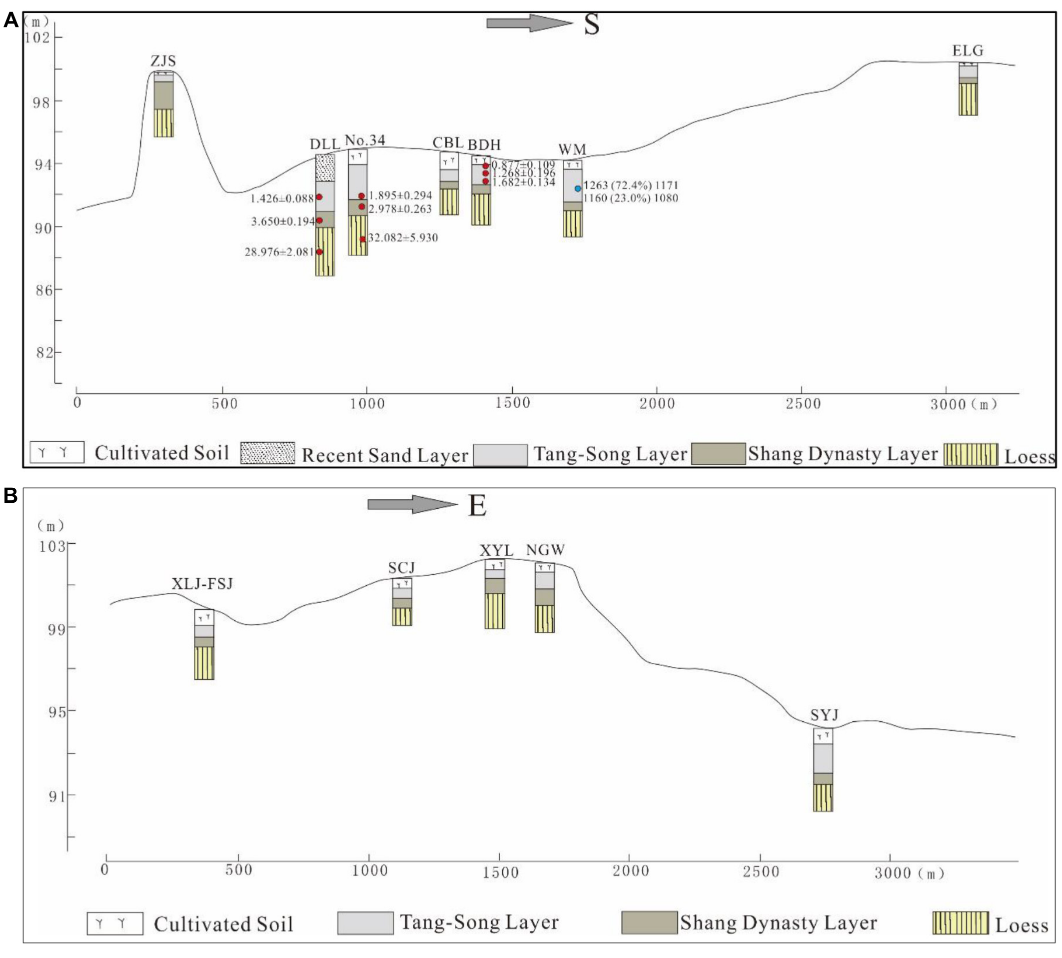

FIGURE 3 | Topographic and sedimentary features in the region of Shang City **(A)**. North - South; **(B)**. West - East. The locations of excavation sites are showed in **Figure 1B**. The OSL (red circle) and ^{14} C (blue circle) ages are marked on the graph.

revealed that the terrain was not level. The prevailing topography, as evidence by locations like Zijinshan (ZJS in the **Figure 3**) and Erligang (ELG in the **Figure 3**), are higher in the west and lower in the east. There is an elevation difference of more than 10 m between the highest and lowest points in the city. However, the central part of the city is around 94 m above sea level.

According to the ceramic chronology and our dating results, the strata at Zhengzhou Shang city can be divided into four phases (**Figure 3**). The uppermost layer is the recently cultivated soil or a disturbed layer. There is usually a sort of dark gray clay underneath this soil layer. Most cultural material in this clay layer dates to the periods of the Tang Dynasty (AD 618-907) and Song Dynasty (AD 960-1279). The dating results of this layer are also concentrated at ca. 1,200 BP (**Figure 3**). Therefore, we called this layer the Tang-Song layer. The underlying stratum is a yellowish silt which mainly contains Shang dynasty material culture. This layer dates to ca. 3,200 BP (**Figure 3**), and we named this layer the Shang dynasty layer. The lowest part of the strata is the ate Pleistocene loess. The dating results returned an age of around 10 to 40 ka. Although the thickness of the strata often changes depending on its geomorphic position, these stratigraphic sequences constitute a general sedimentary framework for the area around Zhengzhou Shang City.

The Holocene Landscape Evolution of Site Area

According to the existing stratigraphic information and the regional depositions' characteristics, we have simulated the topography of four periods, the late Pleistocene, the Shang Dynasty, the Tang-Song period, and the modern land surface of Zhengzhou (**Figure 4**). The results show that the general topographic features of the area have not significantly changed since the late Pleistocene. The area has always maintained a higher area in the southwest and lower area in the northeast. Due to the accumulation of sediment through both natural and human activities, the distribution of these elevated geomorphic

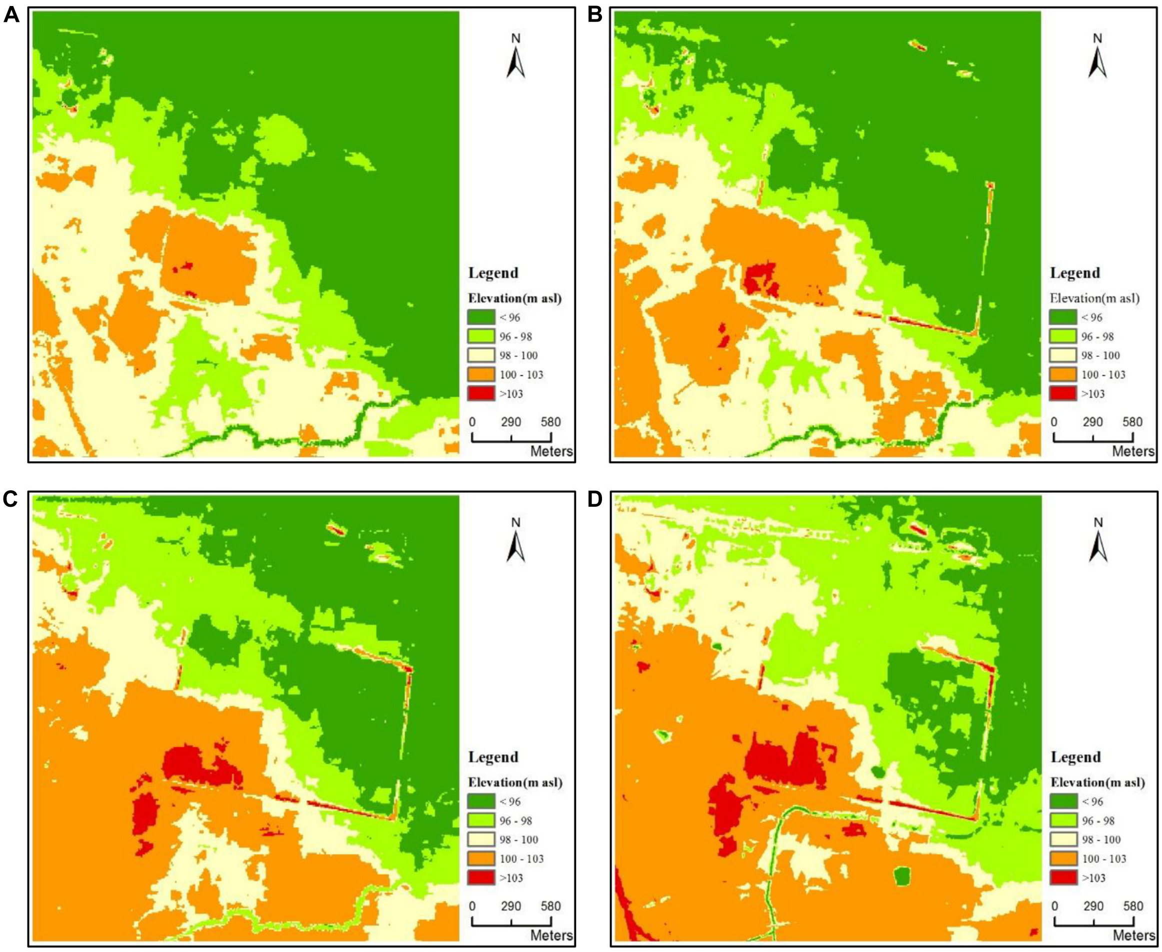

FIGURE 4 | The simulation of the ancient topography. **(A)** Late Pleistocene. The terrain was lower than present. The early course of the Xionger River is clearly shown in the south. **(B)** Shang Dynasty. The terrain was higher than late Pleistocene. People built the city walls according to the terrain. **(C)** Tang-Song Periods. Areas of high elevation continued to increase. People built some new walls in the middle of city. **(D)** Modern. The area has always maintained the topographic characteristics of a high area in the southwest and low area in the northeast since late Pleistocene. The Xionger River is artificially altered with the straighter watercourse.

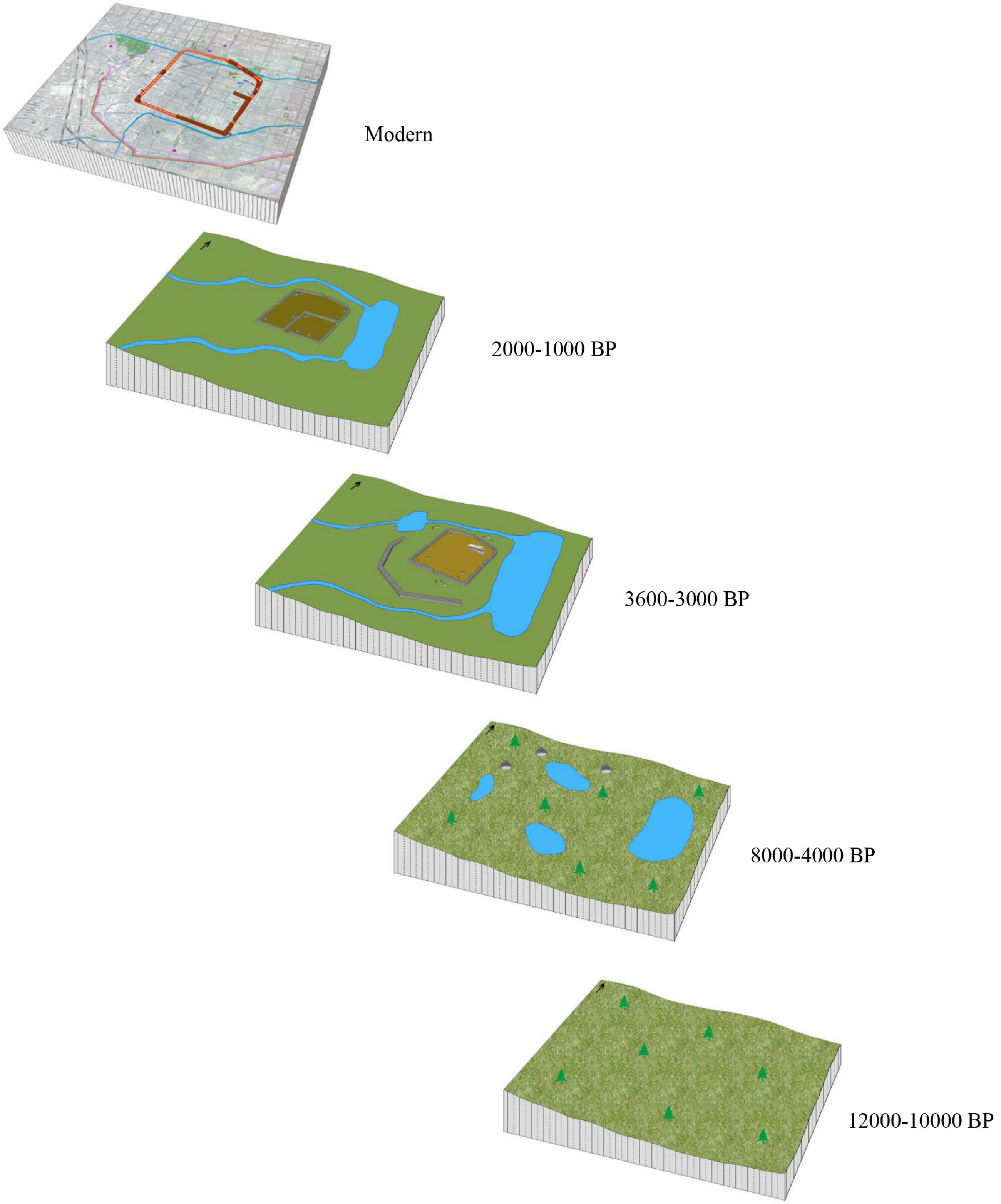

FIGURE 5 | The landscape evolution in the area of Zhengzhou Shang City (During 12,000-10,000 BP, the landform was changed to alluvial plain. During middle Holocene periods (8,000-4,000 BP), there were many natural water areas under a warm and humid climate and river aggradation (Chen et al., 2015; Tan et al., 2020; Lu et al., 2021). In 3,600 BP, the Shang city was built. During 2,000-1,000 BP, the city size was shrank and some watery areas disappeared, consistent with the declining intensity of the summer monsoon on the Loess Plateau (Tan et al., 2020).In the Modern, Zhengzhou city is located on the former site of the Shang City.

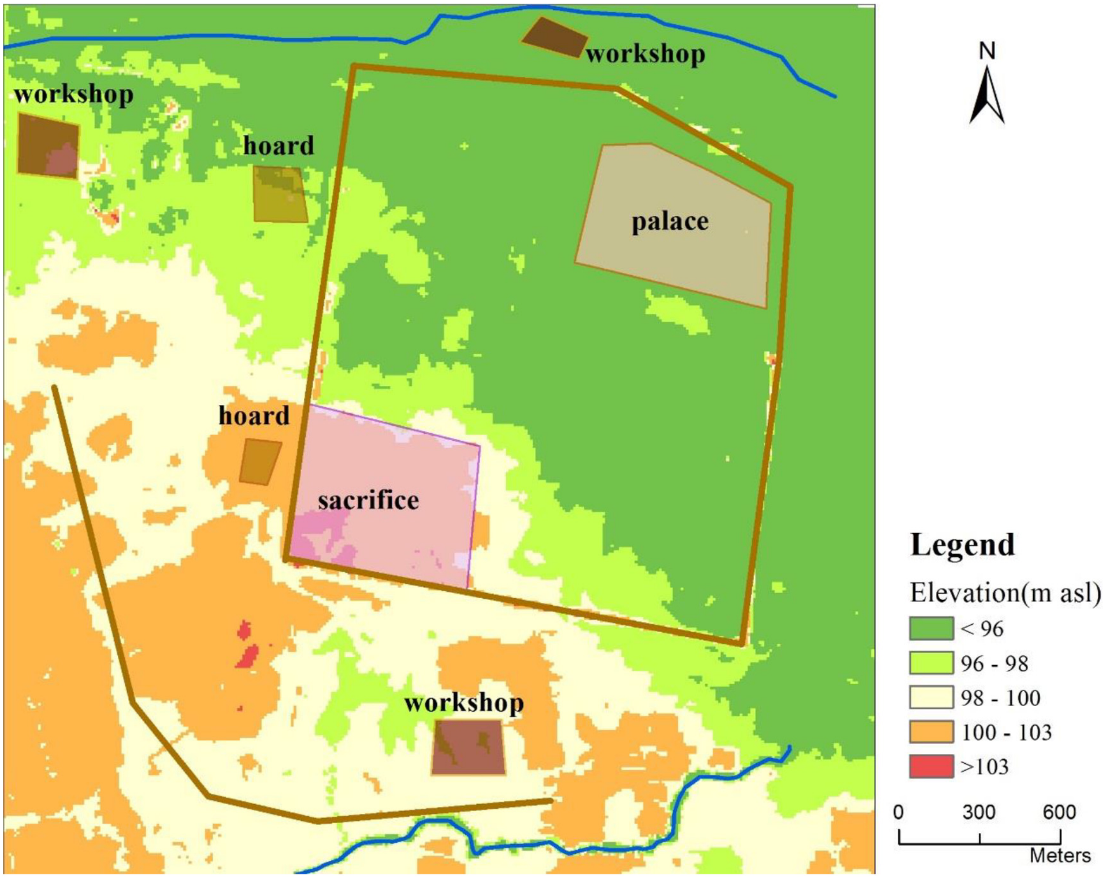

FIGURE 6 | The relationship between the topography and layout of Zhengzhou Shang City. The inner city was located in the flatter terrain. The palace, hoards and sacrifice area were arranged in the higher region. The workshops were close to the rivers.

units have continuously increased since the Shang Dynasty. These elevated geographic units are distributed in discontinuous patches across the plain and constrained the courses of the nearby rivers.

Our map of the ancient topography clearly shows the early course of the Xionger River to the south of the city. The ancient river course is different from the modern river course which has many recent artificial modifications. Although the early course of the Jinshui River to the north of city is not shown on these maps, the straight modern channel indicates that it has been artificially modified. According to the topographic features, the early Jinshui River should be located farther to the north than the modern channel.

The topographic simulation also provided key information to better understand the regional landscape evolution of the area around Zhengzhou Shang City. During 12000-10000 BP, the area exhibited transitional characteristics from loess tableland to alluvial plain (**Figure 5**). During the middle Holocene periods (8000-4000 BP), the regional hydrological conditions were favorable under the background of a warm and humid climate (Chen et al., 2015; Tan et al., 2020) and river aggradation (Lu et al., 2021). There were many natural water areas like lakes and wetlands. Some ancient settlements like the Minzhulu site and Peng Gong Jie site have been found on the elevated geomorphic units (Yan, 2016). During the early Shang dynasty around 3,600 BP, people came here to build a grand capital city with three layers of walls between the Jinshui River and Xionger River. After the climate changed and rivers incised their channels, many areas that originally had water disappeared, with the exception of a few lakes, like Putianze in the east. This is also consistent with the declining intensity of the summer monsoon on the Loess Plateau, as recently reconstructed from stalagmite records (Tan et al., 2020). From 2,000 to 1,000 BP, the size of the city shrank after it was no longer a capital. People built a smaller city that used part of the Shang dynasty walls in the southeast. Modern Zhengzhou city is located on the former site of the Shang City. As a result, the regional landscape, like the terrain and the rivers, has experienced significant changes over the past century.

The Relationship Between Landscape and Function Layout During Shang Periods

When we overlaid the activity areas of Zhengzhou Shang City on a regional terrain map from the Shang period, the results showed a close relationship between the natural landscape and these activity areas (**Figure 6**). The entire inner city was distributed on flat terrain. The palace area was located on the elevated region of the northeastern portion of the inner city. The sacrificial area was located in the highest southwestern part of the inner city. The distribution of workshops, including pottery, copper and bone artifact working areas, is located close to the rivers. The hoards were also located on the elevated geomorphic units.

DISCUSSION

Hou (2018) has argued that Zhengzhou Shang City went through three stages of urbanization. First, the palace city was built. Then, people constructed the inner city. Lastly, they constructed the outer city. During the early Shang dynasty, people built the palace and city walls on the higher and relatively flat geomorphic unit first. Afterward, they built the inner-city walls to protect key places like sacrificial sites. The highlands in the southwest are limited to the inner city. With the increase in settlement size, some of the workshops and hoards were placed outside the inner city to better use the terrain and water. Following this, people built the outer city walls around these workshops and hoards.

In many ways, the urbanization process of Zhengzhou Shang City occurred within the environmental context of the area. Favorable topographic and hydrological conditions in this transitional zone between loess tablelands and alluvial plains was an area well-suited for the construction of a capital city. As the city expanded in size, these topographic conditions began to affect the shape and structure of the ancient city. Both the hypotenuse of the northeast corner of the inner city and the nearly circular shape of outer city were influenced by the topography.

Although Zhengzhou Shang City gradually grew in size, the urban planning of the early city took into account the natural environmental context at that time. The key parts of the city were always arranged on the higher geomorphic units. The workshops were also distributed near the main water bodies. These locations reflect the fact that humans recognized and effectively used the natural environment during the early urbanization process (Tan et al., 2021).

CONCLUSION

In this study, we have analyzed the geomorphic location, terrain characteristics and types of landforms around the area of Zhengzhou Shang City. In this paper, we simulated and reconstructed the regional topographic and landscape evolution. We also discussed the relationship between the functional layouts of the early Shang period and the regional landscapes. The main conclusions are as follows:

(1) Zhengzhou Shang City was located in the transitional zone of loess tableland and plain. The geomorphic position belonged to part of the front of a loess platform extending into the alluvial plain.
(2) The regional topography of Zhengzhou Shang City was generally flat, but there have always been some areas with higher elevation in the area since the late Pleistocene. These units exhibit a distinctive patchy distribution in the plain and people have lived on them since the Neolithic.
(3) The urbanization of Zhengzhou Shang City went through a three phase developmental process, from palace city to inner city to outer city. Environmental factors played a key role in the process as the site selection were deeply influenced by topography, landform type and hydrology.
(4) The functional layout of Zhengzhou Shang City had a close relationship to the regional landscape. The key activity areas like the palace and sacrifice areas were always located on the higher elevated geomorphic units. Workshops were also distributed near the water. These cases reflect the fact that humans recognized and effectively used the natural environment during the process of early urbanization.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

PC and PL designed the study and supervised the field work. PC, PL, SY, HZ, QW, and HW conducted the archeological investigations. XW analyzed OSL samples. JX analyzed particle size analysis samples. RY, MS, LY, and YT analyzed the data. PC drafted the initial manuscript, which was revised by PL and SY. All authors approved the final version.

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REFERENCES

An, J. H., and Yang, Y. B. (1983). The first excavation of the palace site in Zhengzhou Shang dynasty city. *Cult. Relics* 4, 1–14. doi: 10.1525/9780520941519-004

An, Z. M. (1954). Excavation of Zhengzhou Erligang in autumn of 1952. *Acta Archaeol. Sin.* 2, 65–107.

Ayala, G., Wainwright, J., Walker, J., Hodara, R., Lloyd, J. M., Leng, M. J., et al. (2017). Palaeoenvironmental reconstruction of the alluvial landscape of Neolithic Çatalhöyük, central southern Turkey: the implications for early agriculture and responses to environmental change. *J. Archaeol. Sci.* 87, 30–43. doi: 10.1016/j.jas.2017.09.002

Chang, H. Y. (2018). Analysis on the spatial planning of bronze casting workshop in capital cities during Xia-Shang periods. *Cult. Relics Cent. China* 5, 68–81.

Chen, F., Xu, Q., Chen, J., Birks, H. J. B., Liu, J., Zhang, S., et al. (2015). East Asian summer monsoon precipitation variability since the last deglaciation. *Sci. Rep.* 5:11186.

Chen, J. X., and Zeng, X. M. (1991). Investigation and excavation of outer rammed earth wall foundation of Zhengzhou Shang city. *Cult. Relics Cent. China* 1, 87–95.

Chen, Y. C. (1999). *Zhengzhou Cultural Relics Chorography*. Zhengzhou: Henan People's Publishing House.

Getaneh, A., Haile, T., and Sernicola, L. (2018). Three-dimensional modelling of a pre-Aksumite settlement at the archaeological site of Seglamen, Aksum, northern Ethiopia using integrated geophysical techniques. *Archaeol. Prospect.* 25, 231–241. doi: 10.1002/arp.1705

HICRA (2001). *Zhengzhou Shang City*. Beijing: Cultural Relics Publishing House.

HICRA (1993). *Archaeological Discovery and Research in Zhengzhou Shang City*. Zhengzhou: Zhongzhou Ancient Books Publishing House.

HICRA, and ZICRA (1999). *The Shang Dynasty Copper Ware Hoard in Zhengzhou*. Beijing: Science Press.

Hou, W. D. (2018). The urbanization process of Zhengzhou Shang City. *Cult. Relics Cent. China* 3, 36–62.

Huang, F. C. (2011). Analysis on the changes in settlements surrounding the site of Shang dynasty city in Zhengzhou and environment factors affacting the changes. *J. N. China Inst. Water Conservancy Hydroelectr. Power (Soc. Sci.)* 27, 101–103.

Huang, F. C., and Wang, X. G. (2014). The relationship between environment evolution of putianze and cultural geography during pre-Qin to Qin-Han periods. *Agric. Archaeol.* 1, 151–156.

Jiang, N., Wu, Q., and Li, G. Z. (2009). Excavation of Laofengang Shang dynasty site in Zhengzhou City. *Cult. Relics Cent. China* 4, 4–20.

Lai, Z., and Ou, X. (2013). Basic procedures of optically stimulated luminescence (OSL) dating. *Prog. Geogr.* 32, 683–693.

Liu, J. S. (1992). The preliminary research of the Holocene strata in Zhengzhou. *J. Stratigr.* 16, 111–119.

Liu, L. (2004). *The Chinese Neolithic: Trajectories to Early States*. Cambridge: Cambridge University Press. doi: 10.1017/CBO9780511489624

Liu, Y. F., Wu, Q., and Xue, B. (2010). A new investigation of the city layout and the trend of the outline wall of Zhengzhou in Shang Dynast. *J. Zhengzhou Univ. (Philos. Soc. Sci. Edn.)* 43, 164–168.

Lu, P., Lv, J. Q., Zhuang, Y. J., Chen, P., Wang, H., Tian, Y., et al. (2021). Evolution of Holocene alluvial landscapes in the northeastern Songshan region, Central China: chronology, models and socio-economic impact. *Catena* 197:104956. doi: 10.1016/j.catena.2020.104956

Lu, P., Tian, Q., Qiu, S., and Liu, C. (2014). The Pleistocene landform evolution and its drive force of the Suoxu river basin in Henan province. *Areal Res. Dev.* 33, 172–176.

Lu, P., Tian, Y., and Yang, R. X. (2013). The study of size-grade of prehistoric settlement in the Circum-Songshan area based on SOFM network. *J. Geogr. Sci.* 23, 538–548. doi: 10.1007/s11442-013-1027-5

Pan, M. J. (2010). The capital's plan project and its influnce in early stage of Shang dynasty. *J. Northwest Univ. (Nat. Sci. Edn.)* 40, 708–712.

Qian, G. X. (2019). The research on the restoration of spatial pattern of Luoyang outer city in Northern Wei dynasty. *Huaxia Archaeol.* 6, 72–80.

Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Ramsey, C. B., et al. (2013). IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* 55, 1869–1887. doi: 10.2458/azu_js_rc.55.16947

Ren, W., and Liu, Y. F. (2019). *Archaeology Zhengzhou*. Beijing: Science Press.

Renfrew, A. C., and Bahn, P. (1991). *Archaeology Theories Methods and Practice*. New York, NY: Thamed and Hudson Ltd.

Schwerin, J., Richards-Rissetto, H., Remondino, F., Spera, M. G., Auer, M., Billen, N., et al. (2016). Airborne LiDAR acquisition, post-processing and accuracy-checking for a 3D WebGIS of Copan, Honduras. *J. Archaeol. Sci. Rep.* 5, 85–104. doi: 10.1016/j.jasrep.2015.11.005

Shi, Z. M. (1983). *Natural Conditions and Resources of the Henan Province*. Zhengzhou: Henan Scienceand Technology Press.

STCCG (1978). *Particle Size Analysis and Application of Sedimentary Rocks*. Beijing: Geological Publishing House.

Storozum, M., Lu, P., Wang, S., Chen, P., Yang, R., Ge, Q., et al. (2020). Geoarchaeological evidence of the AD 1642 Yellow river flood that destroyed Kaifeng, a former capital of dynastic China. *Sci. Rep.* 10, 1–12. doi: 10.1038/s41598-020-60169-1

Sun, Z. Y., Shao, J., Liu, L., Cui, J., Bonomo, M. F., Guo, Q., et al. (2017). The first Neolithic urban center on China's north Loess Plateau: the rise and fall of Shimao. *Archaeol. Res. Asia* 14, 33–45. doi: 10.1016/j.ara.2017.02.004

Tan, L., Li, Y., Wang, X., Cai, Y., Lin, F., Cheng, H., et al. (2020). Holocene monsoon change and abrupt events on the western Chinese Loess Plateau as revealed by accurately dated stalagmites. *Geophys. Res. Lett.* 47:e2020GL090273.

Tan, L. C., Dong, G. H., An, Z. S., Edwards, R. L., Li, H., Li, D., et al. (2021). Megadrought and cultural exchange along the proto-Silk Road. *Sci. Bull.* 66, 602–610.

Trigger, B. G. (1989). *A History of Archaeological Thought*. Cambridge: Cambridge University Press.

Wheatley, P. (1971). *The Pivot of the Four Quarters- A Preliminary Enquiry into the Origins and Character of the Ancient Chinese City*. Edinburgh: Edinburgh University Press.

Wu, P. F., Liu, D. X., Ma, J. H., Miao, C., Chen, L., Gu, L., et al. (2019). A geoarchaeological reading of the city-overlap-city phenomenon in the lower Yellow river floodplain: a case study of Kaifeng city, China. *Sustainability* 11:1029. doi: 10.3390/su11041029

Yan, T. C. (2016). *Cultural Relics Atlas of Zhengzhou*. Xi'an: Xi 'an Map Publishing House.

Yu, G. (2016). *Sedimentology of Lake-River Systems and Environmental Evolutions in Zhengzhou Regions*. Beijing: Science Press.

Yuan, G. K. (2018). A brief discussion on the trend and age of the outer city wall of Zhengzhou Shang city. *Cult. Relics Cent. China* 3, 30–35.

Yuan, G. K., and Zeng, X. M. (2004). The relationship between inner city and outer city of Zhengzhou Shang city. *Archaeology* 3, 59–67.

Yuan, G. K., Zeng, X. M., Song, G. D., and Jia, L. M. (2004). Investigation and excavation of outer city in Zhengzhou Shang city. *Archaeology* 3, 232–242.

Zeng, X. M., Li, S. T., and Song, G. D. (2000). Excavition of the rammed earth walls in the palace area of Zhengzhou Shang city, Henan province in 1998. *Archaeology* 2, 136–156.

Zhang, G. S. (2018). The nature analysis of bronze hoard pits in Zhengzhou Shang city. *Cult. Relics Cent. China* 1, 53–59.

Zhao, Q. G., Han, W. Z., Pei, M. X., and An, J. H. (1957). Excavation of Zhengzhou Shang dynasty site. *Acta Archaeol. Sin.* 1, 53–73.

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Changes in Wood Utilization Due to Iron Age Jade Mining in the Western Hexi Corridor: Wood Charcoal Investigations

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Charcoal remains from archeological sites are used not only to reconstruct the historical composition of local woodlands but also to examine the history of the human use of wood. Nevertheless, key questions such as how and why people may have selected particular woody taxa from locations long distances from their habitat have rarely been addressed. In the present study, we analyze charcoal remains from the ancient Jingbaoer (JBR) jade mine in the Mazong Mountains (Mazong Shan) of Northwest China to explore patterns in the collection and use of wood by Iron Age people. Factors affecting the choice of wood collected at the JBR site are discussed by combining the results of pollen records and charcoal analysis. Our results suggest that tamarisk (*Tamarix* L.), a shrub dominant in the local area, was the main source of wood for JBR miners and was used as firewood depending upon its local availability. The miners may also have used wood from species sourced further away, such as *Pinus* L. and *Picea* L., because of the local scarcity of these trees in such a dry environment. The agropastoralist subsistence system practiced by the JBR miners supports the hypothesis of the collection of wood from distant locales. This study highlights diverse patterns of wood collection in an area scarce in woody plants and provides new evidence for understanding how Iron Age people adapted to extremely arid environments.

Keywords: charcoal analysis, wood collection, environment, ancient jade mine, western Hexi Corridor

INTRODUCTION

Past interactions between humans and environments have been a popular subject of research in disciplines as diverse as geography, archeological, history, and genetics (Cordaux et al., 2004; Kuper and Kröpelin, 2006; Kawahata et al., 2009; Chen et al., 2015; Bevan et al., 2017; Leipe et al., 2019; Chen N.B. et al., 2020; Kennett et al., 2020). As a source of energy and raw material for production, wood is an essential resource in daily life and has played a critical role in human environmental adaptation throughout history (Martín-Seijo et al., 2015; Medina-Alcaide et al., 2015; Li H. et al., 2017; Masi et al., 2017; Kabukcu, 2018; Liu et al., 2019a,b). Prehistoric humans usually collected locally available wood resources, following the "principle of least effort" (Renfrew and Bahn, 1991; Shackleton and Prins, 1992; Qing et al., 2010; Masi et al., 2017; Bouchaud et al., 2020). However, many studies in different regions of the world have challenged this model that assumes people were more selective in choosing wood for higher social productivity and expressed preferences for certain trees, thus likely requiring the use of wood sourced from trees located long distances from their living areas (Miller, 1985; Marston, 2009; Rubiales et al., 2011; Wang et al., 2011; Deforce et al., 2013; Pichler et al., 2013; An et al., 2014; Tolksdorf et al., 2015). Kabukcu and Chabal (2020) suggested that examining the strategy of wood collection by human communities in the past is inappropriate without considering the environmental contexts and human activity of past wood uses. Therefore, it is of great significance to select study regions exhibiting significant changes in environment and human activities in the past to carry out research on strategies of wood use to yield a nuanced understanding of the relationships among environment, human activity, and wood use strategies.

The western Hexi Corridor (Hexi Zoulang, also known as the Gansu Corridor) is a region that documents significant changes in past environments and human activities in China. It witnessed frequent transitions from agriculture to agropastoralism in human subsistence during the late Neolithic and historic periods (Yang et al., 2019). Human activities here also led to environmental changes, especially variation in woody vegetation, since the late Holocene. Previously published data have shown that wood used in the western Hexi Corridor was derived from local woodlands during the late Neolithic and early historic periods (**Figure 1**) and that large-scale settlements and metallurgical activities undertaken beginning ca. 2000 BCE accelerated the degradation of woody vegetation in the Hexi Corridor and led to the sparser distribution of trees (Li et al., 2011; Li H. M. et al., 2017; Zhou et al., 2012; Shen et al., 2018; Liu et al., 2019b). In the late Bronze and Iron Ages of the first millennium BCE, both the number of woody taxa and the percentage of xerophytes decreased in the western Hexi Corridor (Shen et al., 2018). However, during this period, people engaged in mining jade (*sensu lato*), an activity that must have been supported by the extensive use of wood resources (Chen G.K. et al., 2020). Given the region's scarcity of woody vegetation, the way in which miners in this area collected and used wood for daily use needs to be examined.

The focus of our study is the Iron Age Jingbaoer (JBR) jade mine site in the Mazong Mountains (Mazong Shan) in Northwest China. We used charcoal remains to examine patterns in the miners' wood use strategy. A combination of charcoal analysis from nearby archeological sites, the results of pollen records from lake sediments, and historical documents was used to explore the impact of the local environment on miners' strategies for wood collection and use. This study highlights the diverse patterns of prehistoric wood collection in arid environments.

REGIONAL SETTING AND ARCHEOLOGICAL BACKGROUND

Present Climate and Woody Vegetation

The western Hexi Corridor is located in China's arid zone (**Figure 1**). According to data from the Jiuquan meteorological station located in the western Hexi Corridor, the mean annual temperature is 3.9–9.3°C. A remarkable decrease in annual precipitation is notable from the south to the north. The annual precipitation in the Qilian Mountains is 300 mm, and those at Jiuquan and the Mazong Mountains are 84 and 39 mm, respectively. However, annual evaporation amounts to approximately 2,000–4,000 mm.

Woody vegetation in the area displays a prominent spatial difference owing to spatial changes in regional precipitation (China Forest Editorial Committee, 1997). Conifers such as *Picea crassifolia* Kom., *Sabina przewalskii* Kom., *Picea wilsonii* Mast., and *Pinus tabuliformis* Carr. are distributed mainly in the Qilian Mountains, with broadleaved trees also present, including *Ulmus pumila* L., *Betula* L., and *Salix* L. Dry-tolerant shrubs, such as *Calligonum* L., *Hippophae* L., *Sarcozygium* Bunge., and *Tamarix* L., dominate the piedmont region, and broadleaved trees such as *Populus* L. mainly grow along the area's principal rivers. The Mazong Shan are located in the northern part of the western Hexi Corridor, where woody vegetation is much less diverse than in other areas of the western Hexi Corridor and the wood assemblage is similar to that of the gallery forest along the main river (China Forest Editorial Committee, 1997). Farther north, the Gobi Desert contains few woody plants.

Composition of Woody Plant Communities During the Late Prehistoric and Historic Periods and the JBR Jade Mine Site

The archeological sites from which charcoal has been analyzed are distributed near the Qilian Mountains, along the Hei and Shule Rivers (**Figure 1**). These sites are dated from the Neolithic to the historic period, spanning roughly 2300 BCE–589 CE, including the Machang (2300–2000 BCE), Xichengyi (2000–1700 BCE), Siba (1700–1400 BCE), and Shanma (1000–100 BCE) cultures; the Han dynasty (202 BCE–220 CE); and the period of the Southern and Northern Wei-Jin dynasties (220–589 CE) (Li H. M. et al., 2017; Shen et al., 2018; Liu et al., 2019b). These results show remarkable spatial differences in the composition and distribution of local woody plants in this area during the late Neolithic and Iron Age. Evidence of coniferous trees, such as *Picea* L., *S. przewalskii* Kom., and *Pinus* L., was mostly discovered in archeological sites located near the Qilian Mountains; broadleaved trees with high relative percentages or frequencies were found in archeological contexts along the main rivers. The relative percentage of shrubs was much higher in the northern Hexi Corridor than that of arboreal taxa. This situation in the western Hexi Corridor that emerged since the late Neolithic suggests that the distribution of woody plants gradually decreased from the Qilian Mountains to the Gobi Desert in the north and

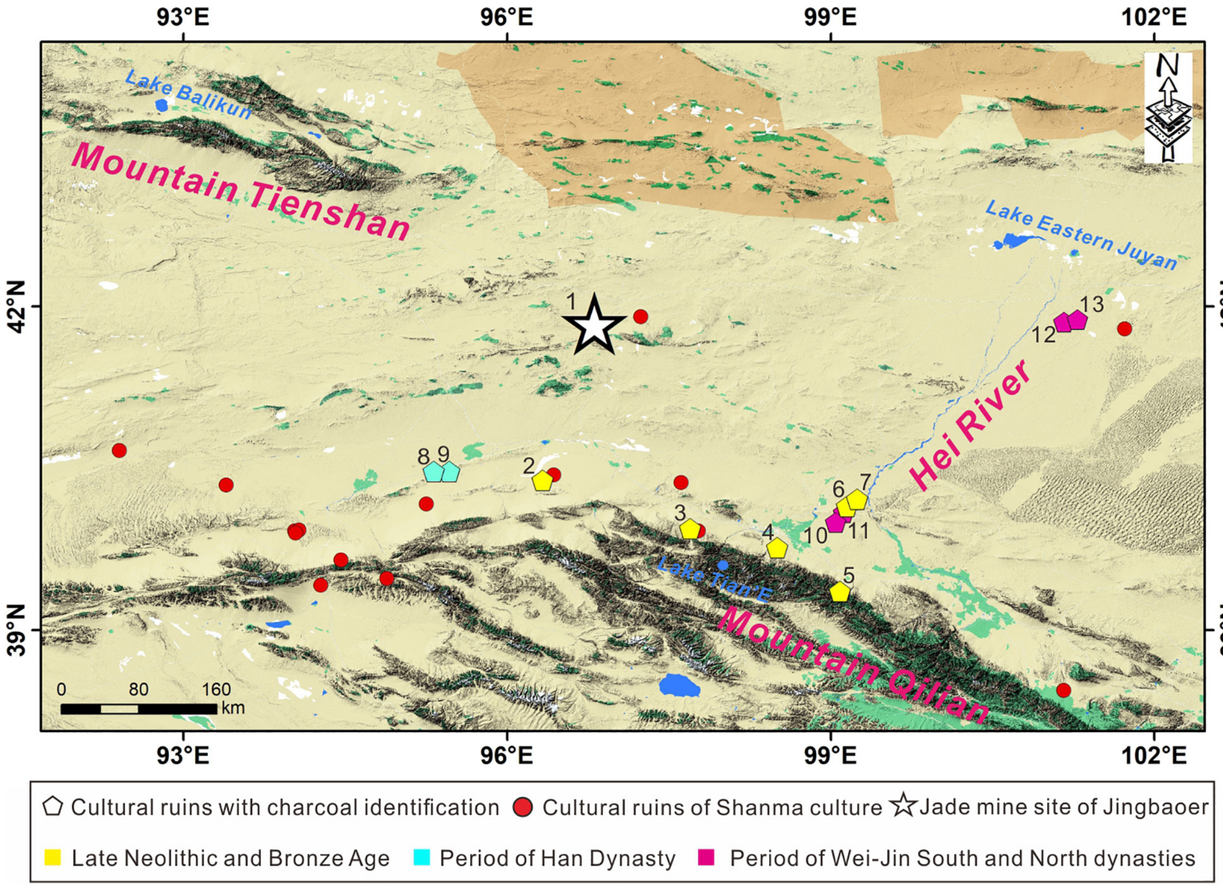

FIGURE 1 | Distribution of archeological sites yielding charcoal analyses and Shanma culture localities in the western Hexi Corridor. (1) JBR jade mine site. (2) Yingwushu. (3) Huoshaogou. (4) Zhaojiashuimo. (5) Xihetan. (6) Ganggangwa. (7) Huoshiliang. (8) Lucaogou 1. (9) Lucaogou 2. (10) Huishui. (11) Xisanjiao. (12) K749. (13) Juyan.

the landscape featured coniferous forests, mixed vegetation, and oasis woodlands in succession, a scenario which is consistent with the composition and distribution of local woody plants at present.

The JBR ancient jade mine is located in the Mazong Mountains, where woody vegetation is much less diverse than in other areas of the western Hexi Corridor (**Figures 2a,b**). The site measures 5,400 m north–south and 1,400–1,850 m east–west, consisting of a defensive area, the mine itself, and a workshop precinct, and is considered one of the earliest jade mining sites thus far discovered in China (Gansu Provincial Institute of Cultural Relics and Archaeology, 2016). Recent archeological excavations have investigated a total of 33 houses, 31 military installations, and more than 290 mining pits. Most of the houses included remains of ash pits, hearths, worktops, and artifacts, including ceramics, objects made of jade, bronze projectile points, and various iron objects (**Figures 2c,d**; Gansu Provincial Institute of Cultural Relics and Archaeology, 2016). Carbonized plant remains were also recovered at JBR, including those of foxtail millet, broomcorn millet, wheat, and barley (Yang, 2017). Excavated ceramics suggest that they are the remains of the Shanma culture and the Han dynasty, ranging from the middle-to-late Warring States period and the early Han dynasty (ca. 400–100 BCE), an era in which people used iron tools extensively in China (Bai, 2005).

Paleoeconomy During the Late Neolithic and Iron Age

Archeological investigations have revealed large-scale human settlements in the western Hexi Corridor beginning in the third millennium BCE (Dong et al., 2018). The Neolithic Majiayao culture (ca. 3300–2000 BCE) adopted a settled lifestyle and was principally engaged in cultivating millet and raising pigs, ovicaprids (sheep and goats), cattle, and dogs in the western Hexi Corridor. This strategy subsequently changed to semi-settled agropastoral production, based on the cultivation of millet, wheat, and barley, and included the utilization of ovicaprids, pigs, cattle, and dogs by the Xichengyi (ca. 2000–1700 BCE) and Siba (ca. 1700–1400 BCE) cultures (Yang et al., 2019). During the Iron Age, the Shanma culture (ca. 1000–100 BCE) occupied the western Hexi Corridor (Xie, 2002). Archeobotanical evidence suggests this culture was still engaged in crop cultivation, with barley, wheat, and millets forming the basis of their subsistence (Yang, 2017). Carbonized remains of these crops were also

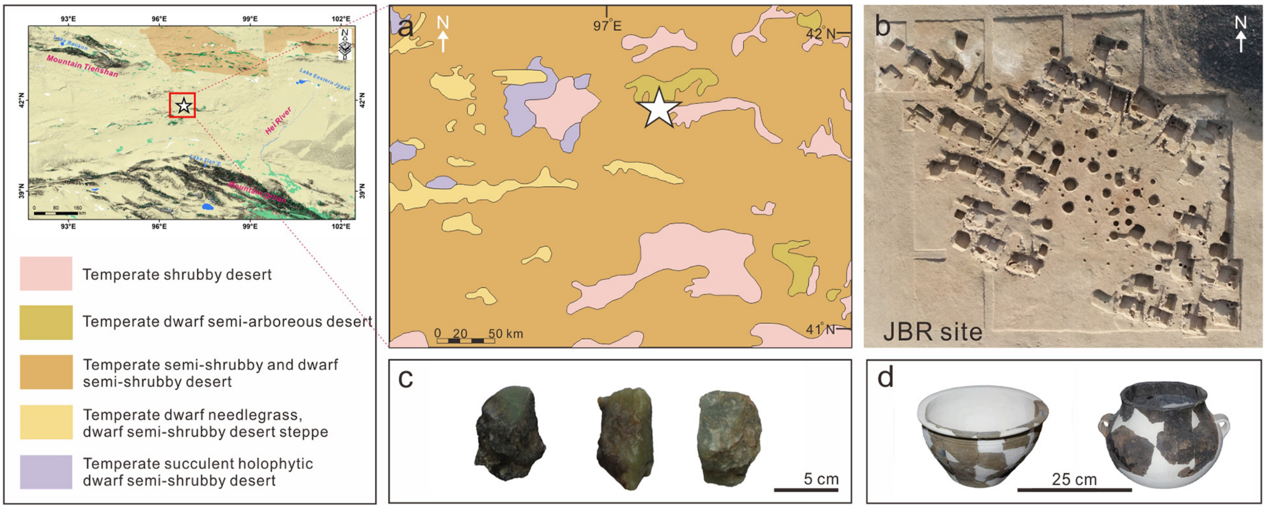

FIGURE 2 | Photos of the JBR jade mine site, excavated artifacts, and the distribution of vegetation around JBR. **(a)** Distribution of vegetation around JBR. **(b)** Excavation area at JBR. **(c)** Jade ores in JBR. **(d)** Shanma culture and Han dynasty ceramics from JBR.

recovered from the JBR site (Yang, 2017). However, the faunal composition and strategies for feeding livestock in the Shanma culture were obviously oriented toward mobile pastoralism. Zooarcheological evidence reveals that dogs, ovicaprids, horses, cattle, and camels were maintained by the Shanma people, but with the notable absence of pigs (Yang et al., 2019). Livestock better suited as long-distance transport animals were widely used by the Iron Age inhabitants of the western Hexi Corridor, as recorded in historical texts such as the *Shiji* (*Records of the Grand Historian*) and *Hanshu* (*Book of Han* or *History of the Former Han*). Shanma culture artifacts unearthed at JBR indicate that the miners there may have also relied on agropastoral subsistence.

MATERIALS AND METHODS

Charcoal analysis was employed at JBR to explore how people inhabiting this arid zone collected and used woody plants during the Iron Age. Considering the diverse behavioral implications of the charcoal remains unearthed from different cultural contexts at the site, soil samples were collected from each feature, including 24 houses, eight ash pits, and 11 hearths. Flotation was used to collect charcoal. Soil samples were bucket-washed through an 80-mesh sieve (aperture size, 0.2 mm) to aggregate carbonized plant remains, which were dried in the shade and then sorted. We chose pieces of charcoal with a diameter of $\geq$2 mm using sieves with apertures of 4, 2, 1, 0.7, and 0.35 mm. The species of charcoal remains were determined according to descriptions of corresponding wood taxa in the *Zhongguo Mucai Zhi* (*Wood Records of China*) (Cheng et al., 1992). Microscopic features were examined, and taxonomic species determined using a metallurgical microscope in the MOE Key Laboratory of Western China's Environmental Systems at Lanzhou University. Calculation of relative percentages and frequencies was carried out to explore patterns of wood use at JBR.

To compare differences in the woody plant assemblage between JBR and other sites in the western Hexi Corridor oasis zone and examine the sources of wood used by the JBR miners, the results of charcoal analysis, including percentages of trees and shrubs and those of different arboreal taxa from JBR and other oasis archeological sites in the western Hexi Corridor, were examined using principal component analysis (PCA). PCA makes each new variable (called the principal component) a linear combination of the original variables. Its aim is to compress the original hyperspace into a new principal component space of reduced dimensionality, while retaining as much of the data variation as possible, and to conveniently allow direct comparison of similarities or differences among sample groups. This statistical method has been widely used in discussions of past human–land interactions (e.g., Cui et al., 2015; Zhang et al., 2017). In this study, the R environment software was used to analyze our data (R Core Team, 2019, R version 3.6.3).

RESULTS

Through flotation, 1,940 pieces of charcoal were identified from 87 JBR soil samples, including 1,412 pieces of charcoal from 65 soil samples from houses, 238 pieces from 12 hearth soil samples, and 290 pieces from 10 ash pit soil samples (**Supplementary Table 1**). A total of 14 woody taxa, including conifers, broadleaved trees, and shrubs, were identified. The coniferous taxa included only *Picea* L. and *Pinus* L.; the deciduous trees were represented by *Quercus*, *Betula*, *Carpinus cordata* Bl., *Acer* L., *Populus*, and *Salix*; and the shrubs included *Tamarix* L., *Caragana sinica* (Buc'hoz) Rehder., and *Elaeagnus angustifolia* L. Three specimens that could not be taxonomically identified were labeled Unknown 1, Unknown 2, and Unknown 3. Microstructural characteristics of these unknown taxa suggest that they may represent broadleaved woody plants. Scanning

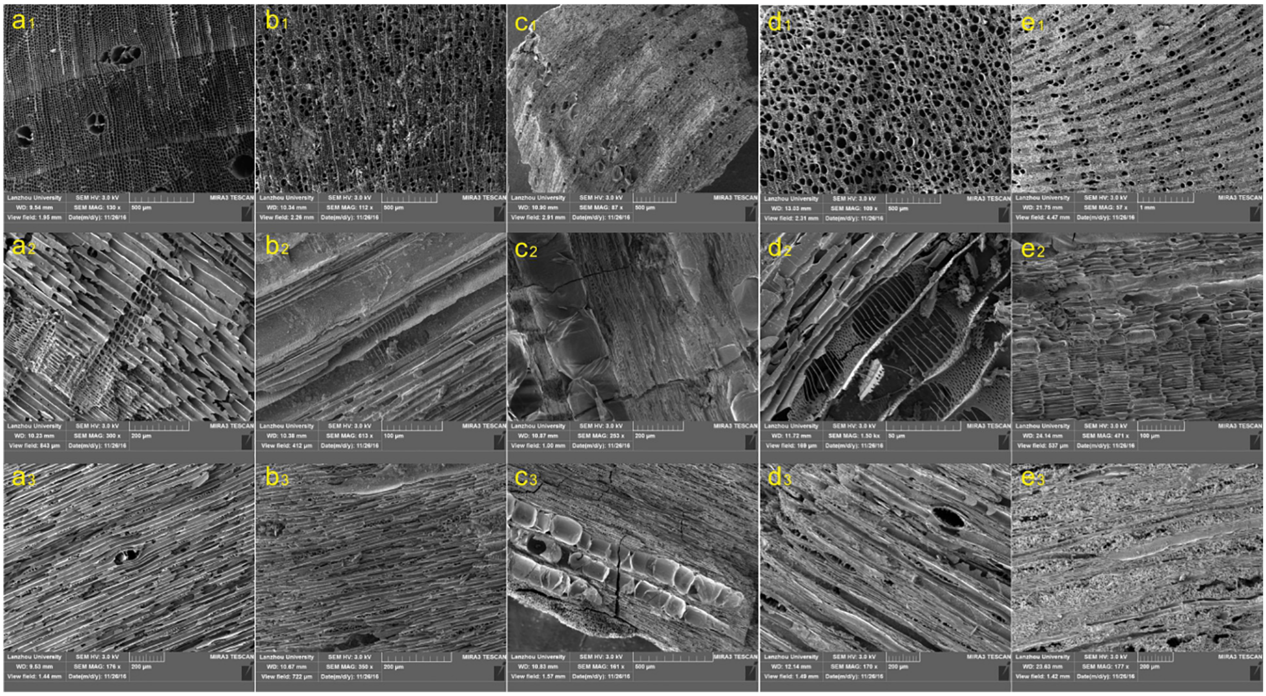

FIGURE 3 | Charcoal remains identified at JBR. **(a$_1$,a$_2$,a$_3$)** *Pinus* L.; **(b$_1$,b$_2$,b$_3$)** *Betula*; **(c$_1$,c$_2$,c$_3$)** *Quercus*; **(d$_1$,d$_2$,d$_3$)** *Carpinus cordata* Bl.; **(e$_1$,e$_2$,e$_3$)** *Tamarix* L. **(a)** Transverse section of charcoal; **(b)** radial section of charcoal; **(c)** tangential section of charcoal.

electron microscopy (SEM) photos of some of the carbonized woody plants are shown in **Figure 3**. The specific identification results of charcoal remains recovered from houses, hearths, and ash pits are as follows.

A total of 65 soil samples were collected from 24 houses, and 1,412 pieces of charcoal were identified. Among them, 12 different species were identified, namely, *Picea* L., *Pinus* L., *Quercus*, *Betula*, *C. cordata* Bl., *Acer* L., *Populus*, *Salix*, *Tamarix* L., *C. sinica* (Buc'hoz) Rehder., *E. angustifolia* L., and Unknown 3. Twelve soil samples collected from 10 hearths yielded 238 pieces of charcoal representing nine woody plant taxa. Compared with analytical results from excavated houses, *Quercus*, *Acer* L., *E. angustifolia* L., and Unknown 3 were not identified in the hearth samples. Only one piece (Unknown 2) was discovered. A total of 290 pieces of charcoal from 10 soil samples representing eight ash pits were identified, including 11 taxa. The ash pit samples did not include *Acer* L., Unknown 2, and Unknown 3, and only three pieces of Unknown 1 were discovered there. The relative percentages and frequencies of the arboreal taxa identified in different cultural units at JBR are presented in **Table 1** and **Figures 4**, **5**.

A score plot of the first two principal components for the data is shown in **Figure 6**. The data are derived from the results of charcoal analysis in archeological sites located in the western Hexi Corridor oasis and the JBR jade mining site. Independent PCAs were carried out, including percentages of trees and shrubs in **Figure 6A** and those of different arboreal taxa in **Figure 6B**. There is no obvious cluster identified in terms of the percentages of trees and shrubs in the results of charcoal analysis between the oasis archeological sites and the JBR site (**Figure 6A**). However, two main clusters were identified, respectively, in terms of the percentages of different tree taxa in the results of charcoal analysis between the oasis archeological sites and the JBR site (**Figure 6B**). The results of the percentages of different arboreal taxa identified through charcoal analysis from six oasis archeological sites appear as a cluster characterized by negative Dim1 values. Only the analytical results of the JBR site appear as another cluster, characterized by positive Dim1 values.

DISCUSSION

Use of Wood at the JBR Jade Mine During the Iron Age

Wood has long played a significant role in human livelihoods and social organization as a raw material for construction, cooking, fire making, heating, and artifact production (Rubiales et al., 2011; Salavert and Dufraisse, 2014; Wang et al., 2014a,b; Medina-Alcaide et al., 2015; Kabukcu, 2018). Charcoal remains derived from cultural features with clear functional attributes are the result of conscious choice and can reflect information on wood use and the patterns of its collection in the past (Li et al., 2012; Marcos and Ortega, 2014; Wang et al., 2014a; Rhode, 2016; Hazell et al., 2017; Kováčik and Cummings, 2017; Mafferra, 2017; Mota and Scheel-Ybert, 2019; Kabukcu and Chabal, 2020). *Tamarix* L. was the most abundant taxon in houses, hearths, and ash pits at JBR. Because the tamarisk shrub usually grows on alluvial and silty plains in arid and semi-arid areas of Northwest China,

TABLE 1 | Relative percentages and frequencies of woody taxa identified at the Iron Age JBR jade mine site in the western Hexi Corridor.

		Picea L.	*Pinus* L.	*Quercus*	*Betula*	*Carpinus cordata* Bl.	*Acer* L.	*Populus*	*Salix*	*Tamarix* L.	*Elaeagnus angustifolia* L.	*Caragana sinica* (Buc'hoz) Rehder	Unknown 1	Unknown 2	Unknown 3
Relative percentage	Houses	2.97%	0.50%	1.06%	3.26%	0.85%	0.07%	1.70%	1.20%	82.44%	0.28%	5.45%	0.00%	0.00%	0.21%
	Hearths	4.62%	2.52%	0.00%	10.08%	0.42%	0.00%	2.94%	7.56%	70.59%	0.00%	0.84%	0.00%	0.42%	0.00%
	Ash pits	23.45%	2.41%	12.41%	3.10%	1.03%	0.00%	4.14%	3.10%	48.28%	0.34%	0.69%	1.03%	0.00%	0.00%
Frequency	Houses	32.31%	9.23%	7.69%	35.38%	13.85%	1.54%	10.77%	16.92%	98.46%	6.15%	16.92%	0.00%	0.00%	1.54%
	Hearths	50.00%	25.00%	0.00%	41.67%	8.33%	0.00%	16.67%	33.33%	100.00%	0.00%	16.67%	0.00%	8.33%	0.00%
	Ash pits	70.00%	20.00%	20.00%	60.00%	30.00%	0.00%	20.00%	40.00%	100.00%	10.00%	20.00%	30.00%	0.00%	0.00%

its branches are ideal for making agricultural implements and fences, as well as for fuel. Archeobotanical evidence suggests the universal use of *Tamarix* L. in archeological sites in the western Hexi Corridor during both prehistoric and early historical periods (Li et al., 2011; Wang et al., 2014a; Liu et al., 2019a,b). The highest relative percentage and frequency of *Tamarix* L. occurred in hearths and ash pits, indicating that it was at least used as firewood at JBR (**Figures 4**, **5**). The shrubby *C. sinica* (Buc'hoz) Rehder and *E. angustifolia* L. are widely distributed in arid areas and were also used at JBR. However, the lower relative percentages and frequencies of these two taxa in house and ash pit samples and the absence of *E. angustifolia* L. in hearths indicate that they were probably not used as fuel, perhaps due to their relatively high economic value (Flora of China Editorial Committee, 2004).

In addition to shrubs, some arboreal taxa were also identified. Despite low relative percentages, their higher frequencies indicate that trees were also used by Iron Age miners. All the arboreal taxa except *Acer* L. were found in both hearths and ash pits, suggesting that they were used as fuel. Remains of maple (*Acer* L.) were found only in houses. Due to the absence of post holes in habitation structures, the potential use of *Acer* L. as a building material for house construction requires further investigation.

The use of wood in the Hexi Corridor has a long history. The expansion of millet cultivation in the third millennium BCE promoted wood use for residential construction, as fuel in ceramic kilns, and, later, for smelting (Xie, 2002; Li et al., 2011; Yang et al., 2016; Zhang et al., 2017; Dong et al., 2018). Based on the results of charcoal analysis in archeological sites, it is clear that the wood taxa used by people were not diverse and generally did not exceed five categories in each ancient site located in the western Hexi Corridor (Li et al., 2011; Shen et al., 2018). The relatively simple composition of woody taxa used is likely the result of the gradual emergence of a cold-and-dry climate as well as increasing social complexification since the late Neolithic (Li et al., 2011; Zhou et al., 2012). However, our results suggest that the JBR jade mine site preserves a remarkably diverse range of woody taxa, considerably different from that of other archeological sites in the western Hexi Corridor (**Figures 4**, **5**). Therefore, we asked where the JBR miners collected their wood.

Strategy of Wood Collection at the JBR Jade Mine Site and Its Relation to the Iron Age Environment of Northwest China

Preferences in the choice and use of firewood by early human groups have attracted more and more attention in archeobotanical research. The "principle of least effort" that supposedly determined early wood collection strategies has been challenged by many case studies suggesting that selective choices in the collection of woody plants from trees located long distances from people's living areas due to certain environmental factors were common (Rubiales et al., 2011; Wang et al., 2011; Deforce et al., 2013; Pichler et al., 2013; An et al., 2014; Tolksdorf et al., 2015). Our results indicate that *Tamarix* L. appears in all

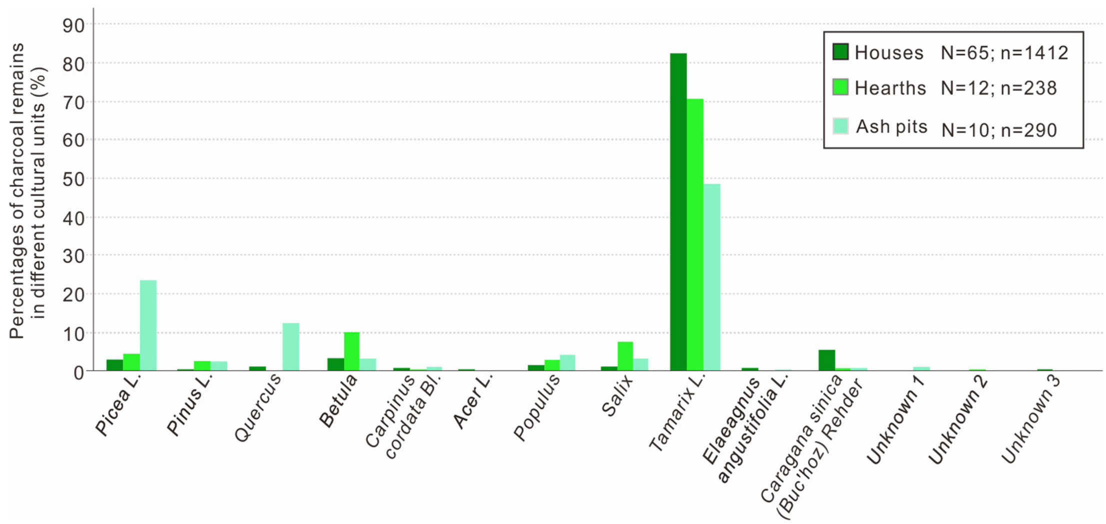

FIGURE 4 | Relative percentages of woody taxa in different cultural contexts at JBR.

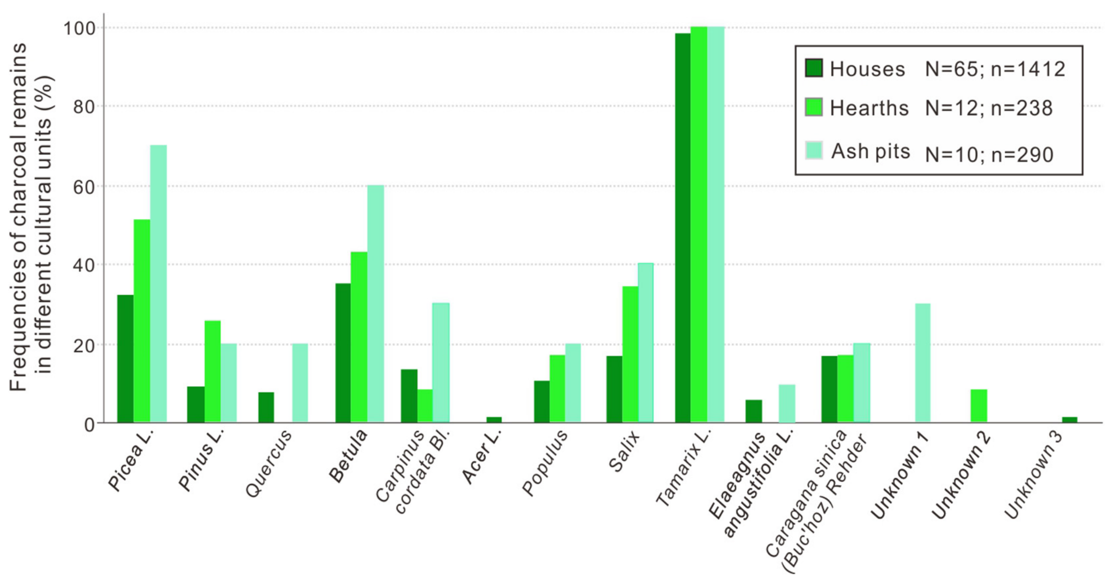

FIGURE 5 | Frequencies of woody taxa in different cultural contexts at JBR.

samples and maintains high percentages in the houses, hearths, and ash pits, which may be closely related to the ecology and environment at JBR.

The Mazong Mountains, where the JBR site is located, lie in the northern expanse of the western Hexi Corridor and have harbored an oasis woodland ecology since the late Holocene due to low annual precipitation, confirming the deduction based upon PCA that yields a similar composition of woody plants in the Mazong Mountains and the oasis gallery forests bordering rivers in the western Hexi Corridor (**Figure 6A**). *Tamarix* L. as well as *C. sinica* (Buc'hoz) Rehder and *E. angustifolia* L. shrubs usually grow on alluvial and silty plains in arid and semi-arid areas and often in oases along the main rivers in the western Hexi Corridor (China Forest Editorial Committee, 1997). Thus, it can be concluded that the shrubs used by miners at JBR may have been collected in the vicinity of the site.

On the other hand, the number and composition of arboreal taxa at JBR are significantly different from those in the western Hexi Corridor oases (**Figure 6B**). We compared the use of wood at JBR with archeological sites in the western Hexi Corridor, including the percentages of trees and shrubs as well as the number of arboreal taxa identified. **Figure 7** reveals that no more than five taxa of woody plants were discovered at each site in the western Hexi Corridor since the late Holocene (Shen et al., 2018). A clear contrast can be seen with JBR where at least eight tree taxa were identified (**Figure 7**). The

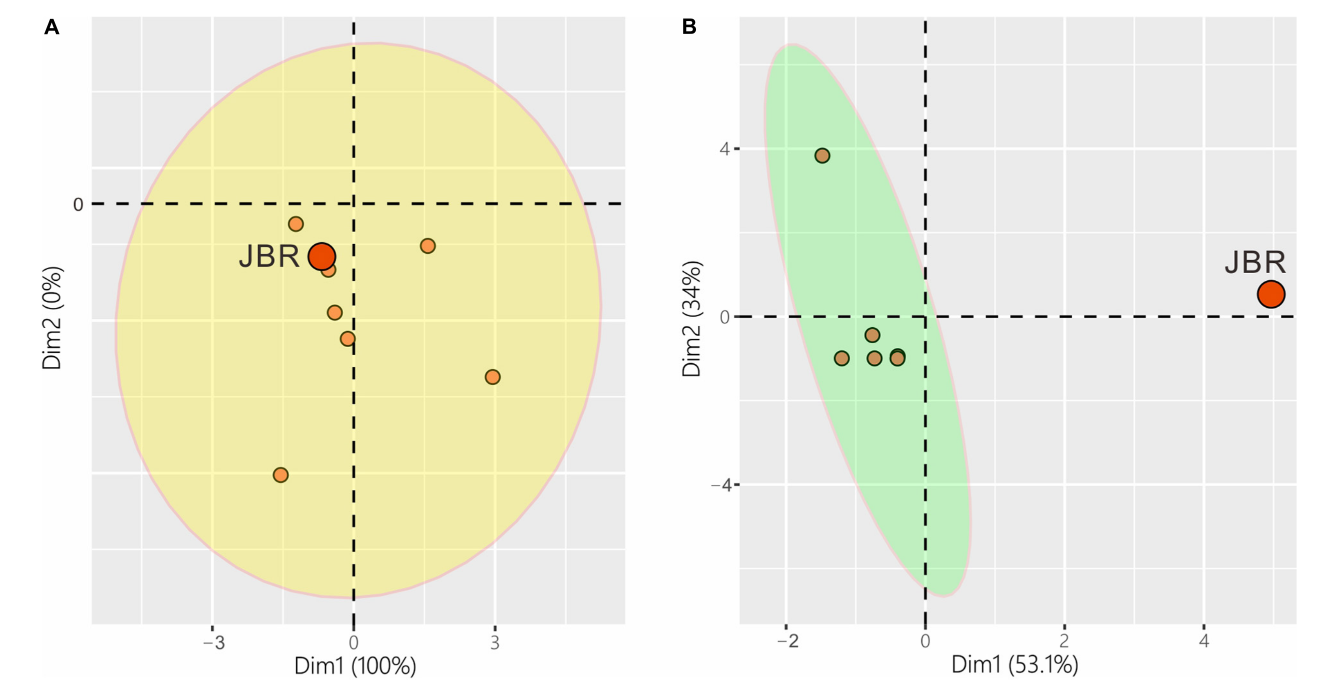

FIGURE 6 | PCA score of the first two principal components for the results of the charcoal analysis at JBR and archeological sites in the western Hexi Corridor oases. The red color represents results from JBR, and the orange color archeological sites in the oasis zone. **(A)** Comparisons of percentages of trees and shrubs between JBR and archeological sites in the oasis zone. **(B)** Comparisons of the percentages of different arboreal taxa between JBR and archeological sites in the oasis zone.

percentages of trees and shrubs identified at JBR were similar with those in the western Hexi Corridor oases (**Figure 7**), while the assemblage of arboreal taxa reflected a different forest composition. The composition of tree taxa revealed by our charcoal analysis reflects a mixed forest and a relatively cold and humid environment around the JBR site. However, low annual precipitation in the Mazong Shan did not support the growth of arboreal taxa, especially *Picea* L. and *Pinus* L., and this also conflicted with the assumed dominant use of *Tamarix* L. by the miners. Therefore, the tree taxa discovered at JBR were likely distributed only sparsely in the Mazong Mountains during the Iron Age (**Figure 7**). Based on extant paleoenvironmental records, the Hexi Corridor experienced obvious degradation of woody vegetation and desertification since the late Holocene, both due to the drier climate and human metallurgical activities (Zhou et al., 2012). The use of diverse woody plants by people in the Hexi Corridor decreased during the late Bronze Age (Shen et al., 2018). By the Iron Age, the number of arboreal taxa was no more than five in all known archeological sites, indicating that the diversity and distribution of woody plants may have been far less than those during the Bronze Age. However, the pre-industrial exploitation of jade must have been supported by large amounts of wood resources. Compared with shrubs, trees are more suitable for the sort of construction associated with mining jade, housing and military installations, and durable toolmaking. The local arid ecology likely constrained the diversity of tree communities in the Iron Age; thus, the trees used by the JBR miners were probably not collected in the immediate vicinity of the site due to this prevailing arid environment. Therefore, it is important to ask where the trees used at JBR came from.

Wood Collection Far From Living Areas and Its Relationship to the Subsistence Strategy of the JBR Jade Miners

Constraints imposed by the dry environment on the arboreal community identified in our research suggest that the trees used by the JBR miners were not collected locally. To examine the possible source of those trees, understanding the regional vegetation and its historical changes plays a critical role (Pickarski et al., 2015; Schiferl et al., 2017; Xu et al., 2017; Lézine et al., 2019; Park et al., 2019; Zhao et al., 2020). Pollen analysis of natural sediments has recently been used to outline the evolution of vegetation and explore the relationship between human activities and environmental changes in the past (Hou et al., 2015; Huang et al., 2017, 2018; Pini et al., 2017; Cheng et al., 2018; Novenko et al., 2018; Qiu et al., 2020). Palynological analysis of lacustrine cores from the western Hexi Corridor, that of Lake Tian'e in the western Qilian Range in particular, reveals the presence of *Picea* L. and *Betula* in the late Bronze and Iron Ages (Zhang et al., 2018). *Picea* L., *Pinus* L., *Betula*, *Salix*, and *Ulmus* appeared during the same period in the pollen records from Eastern Lake Juyan (also known as Sogo Nuur) on the lower reach of the Heihe River and Lake Balikun in the eastern Tianshan Mountains (Herzschuh et al., 2004; Tao et al., 2010). In the eastern Hexi Corridor, the presence of *Picea* L., *Pinus*, and *Sabina* also in the late Bronze and Iron Ages has been noted in pollen profiles from the Sanjiaocheng

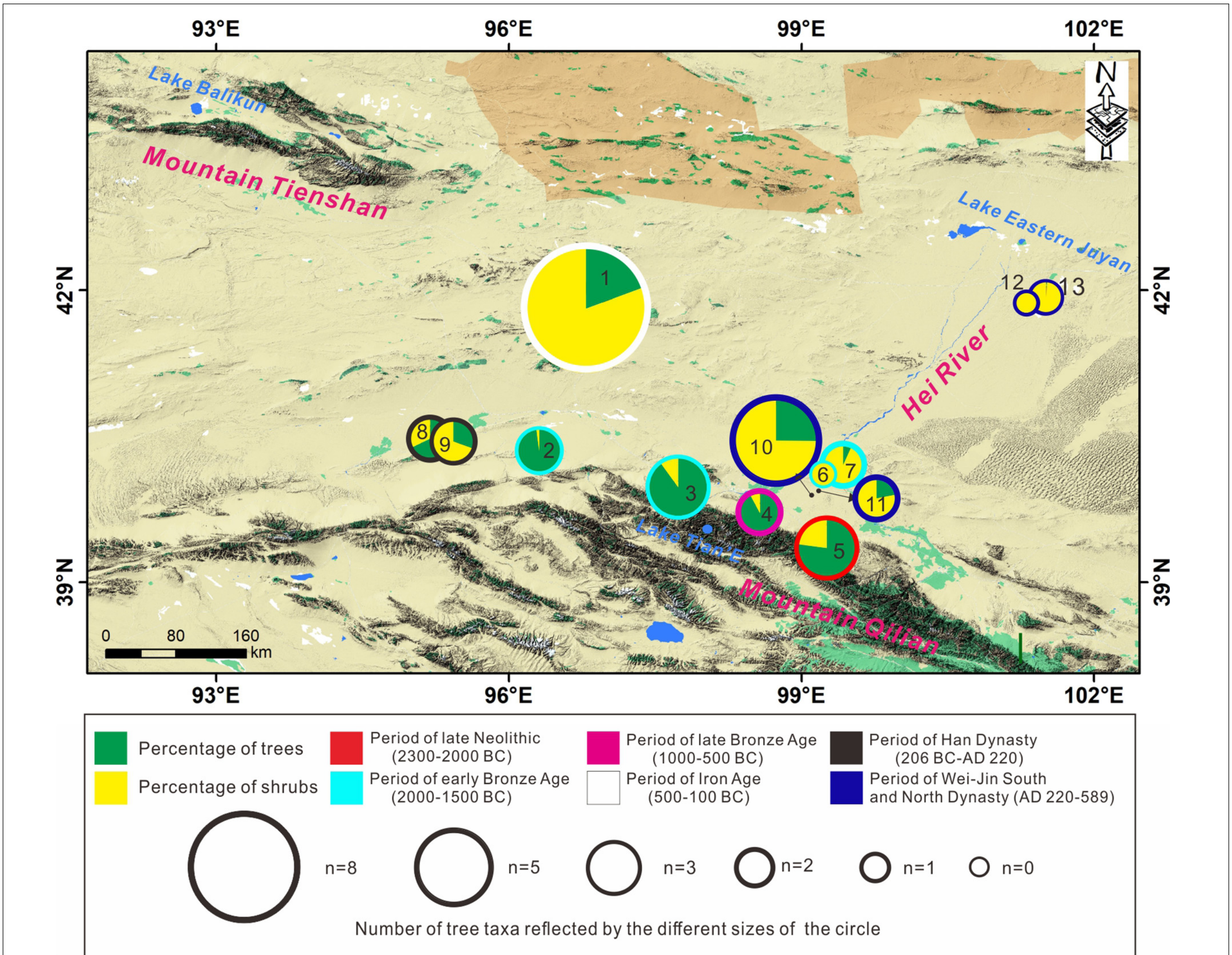

FIGURE 7 | Comparison of the uses of wood at JBR and archeological sites in the western Hexi Corridor, including percentages of trees and shrubs as well as the number of arboreal taxa identified in archeological sites. Varying sizes of circles reflect the number of arboreal taxa identified at each site, and "n" represents the number of tree species identified. The Arabic numerals in the circles represent the relevant archeological site: (1) JBR jade mine. (2) Yingwushu. (3) Huoshaogou. (4) Zhaojiashuimo. (5) Xihetan. (6) Ganggangwa. (7) Huoshiliang. (8) Lucaogou 1. (9) Lucaogou 2. (10) Huishui. (11) Xisanjiao. (12) K749. (13) Juyan.

section, and such broadleaved trees as *Betula*, *Quercus*, *Corylus*, and *Ulmus* have been identified there (Chen et al., 2006). The pollen records from lakes and stratigraphic sections seem to suggest a diverse arboreal community in mountain areas in the Hexi Corridor. Most tree taxa identified at JBR were also observed in pollen records from these lakes and sedimentary sections, indicating that trees destined for the jade mine were collected from surrounding mountainous areas located far from habitation areas.

Our results indicate that wood used at JBR was collected at some significant distance from the site's living areas, which is at variance with other archeological sites in the Hexi Corridor and, more broadly, eastern China (Wang et al., 2013; Li et al., 2014; Li H. M. et al., 2017; Yan et al., 2017; Shen et al., 2018; Liu et al., 2019a,b). Archeological evidence suggests that a critical transformation occurred in the pattern of wood collection in the past, from dead wood collected in the Paleolithic to fresh wood utilized in the Neolithic (Rubiales et al., 2011; Wang et al., 2016; Allué et al., 2017; Vidal-Matutano et al., 2017; Mota and Scheel-Ybert, 2019). This transformation in wood acquisition was presumably closely related to changes in people's subsistence strategies and their increasingly sophisticated technologies. These differences occurred at JBR also owing to changes in subsistence strategies that took place during the late Bronze Age and Iron Age.

Larger-scale human settlements in the western Hexi Corridor can be traced back to the third millennium BCE (Dong et al., 2018). Suitable climatic conditions promoted the westward diffusion of the Neolithic Majiayao culture (ca. 3000–2000 BCE), and an agricultural economy based on millet cultivation was established in the Hexi Corridor at this time (Dong et al., 2013).

With the gradual enhancement of cultural exchange between the East and the West during the second millennium BCE, domesticated wheat and barley, sheep, and metallurgical technology were introduced to the Hexi Corridor, where they transformed human subsistence strategies in the region from reliance on agriculture to agropastoralism (Yang et al., 2019). During this period, people mainly settled in oases and used shrubs such as *Tamarix* L. as fuel for metallurgical activities like smelting (Li et al., 2011). When the physical and chemical properties of the main coniferous and broadleaved trees or shrubby taxa are compared, the caloric value of conifers is significantly higher than that of broadleaved arboreal species and shrubs, making them more suitable for metallurgical activities. However, conifers were only widely used by people who settled near mountainous areas (**Figure 7**). This is likely related to the fact that large livestock species, such as horses, cattle, and camels which can be used to transport resources over long distances, were not yet widely used during this period. In the late first millennium BCE, a prevailing cold-and-dry climate led to less intense patterns of human settlement but promoted the establishment of agropastoralism across Eurasia (Kuz'mina, 2008). Archeological evidence suggests a rapid growth of agropastoralism along the Great Wall of China, including the Hexi Corridor (Han, 2008; Yang et al., 2019). Bones of pigs (*Sus scrofa domesticus*) are absent from archeological sites of this period in the Hexi Corridor, where they appear to have been replaced by grazing livestock, such as horses, cattle, sheep, and camels, indicating the establishment of agropastoralism (Yang et al., 2019). Horses and camels can be used for long-distance transportation, an advantage that can significantly expand the resource catchment area for people to exploit and obtain resources for production and daily life, including wood (Wu, 2002; Guo, 2012; Li et al., 2020). Recent data reveal that agropastoralism was much more common in the western Hexi Corridor during the Iron Age, e.g., the Shanma culture (Yang et al., 2019); thus, it is logical to assume that the JBR miners or other local people used traction animals to transport wood over long distances.

CONCLUSION

This study analyzed charcoal remains from an ancient jade mining site at JBR, Gansu, to explore the history of wood use in the western Hexi Corridor during the Iron Age. By combining these results with pollen records obtained from nearby lakes and sedimentary sections, we identified the pattern of wood collection at this site and the ways in which it was different from that of other broadly contemporary archeological sites in the Hexi Corridor. Our results indicate that *Tamarix* L. was the principal source of firewood for Iron Age miners at JBR. Some arboreal taxa were also used as fuel but were not collected locally due to the extremely arid environment of the Mazong Range that did not support the growth of such trees. The pollen records indicate that tree taxa present at the site were likely collected from mountainous areas far from the site. The pattern of wood collection exhibited by the JBR miners was closely related to their pastoral subsistence mode. This study provides information on the diversity and particularity of wood collection and use in arid areas in the past and reflects on important local environmental impacts on human adaptations.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

HCZ and GKC conceived this study. FWL undertook the identification of charcoal remains and wrote the manuscript. YSY and SJZ discussed the data. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2021.636534/full#supplementary-material

REFERENCES

Allué, E., Solé, A., and Burguet-Coca, A. (2017). Fuel exploitation among Neanderthals based on the anthracological record from Abric Romaní (Capllades, NE Spain). *Quat. Int.* 431, 6–15. doi: 10.1016/j.quaint.2015.12.046

An, C. B., Li, H., Dong, W. M., Chen, Y. F., Zhao, Y. T., and Shi, C. (2014). How prehistoric humans used plant resources to adapt to environmental change: a cause study in the western Chinese Loess Plateau during the Qijia Period. *Holocene* 24, 512–517. doi: 10.1177/0959683613520259

Bai, Y. X. (2005). *Archaeological Study of Iron Tools In pre-Qin and Han Dynasty*. Beijing: Science Press, 49–351. (In Chinese).

Bevan, A., Colledge, S., Fuller, D., Ralph, F., Stephen, S., and Chris, S. (2017). Holocene fluctuations in human population demonstrate repeated links to food production and climate. *Proc. Natl. Acad. Sci. U.S.A.* 114, E10524–E10531.

Bouchaud, C., Huchet, J., Faucher, T., Redon, B., and Noûs, C. (2020). Providing fuel, building materials and food for gold exploitation in the Eastern Desert, Egypt: multidisciplinary dataset of the Ptolemaic site of Samut North (late 4th c. BCE). *J. Archaeol. Sci. Rep.* 35:102729. doi: 10.1016/j.jasrep.2020.102729

Chen, F. H., Cheng, B., Zhao, Y., Zhu, Y., and Madsen, D. B. (2006). Holocene environmental change inferred from a high-resolution pollen record, Lake Zhuyeze, arid China. *Holocene* 16, 675–684. doi: 10.1191/0959683606hl951rp

Chen, F. H., Dong, G. H., Zhang, D. J., Liu, X. Y., Jia, X., An, C. B., et al. (2015). Agriculture facilitated permanent human occupation of the Tibetan Plateau after 3600 BP. *Science* 347, 248–250. doi: 10.1126/science.1259172

Chen, G. K., Qiu, Z. L., Wang, H., and Yang, Y. S. (2020). An overview of archaeological investigation and excavation of early jade mining sites in the Hexi Corridor. *Silk Road* 1, 38–41. (In Chinese),

Chen, N. B., Ren, L. L., Du, L. Y., Hou, J. W., Mullin, V. E., Wu, D., et al. (2020). Ancient genomes reveal tropical bovid species in the Tibetan. Plateau contributed to the prevalence of hunting game until the late Neolithic. *Proc. Natl. Acad. Sci. U.S.A.* 117, 28150–28159. doi: 10.1073/pnas.2011696117

Cheng, J. Q., Yang, J. J., and Liu, P. (1992). *Wood Records of China (Zhongguo Mucai Zhi)*. Beijing: China Forestry Publishing House.

Cheng, Z. J., Weng, C. Y., Steinke, S., and Mohtadi, M. (2018). Anthropogenic modification of vegetated landscapes in southern China from 6,000 years ago. *Nat. Geosci.* 11, 939–943. doi: 10.1038/s41561-018-0250-1

China Forest Editorial Committee (1997). *Forests in China (Volumes I and II)*. Beijing: China Forestry Publishing House. (In Chinese).

Cordaux, R., Deepa, E., Vishwanathan, H., and Stoneking, M. (2004). Genetic evidence for the demic diffusion of agriculture to India. *Science* 304:1125. doi: 10.1126/science.1095819

Cui, Y. F., Dong, G. H., Li, H. M., An, T., Liu, X. Y., Wang, J., et al. (2015). Early ceramic trade in Gansu and Qinghai regions, northwest China: a comparative element analysis on sherds of Majiayao Culture, Yangshao Culture and Qijia Culture. *J. Archaeol. Sci. Rep.* 3, 65–72. doi: 10.1016/j.jasrep.2015.05.018

Deforce, K., Boeren, I., Adriaenssens, S., Bastiaens, J., Keersmaeker, L. D., Haneca, K., et al. (2013). Selective woodland exploitation for charcoal production. A detailed analysis of charcoal kiln remains (ca. 1300-1900 AD) from Zoersel (northern Belgium). *J. Archaeol. Sci.* 40, 681–689. doi: 10.1016/j.jas.2012.07.009

Dong, G. H., Wang, L., Cui, Y. F., Robert, E., and Chen, F. H. (2013). The spatiotemporal pattern of the Majiayao cultural evolution and its relation to climate change and variety of subsistence strategy during late Neolithic period in Gansu and Qinghai Provinces, northwest China. *Quat. Int.* 316, 155–161. doi: 10.1016/j.quaint.2013.07.038

Dong, G. H., Yang, Y. S., Liu, X. Y., Li, H. M., Cui, Y. F., Wang, H., et al. (2018). Prehistoric trans-continental cultural exchange in the Hexi Corridor, northwest China. *Holocene* 28, 621–628. doi: 10.1177/0959683617735585

Flora of China Editorial Committee (2004). *Flora of China*. Beijing: Science Press. (In Chinese).

Gansu Provincial Institute of Cultural Relics and Archaeology (2016). The Excavation of the jade mining site at the jingbaoer pasture of mazhongshan town in subei county, gansu in 2016. *Cult. Relics* 4, 31–45.

Guo, J. Y. (2012). Horse training, horse riding and nomads in ancient Asia. *Soc. Sci. China (Zhongguo Shehui Kexue)* 6, 184–204. (In Chinese),

Han, J. Y. (2008). The underground world of nomads along the great wall during the spring and autumn and warring states periods. *South. Cult. Relics (Nanfang Wenwu)* 4, 67–73.

Hazell, Z., Crosby, V., Oakey, M., and Marshall, P. (2017). Archaeological investigation and charcoal analysis of charcoal burning platforms, Barbon, Cumbria, UK. *Quat. Int.* 458, 178–199. doi: 10.1016/j.quaint.2017.05.025

Herzschuh, U., Tarasov, P., Wünnemann, B., and Hartmann, K. (2004). Holocene vegetation and climate of the Alashan Plateau, NW China, reconstructed from pollen data. *Palaeogeogr. Palaeoecol.* 211, 1–17. doi: 10.1016/j.palaeo.2004.04.001

Hou, G. L., Yang, P., Cao, G. C., Chongyi, Y. E., and Wang, Q. B. (2015). Vegetation evolution and human expansion on the Qinghai-Tibet Plateau since the Last Deglaciation. *Quat. Int.* 430, 82–93. doi: 10.1016/j.quaint.2015.03.035

Huang, X. Z., Liu, S. S., Dong, G. H., Qiang, M. R., Bai, Z. J., Zhao, Y., et al. (2017). Early human impacts on vegetation on the northeastern Qinghai-Tibetan Plateau during the middle to late Holocene. *Prog. Phys. Geog.* 41, 286–301. doi: 10.1177/0309133317703035

Huang, X. Z., Peng, W., Rudaya, N., Grimm, E. C., Chen, X. M., Cao, X. Y., et al. (2018). Holocene vegetation and climate dynamics in the Altai mountains and surrounding areas. *Geophys. Res. Lett.* 45, 6628–6636. doi: 10.1029/2018gl078028

Kabukcu, C. (2018). Identification of woodland management practices and tree growth conditions in archaeological fuel waste remains: a case study from the site of Çatalhöyük in central Anatolia, Turkey. *Quat. Int.* 463, 282–297. doi: 10.1016/j.quaint.2017.03.017

Kabukcu, C., and Chabal, L. (2020). Sampling and quantitative analysis methods in anthracology from archaeological contexts: achievements and prospects. *Quat. Int.* (in press). doi: 10.1016/j.quaint.2020.11.004

Kawahata, H., Yamamoto, H., Ohkushi, K., Yokoyama, Y., Kimoto, K., Ohshima, H., et al. (2009). Changes of environments and human activity at the Sannai-Maruyama ruins in Japan during the mid-Holocene Hypsithermal climatic interval. *Quat. Sci. Rev.* 28, 964–974. doi: 10.1016/j.quascirev.2008.12.009

Kennett, D. J., Prufer, K. M., Culleton, B. J., George, R. J., Robinson, M., Trask, W., et al. (2020). Early isotope evidence for maize as a staple grain in the Americas. *Sci. Adv.* 6:eaba3245. doi: 10.1126/sciadv.aba3245

Kováčik, P., and Cummings, L. S. (2017). Reconstruction of woodland vegetation and firewood exploitation in Nine Mile Canyon, Utah, based on charcoal and pollen analysis. *Quat. Int.* 463, 312–326. doi: 10.1016/j.quaint.2017.06.052

Kuper, R., and Kröpelin, S. (2006). Climate- controlled holocene occupation in the sahara: motor of Africa's evolution. *Science* 313, 803–807. doi: 10.1126/science.1130989

Kuz'mina, E. E. (2008). *The Prehistory of the Silk Road*. Philadelphia,PA: University of Pennsylvania Press, 39–80.

Leipe, C., Long, T., Sergusheva, E. A., Wagner, M., and Tarasov, P. E. (2019). Discontinuous spread of millet agriculture in eastern Asia and prehistoric population dynamics. *Sci. Adv.* 5:eaax6225. doi: 10.1126/sciadv.aax6225

Lézine, A., Izumi, K., Kageyama, M., and Achoundong, G. (2019). A 90,000-year record of Afromontane forest responses to climate change. *Science* 363, 177–181. doi: 10.1126/science.aav6821

Li, H., An, C. B., Dong, W. M., Wang, S. Z., and Dong, G. H. (2014). Charcoal records of Qijia sites in the Longdong Basin and their significance. *Quat. Sci.* 34, 35–42. (In Chinese),

Li, H., An, C. B., Dong, W. M., Wang, W., Hu, Z. Y., Wang, S. Z., et al. (2017). Woodland vegetation composition and prehistoric human fuel collection strategy at the Shannashuzha site, Gansu Province, northwest China, during the middle Holocene. *Veg. Hist. Archaeobot.* 26, 213–221. doi: 10.1007/s00334-016-0585-8

Li, H. M., Liu, F. W., Cui, Y. F., Ren, L. L., Storozum, M. J., Qin, Z., et al. (2017). Human settlement and its influencing factors during the historical period in an oasis-desert transition zone of Dunhuang, Hexi Corridor, northwest China. *Quat. Int.* 458, 113–122. doi: 10.1016/j.quaint.2016.11.044

Li, X. Q., Sun, N., Dodson, J., Ji, M., Zhao, K. L., and Zhou, X. Y. (2011). The impact of early smelting on the environment of Huoshiliang in Hexi Corridor, NW China, as recorded by fossil charcoal and chemical elements. *Palaeogeogr. Palaeoecol.* 305, 329–336. doi: 10.1016/j.palaeo.2011.03.015

Li, X. Q., Sun, N., Dodson, J., and Zhou, X. Y. (2012). Human activity and its impact on the landscape at the Xishanping site in the western Loess Plateau during 4800–4300 cal yr BP based on the fossil charcoal record. *J. Archaeol. Sci.* 39, 3141–3147. doi: 10.1016/j.jas.2012.04.052

Li, Y., Zhang, C. R., Taylor, W. T. T., Chen, L., Flad, R. K., Boivin, N., et al. (2020). Early evidence for mounted horseback riding in northwest China. *Proc. Natl. Acad. Sci. U.S.A.* 117, 29569–29576. doi: 10.1073/pnas.2004360117

Liu, F. W., Li, H. M., Cui, Y. F., Yang, Y. S., Lee, H. F., Ding, D. T., et al. (2019a). Chronology and plant utilization from the earliest walled settlement in the Hexi corridor, northwestern China. *Radiocarbon* 61, 971–989. doi: 10.1017/rdc.2019.57

Liu, F. W., Yang, Y. S., Shi, Z. L., Storozum, M. J., and Dong, G. H. (2019b). Human settlement and wood utilization along the mainstream of Heihe River Basin, northwest China in historical period. *Quat. Int.* 516, 141–148. doi: 10.1016/j.quaint.2018.05.033

Mafferra, L. E. (2017). Forest landscape around the colonial city of Mendoza based on archaeological charcoal remains. *Intersecciones Antropol.* 18, 43–53.

Marcos, M. A., and Ortega, V. (2014). Paleoenvironments and use of wood resources by hunter-gatherers of northeastern Patagonia since the middle Holocene. *Magallania* 42, 147–163.

Marston, J. M. (2009). Modeling wood acquisition strategies from archaeological charcoal remains. *J. Archaeol. Sci.* 36, 2192–2220. doi: 10.1016/j.jas.2009.06.002

Martín-Seijo, M., Silva, V. M. F., and Bettencourt, A. M. S. (2015). Carbonised wooden objects and wood charcoal from an Iron Age feasting context in North-western Iberia: the case study of Frijão (Braga, Portugal). *J. Archaeol. Sci. Rep.* 2, 538–550. doi: 10.1016/j.jasrep.2015.05.005

Masi, A., Restelli, F. B., Sabato, D., Vignola, C., and Sadori, L. (2017). Timber exploitation during the 5^{th}-3^{rd} millennia BCE at Arslantepe (Malatya, Turkey): environmental constraints and cultural choices. *Archaeol. Anthropol. Sci.* 10, 465–483. doi: 10.1007/s12520-017-0499-0

Medina-Alcaide, M., Torti, J. L. S., and Peña, L. Z. (2015). Lighting the dark: wood charcoal analysis from Cueva de Nerja (Málaga, Spain) as a tool to explore the context of Palaeolithic rock art. *Comptes Rendus Palevol.* 14, 411–422. doi: 10.1016/j.crpv.2015.03.010

Miller, N. F. (1985). Paleoethnobotanical evidence for deforestation in ancient Iran: a case study of urban Malyan. *J. Ethnobiol.* 5, 1–19. doi: 10.1057/udi.2013.6

Mota, L., and Scheel-Ybert, R. (2019). Landscape and firewood use in Toca do Boqueirão da Pedra Furada (Piauí, Brazil) during early and Mid-Holocene. *J. Archaeol. Sci. Rep.* 23, 281–290. doi: 10.1016/j.jasrep.2018.10.034

Novenko, E. Y., Tsyganov, A. N., Payne, R. J., Mazei, N. G., Volkova, E. M., Chernyshov, V. A., et al. (2018). Vegetation dynamics and fire history at the southern boundary of the forest vegetation zone in European Russia during the middle and late Holocene. *Holocene* 28, 308–322. doi: 10.1177/0959683617721331

Park, J., Park, J., Yi, S., Kim, J. C., Lee, E., and Choi, J. (2019). Abrupt Holocene climate shifts in coastal East Asia, including the 8.2 ka, 4.2 ka, and 2.8 ka BP events, and societal responses on the Korean Peninsula. *Sci. Rep. U.K.* 9:10806.

Pichler, T., Nicolussi, K., Goldenberg, G., Hanke, K., Kovács, K., and Thurner, A. (2013). Charcoal from a prehistoric copper mine in the Austrian Alps: dendrochronological and dendrological data, demand for wood and forest utilisation. *J. Archaeol. Sci.* 40, 992–1002. doi: 10.1016/j.jas.2012.09.008

Pickarski, N., Kwiecien, O., Djamali, M., and Litt, T. (2015). Vegetation and environmental changes during the last interglacial in eastern Anatolia (Turkey): a new high-resolution pollen record from Lake Van. *Palaeogeogr. Palaeoecol.* 435, 145–158. doi: 10.1016/j.palaeo.2015.06.015

Pini, R., Ravazzi, C., Raiteri, L., Guerreschi, A., Castellano, L., Comolli, R., et al. (2017). Data from: from pristine forests to high-altitude pastures: an ecological approach to prehistoric human impact on vegetation and landscapes in the western Italian Alps. *J. Ecol.* 105, 1580–1597. doi: 10.1111/1365-2745.12767

Qing, L., Fuller, D. Q., and Zhang, H. (2010). Modelling wild food resources catchments amongst early farmers: case studies from the lower Yangzi and central China. *Quat. Sci.* 30, 245–261. (In Chinese),

Qiu, Z. W., Jiang, H. E., Ding, L. L., and Shang, X. (2020). Late Pleistocene-Holocene vegetation history and anthropogenic activities deduced from pollen spectra and archaeological data at Guxu Lake, eastern China. *Sci. Rep.U.K.* 10:9306.

R Core Team (2019). *R: A Language and Environment for Statistical Computing.* Vienna: R Foundation for statistical computing.

Renfrew, C., and Bahn, P. G. (1991). *Archaeology: Theories, Methods and Practice.* London: Thames and Hudson Ltd.

Rhode, D. (2016). Wood charcoal from archaeological sites in the Qinghai Lake Basin, western China: implications for human resources use and anthropogenic environmental change. *J. Ethnobiol.* 36, 571–594. doi: 10.2993/0278-0771-36.3.571

Rubiales, J. M., Hernández, L., Romero, F., and Sanz, C. (2011). The use of forest resources in central Iberia during the Late Iron Age. insights from the wood charcoal analysis of Pintia, a Vaccaean oppidum. *J. Archaeol. Sci.* 38, 1–10. doi: 10.1016/j.jas.2010.07.004

Salavert, A., and Dufraisse, A. (2014). Understanding the impact of socio-economic activities on archaeological charcoal assemblages in temperate areas: a comparative analysis of firewood management in two Neolithic societies in western Europe (Belgium, France). *J. Anthropol. Archaeol.* 35, 153–163. doi: 10.1016/j.jaa.2014.05.002

Schiferl, J. D., Bush, M. B., Silman, M. R., and Urrego, D. H. (2017). Vegetation responses to late Holocene climate changes in an Andean forest. *Quat. Res.* 89, 60–74. doi: 10.1017/qua.2017.64

Shackleton, C. M., and Prins, F. (1992). Charcoal analysis and the "principle of least effort"—a conceptual model. *J. Archaeol. Sci.* 19, 631–637. doi: 10.1016/0305-4403(92)90033-y

Shen, H., Zhou, X. Y., Zhao, K. L., Betts, A., Jia, P. W., and Li, X. Q. (2018). Wood types and human impact between 4300 and 2400 yr BP in the Hexi Corridor, NW China, inferred from charcoal records. *Holocene* 28, 629–639. doi: 10.1177/0959683617735586

Tao, S. C., An, C. B., Chen, F. H., Tang, L. Y., Wang, Z. L., Lv, Y. B., et al. (2010). Pollen-inferred vegetation and environmental changes since 16.7 cal ka BP at Balikun Lake, Xinjiang. *Chin. Sci. Bull.* 11, 1026–1035.

Tolksdorf, J. F., Elburg, R., Schröder, F., Knapp, H., Herbig, C., Westphal, T., et al. (2015). Forest exploitation for charcoal production and timber since the 12th century in an intact medieval mining site in the Niederpöbel Valley (Erzgebirge, Eastern Germany). *J. Archaeol. Sci. Rep.* 4, 487–500. doi: 10.1016/j.jasrep.2015.10.018

Vidal-Matutano, P., Henry, A., and Théry-Parisot, I. (2017). Dead wood gathering among Neanderthal groups: charcoal evidence from Abric del Pastor and El Salt (eastern Iberia). *J. Archaeol. Sci.* 80, 109–121. doi: 10.1016/j.jas.2017.03.001

Wang, S. Z., Li, H., Zhang, L. R., Chen, G. K., Wang, P., and Zhao, Z. J. (2014a). Tree exploitation and palaeoenvironment at Heishuiguo Xichengyi site, Zhangye city, Gansu Province–revealed by excavated charcoal analysis. *Quat. Sci.* 34, 43–50. (In Chinese), doi: 10.2305/iucn.ch.2014.parks-21-1mrb.en

Wang, S. Z., Wang, Q. Q., Wang, Z. X., Liang, G. J., Qi, W. Y., and Ren, X. Y. (2016). Wood utilization and ecological environment indicated by charcoal remains at the Jinchankou site during the middle and late Qijia Culture. *Agric. Archaeol. (Nongye Kaogu)* 1, 9–15. (In Chinese)

Wang, S. Z., Wang, Z. L., and He, N. (2011). Charcoal analysis in Taosi site. *Archaeology (Kaogu)* 3, 91–97. (In Chinese),

Wang, S. Z., Yue, H. B., Tang, J. G., Yue, Z. W., He, Y. L., and Zhao, Z. J. (2014b). Human wood utilization during the mid-late Shang Dynasty—charcoal analysis in Shangcheng and Yin ruins of Huanbei. *Cult. Relics South. China* 3, 117–129. (In Chinese),

Wang, Y. Q., Wang, S. Z., and Jin, G. Y. (2013). Research of charcoal remains at the Beiqian site, Jimo, Shandong Province. *East Asia Archaeol.* 216–238. (In Chinese)

Wu, E. (2002). Some ideas on the early nomadic culture in the Eurasian steppe. *Acta Archaeol. Sin.* 4, 437–470. (In Chinese),

Xie, D. J. (2002). *Prehistoric Archaeology of Gansu Province and Qinghai Province.* Beijing: Cultural Relics Press. (In Chinese).

Xu, Q. H., Chen, F. H., Zhang, S. R., Cao, X. Y., Li, J. Y., Li, Y. C., et al. (2017). Vegetation succession and East Asian summer monsoon changes since the last deglaciation inferred from high-resolution pollen record in Lake Gonghai, Shanxi province, China. *Holocene* 27, 835–846. doi: 10.1177/0959683616675941

Yan, X., Wang, S. Z., Jiang, M., and He, K. Y. (2017). Preliminary study of charcoal remains unearthed from the Baodun Site in 2013-2014. *South. Ethnol. Archaeol.* 2, 311–328. (In Chinese),

Yang, Y. S. (2017). *The Transition of Human Subsistence Strategy and its Influencing Factors During Prehistoric Times and in the Hexi Corridor, Northwest China.* Doctoral dissertation. Lanzhou: Lanzhou University. 68–69.

Yang, Y. S., Dong, G. H., Zhang, S. J., Cui, Y. F., Li, H. M., Chen, G. K., et al. (2016). Copper content in anthropogenic sediments as a tracer for detecting smelting activities and its impact on environment during prehistoric period in Hexi corridor, Northwest China. *Holocene* 27, 282–291. doi: 10.1177/0959683616658531

Yang, Y. S., Ren, L. L., Dong, G. H., Cui, Y. F., and Chen, F. H. (2019). Economic Change in the Prehistoric Hexi Corridor (4800-2200 BP), North-West China. *Archaeometry* 61, 957–976. doi: 10.1111/arcm.12464

Zhang, J., Huang, X. Z., Wang, Z. L., Yan, T. L., and Zhang, E. Y. (2018). A late-Holocene pollen record from the western Qilian mountains and its implications for climate change and human activity along the Silk Road, northwestern China. *Holocene* 28, 1141–1150. doi: 10.1177/0959683618761548

Zhang, S. J., Yang, Y. S., Storozum, M. J., Li, H. M., Cui, Y. F., and Dong, G. H. (2017). Copper smelting and sediment pollution in Bronze Age China: a case study in the Hexi Corridor, Northwest China. *Catena* 156, 92–101. doi: 10.1016/j.catena.2017.04.001

Zhao, Y., Tzedakis, P. C., Li, Q., Qin, F., Cui, Q. Y., Liang, C., et al. (2020). Evolution of vegetation and climate variability on the Tibetan Plateau over the past 1.74 million years. *Sci. Adv.* 6:eaay6193. doi: 10.1126/sciadv.aay6193

Zhou, X. Y., Li, X. Q., Dodson, J., Zhao, K. L., Atahan, P., Sun, N., et al. (2012). Land degradation during the Bronze Age in Hexi Corridor (Gansu, China). *Quat. Int.* 254, 42–48. doi: 10.1016/j.quaint.2011.06.046

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Environmental Influences on Human Subsistence Strategies in Southwest China During the Bronze Age: A Case Study at the Jiangxifen Site in Yunnan

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The study of human dietary structures is an effective means of elucidating the subsistence patterns of our prehistoric ancestors and can highlight the processes through which humans interacted with the environment. We conducted stable isotope and archeobotanical analyses of human, animal, and plant remains at the Jiangxifen site, dated to ~900–400 BC, to explore human paleodiets and determine the environmental adaptation strategies adopted by humans in the middle valley of the Jinshajiang River in Yunnan Province. Humans predominantly consumed C_4 foods (e.g., millet) and C_4 food-fed animal protein sources, with smaller contributions from C_3 food plants (e.g., rice) and C_3 food-fed animal protein sources. We argued that the local dry-hot environment was the reason for the accessibility of C_4 plants in the studied area. A comparison of our results with previously published archeobotanical data and isotopic evidence from human bones in other Bronze Age sites in Yunnan Province revealed high spatial variability in diets of human and subsistence strategies during this period. These differences were caused by the highly varying living environment of each region, which was related to fragmentation resulting from the geomorphological features of Yunnan Province.

Keywords: living environment, Bronze Age, subsistence strategy, human-land relationship, Jinshajiang River Valley

INTRODUCTION

In Eurasia, major changes in subsistence took place during the transition from the Neolithic to the Bronze Age (Dong et al., 2017; Hanks et al., 2018), changes that were profoundly impacted by the emergence and intensification of early trans-Eurasian exchanges (Svyatko et al., 2013; Dong et al., 2020). In East Asia, the transformation of human subsistence strategies was asynchronous during the Bronze Age. Exotic crops (wheat and barley) and livestock (sheep, cattle, etc.) encompassed the dominant forms of human subsistence in northwest China during the second millennium BC (Chen et al., 2015; Zhou et al., 2016; Dong et al., 2021), whereas indigenous millet cultivation dominated in the Central Plains of North China until the late first millennium BC (Li et al., 2020). However, the spatial pattern of means of human livelihood in Yunnan Province in Southwest China, another important region for transcontinental exchange during the Bronze Age (Gao et al., 2020), remains unclear.

Archeobotanical, zooarcheological, and stable isotope analyses are effective methods for studying human subsistence strategies during prehistoric periods (d'Alpoim Guedes et al., 2014; Ma et al., 2016; Ren et al., 2020). Archeobotany and zooarcheology encompass systematic studies aimed at elucidating animal and plant exploitation strategies (Isaakidou and Halstead, 2018). However, the acidic soils in Yunnan Province are unsuitable for macro-fossil preservation, and the animals buried in tombs might not be representative of the prevalent fauna (Yuan, 2015; Hou et al., 2019); this prevents the study of prehistoric subsistence strategies in this area. Stable isotope analysis can be used to reconstruct the diet structure of humans and animals (Kohn, 1999; Richards, 2015), but it only yields C_3/C_4 signals, rather than elucidating specific food types. Therefore, it is necessary to combine a variety of methods to comprehensively reconstruct human subsistence strategies in prehistoric times. Archeobotanical and stable isotope analyses for Bronze Age sites in Yunnan are particularly scarce, with only limited evidence from a small number of sites, such as Dayingzhuang (Dal Martello et al., 2021), Haimenkou (Xue, 2010), Shilinggang (Li et al., 2016; Ren et al., 2017), Jinlianshan–Xueshan (Zhang, 2011; Wang, 2014), and Mayutian (Zhang et al., 2014). Therefore, our current understanding of subsistence during the Bronze Age in this region is limited. Yunnan province is geographically highly diverse and is characterized by the presence of large mountain chains and deeply cut rivers in the eastern margin of the Tibetan Plateau. Deep river valleys which include the valleys of the Lancangjiang, Nujiang, and Jinshajiang Rivers, and large lakes characterize this landscape.

In the present study, we analyzed the stable carbon (C) and nitrogen (N) isotopes of human and animal bones and identified plant remains from the Jiangxifen Bronze Age site, which is located in the Jinshajiang River Valley. We also conducted radiocarbon dating at the site to reconstruct the diets of ancient locals. These results were also compared with previously published data from contemporaneous sites in Yunnan Province to explore the spatial patterning in ancient human diets and their relationship with the local environment. Our study findings contribute to our understanding of past human-land relationships in Southwest China during the Bronze Age before the region was controlled by a unified regime.

STUDY AREA

Yunnan province is located in the low latitude plateau, and it is mainly dominated by the Indian summer monsoon and East Asian summer monsoon (Cao et al., 2012). The temperature in January is about 9–11°C, and in July is about 22°C. The annual mean precipitation is 1,100–1,600 mm (Shi and Chen, 2018). However, the local climate in Yunnan is diverse owing to the presence of many rivers and high mountains. In different valleys, rain shadows can lead to drier and hotter conditions.

The Jiangxifen site (26.18°N and 102.23°E) is located in Jiyi town, Wuding County, Yunnan Province (**Figure 1**). The site is in the Jinshajiang River Valley with dry and mega-thermal climate, the annual average temperature and the $\geq$ 10°C accumulated temperature are 21.5°C and 7,400°C, respectively, and the annual precipitation is $\leq$ 630 mm (Yang, 2006). Shrubs and the Savanna shrubs dominate below 1,700 m in this valley (Jin and Ou, 2000; Zhang et al., 2005), and the coniferous forest is mainly distributed above 1,700 m. The Jinshajiang River flows through the study area from southwest to northeast, and the site is located on the second fluvial terrace at the south bank of the Jinshajiang River with an altitude of 900 m. The terrain of the region is complex and highly fragmented due to geomorphic uplift and erosion (Nie et al., 2008). High mountains flank the east and west sides of the river. Red sandstone is exposed and geological disasters occur frequently. Modern plant vegetation surveys (Cao and Jin, 1989; Ou, 1994; Jin, 1999; Li et al., 2009) have indicated that a large amount of C_4 vegetation is distributed in the dry-hot valley of the Jinshajiang River. Analyses of pollen assemblages (Xiao et al., 2014, 2018, 2020; Zheng et al., 2014) and the stable C isotopes (δ^{13}C) of long-chain *n*-alkanes from sediments (Cui et al., 2015, 2019) indicated the existence of a forest in Yunnan Province during the late Holocene (after 3,300 BP).

In total, 530 tombs were identified during the excavation of the Jiangxifen site in the period from November 2018 to April 2019. The characteristics of the unearthed cultural relics and funeral objects from the site are indicative of the Bronze Age (Yunnan Institute of Cultural Relics and Archaeology, 2019).

MATERIALS AND METHODS

Collagen Preparation and Isotope Analysis

In total, 74 human and 35 animal bone samples were collected from the Jiangxifen site. Of these, 68 human and three animal bone collagen samples were extracted (**Supplementary Table 1**).

Bone collagen was extracted at the Key Laboratory of Western China's Environmental Systems (MOE), Lanzhou University, Gansu Province, China. Based on the method described by Richards and Hedges (1999), we placed 0.5–1.5 g of bones in 0.5 mol/L HCl and 0.125 mol/L NaOH to remove inorganic matter and humic acids, respectively. The bones were then placed in a weakly acidic solution (pH = 3) for acidification and subsequently filtered and freeze-dried to obtain collagen.

The C and N percentages in the five collagen samples were measured using the Elementar Vario EL Cube elemental analyzer (Elementar Analysensysteme GmbH, Germany) at the State Key Laboratory of Applied Organic Chemistry, Lanzhou University. Isotope analysis was conducted using the Thermo Fisher Flash EA1112–MAT253 mass spectrometer (Thermo Fisher Scientific, Germany) at the Key Laboratory of Western China's Environmental Systems (MOE), Lanzhou University. Sixty-six collagen samples were examined using an IsoPrime-100 IRMS mass spectrometer combined with a vario PYRO cube elemental analyzer (Elementar, Germany) at the archaeological stable isotope laboratory, the University of Chinese Academy of Sciences. The C and N isotope ratios were expressed as δ^{13}C and δ^{15}N, relative to the international standards V-PDB and AIR, respectively. The isotopic analytical precision was 0.2‰.

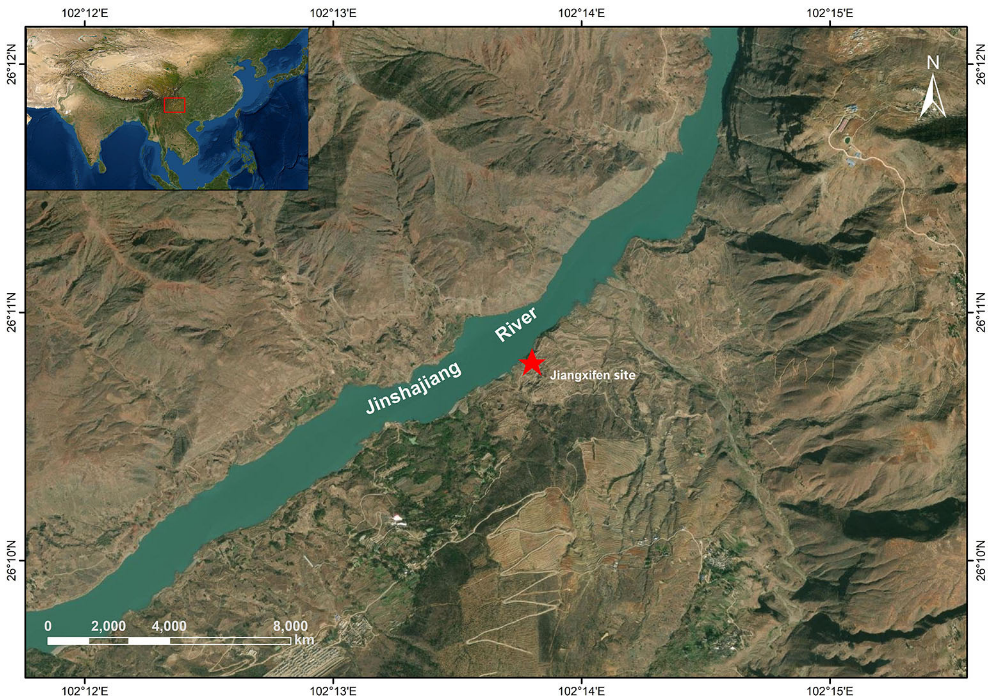

FIGURE 1 | Location of the Jiangxifen site.

TABLE 1 | Radiocarbon dates at the Jiangxifen site.

Lab no.	Context	Sample no.	Species	^{14}C date BP	Calibrated age BC/AD (95.4% prob.)
Beta-547362	2018YnJM205-1	R-15	Human bone	2,660 ± 30	899 cal BC ∼ 790 cal BC
Beta-544140	2018YnJM230	R-34	Human bone	2,560 ± 30	805 cal BC ∼ 563 cal BC
LZU19287	2018YnJM199	R-12	Human bone	2,560 ± 30	805 cal BC ∼ 563 cal BC
Beta-544139	2018YnJM207	R-17	Human bone	2,550 ± 30	801 cal BC ∼ 550 cal BC
Beta-544141	2018YnJM270	R-62	Human bone	2,540 ± 30	796 cal BC ∼ 547 cal BC
LZU19288	2018YnJM204-1	R-13	Human bone	2,530 ± 30	794 cal BC ∼ 544 cal BC
Beta-547363	2018YnJM249	R-45	Human bone	2,520 ± 30	789 cal BC ∼ 544 cal BC
Beta-544137	2018YnJM217	D-37	Bovid bone	2,480 ± 30	772 cal BC ∼ 476 cal BC
LZU19289	T3503⑦	D-27	Pig bone	2,470 ± 30	766 cal BC ∼ 422 cal BC

Radiocarbon Dating

Seven human and two animal collagen samples were selected for accelerated mass spectrometry radiocarbon dating at Peking University, Beijing; and at Beta Analytic Inc., Florida, United States (**Table 1**). The ^{14}C dates were calibrated using Oxcal version 4.4.2 (Ramsey, 2017) with the IntCal20 curve (Reimer et al., 2020) and reported as "cal BC."

Plant Remains

About 17 samples of plant remains were collected *via* flotation sampling from soil (a total of 194 L). Three flotation samples were collected from the ash pits, and 14 flotation samples were collected from the cultural layers. Plant identification was carried out at the key laboratory of Western China's environmental systems (MOE), Lanzhou University.

RESULTS

Chronology

The radiocarbon dating results are presented in **Table 1**. The Jiangxifen site was dated to 899–422 cal BC, with a range of 95.4%. This period covers the middle Western Zhou Dynasty (1,046–771 BCE) to the early Warring States Period (475–221 BC) in the Central Plains.

Isotope Analysis

The isotope data for human and animal bone collagen are presented in **Supplementary Table 1**, **Table 2**, **Figure 2**. The collagen of C:N ratios ranged from 3.1 to 5.7, with yields of 0.1–4.7%. Three human collagen samples were poorly preserved and excluded from further analyses, as their C:N ratios were outside the range of 2.9–3.6

TABLE 2 | Summary of results of C and N isotopes for humans and animals at the Jiangxifen site.

Species	Number	$\delta^{13}C$ (‰)			$\delta^{15}N$ (‰)		
		Mean	SD	Range	Mean	SD	Range
Human	65	−14.2	1.6	−18.6 ∼ −9.4	9.8	1.0	5.9 ∼ 12.4
Pig	2	−19.5	2.3	−21.1∼ −17.8	6.2	1.6	5.1 ∼ 7.3
Bovid	1	−8.1	–	−8.1	4.6	–	4.6

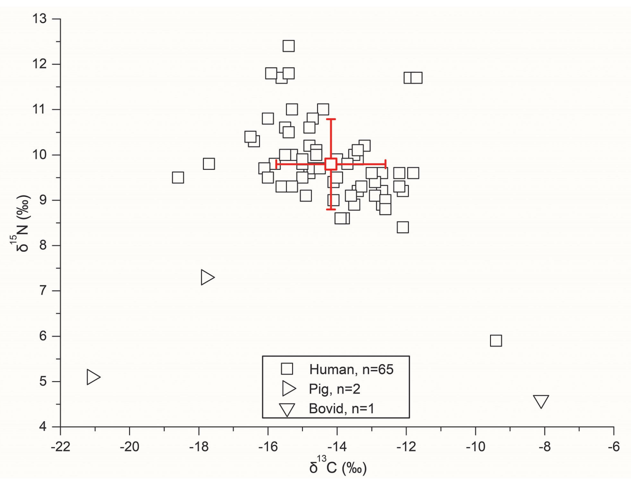

FIGURE 2 | Scatter diagram of carbon (C) and nitrogen (N) isotopes values for human and animal bone collagen.

(DeNiro, 1985; Ambrose, 1990). In addition, samples with a yield <1% and with C:N ratios between 2.9 and 3.6 were considered to be well-preserved and conformed to the analytic standard.

The $\delta^{13}C$ and $\delta^{15}N$ values of human collagen ($n = 65$) ranged from −18.6 to −9.4‰ (mean = −14.2 ± 1.6‰) and from 5.9 to 12.4‰ (mean = 9.8 ± 1.0‰), respectively. The $\delta^{13}C$ and $\delta^{15}N$ values of pig collagen ($n = 2$) ranged from −21.1 to −17.8‰ (mean = −19.5 ± 2.3‰) and from 5.1 to 7.3‰ (mean = 6.2 ± 1.6‰), respectively. Only one bovid bone collagen was extracted, and its $\delta^{13}C$ and $\delta^{15}N$ values were −8.1‰ and 4.6‰, respectively (**Table 2**).

Plant Remains

Although we collected a total of 17 flotation samples, only a few plant macrofossils were identified from the ash pits. In total, 203 charred plant seeds were identified. The identified crop remains included eight caryopses of foxtail millet (*Setaria italica*), three caryopses of common millets (*Panicum miliaceum*), 83 whole rice seeds (*Oryza sativa*), and 107 broken rice seeds, as shown in **Table 3**, **Figure 3**. We also identified the remains of two wild plant species: the three-horned bedstraw (*Galium tricornutum*) and lambsquarters (*Chenopodium album* L.).

DISCUSSION

Human Diets and Subsistence at the Jiangxifen Site During the Period ∼900–400 BC

Natural vegetation surveys (Cao and Jin, 1989; Ou, 1994; Jin, 1999; Ward et al., 1999; Nelson et al., 2004; Li et al., 2009) and analyses of $\delta^{13}C$ values in the Holocene sediments (Cui et al., 2015, 2019) indicated that C_4 plants have an advantage in the hot and dry climate of the Jinshajiang River Valley in both modern times and throughout the Holocene. In contrast, C_3 vegetation dominates the higher altitude. Therefore, we urge caution in the interpretation of the C_4 signal in humans and animals in this region, even though in North China, C_3 food resources in human diets are typically associated with wheat and rice, whereas C_4 resources are typically associated with millet (Zhang et al., 2015; Zhou and Garvie-Lok, 2015; Ma et al., 2016; Cheung et al., 2019). Evidence from charred plants at the Baiyangcun site revealed that the earliest rice and foxtail millet remains in Yunnan were dated between 2,624–2,475 cal BC and 2,868–2,573 cal BC, respectively (Dal Martello et al., 2018). In Yunnan, wheat was cultivated later, with the earliest occurrence dated to 3,125 ± 30 BP, as determined in the second phase of the Haimenkou site (Xue, 2010). However, both rice and millet accounted for a certain proportion of plant food sources in the dry-hot valley of the Jinshajiang River during the prehistoric period; this is supported by evidence from unearthed plant remains from the Dadunzi and Baiyangcun sites (Jin et al., 2014; Dal Martello et al., 2018), as well as those from the Jiangxifen site in the present study (**Figure 3**).

Animal isotope data are typically used to explain human isotope values for the reconstruction of human diets. In the present study, the average $\delta^{13}C$ value for the two pigs (−19.5 ± 2.3‰) indicated a predominately C_3 food-based diet, which suggested either that the pigs foraged or were captured in the high-altitude forests or that humans fed them C_3 food (e.g., C_3 plants, rice by-products etc.; **Table 2**, **Figure 2**). The $\delta^{13}C$ value for single bovid (−8.1‰) indicated a C_4 plant-based diet, which suggested that the bovid might have been fed C_4 plants by humans, as the natural vegetation in the dry-hot valley included both C_3 and C_4 vegetation (**Table 2**, **Figure 2**).

The $\delta^{13}C$ and $\delta^{15}N$ values for humans ($n = 65$) ranged from −18.6 to −9.4‰ (mean = −14.2 ± 1.6‰) and from 5.9 to 12.4‰ (mean = 9.8 ± 1.0‰), respectively, indicating a range of C_4, mixed C_3/C_4, and mainly C_4 diets (**Table 2**, **Figure 2**). The wide range of human $\delta^{13}C$ values implies the use of highly varying food resources. However, the $\delta^{13}C$ values

TABLE 3 | Number of identified samples of charred seeds from the flotations at the Jiangxifen site.

Sample No.	Soil flotation quantity(L)	*Setaria italica*	*Panicum miliaceum*	*Oryza sativa* (Whole)	*Oryza sativa* (Broken)	*Galium tricornutum* Dandy	*Chenopodium album L.*
T3101 H12	10	7	3	–	–	1	–
H6	7.3	1	–	83	107	–	–
H4	10	–	–	–	–	–	1
Total	27.3	8	3	83	107	1	1

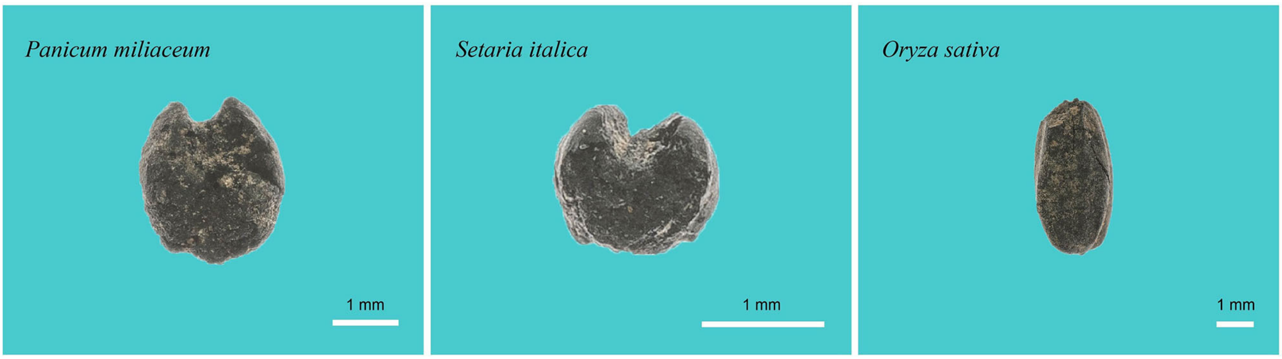

FIGURE 3 | Remains of crops identified at the Jiangxifen site.

for most individuals (60 out of 65) demonstrated mixed C_3/C_4 diets, implying the predominant consumption of both C_3 and C_4 foods. Furthermore, the average human δ^{13}C value (-14.2 ± 1.6‰) indicated a preference for C_4 foods; however, a single individual consumed a significant amount of C_3 foods. Moreover, the δ^{13}C values for four individuals indicated a predominance of C_4 foods. As the plant remains from this and other sites in the region indicated that millet and rice were the staple plant foods during the Bronze Age, we assumed that the C_3-consuming humans mainly relied on rice and C_3 food-fed animal protein, and so on, whereas the C_4-consuming humans mainly relied on millet and C_4 food-fed animal protein, and so on. Consumers of both C_3 and C_4 foods likely relied on both C_3 (rice, C_3 food-fed animal protein, etc.) and C_4 (millet, C_4 food-fed animal protein, etc.) foods. Undoubtedly, all humans likely foraged for both C_3 and C_4 plant foods in the wild, but wild plant consumption was probably limited owing to the prevalence of mixed millet and rice agriculture in Jiangxifen. Overall, humans at the Jiangxifen site might have preferred to consume C_4 foods, implying the predominance of millet agriculture.

The occurrence of mixed millet and rice agriculture in the region suggested the potential adaptation of humans to the specific environment of the dry-hot valley. The river valley is suitable for rice agriculture because this crop requires considerable amounts of water. In contrast, the hillside far away from the river is suitable for millet agriculture, as dry conditions are preferable for the cultivation of this crop. Furthermore, ancient humans likely relied on millet agriculture because the Jinshajiang River Valley was predominantly hot and dry, with only a limited area on the waterfront suitable for rice production.

Nitrogen isotopes are typically used to measure protein consumption (Hu et al., 2008; Ma et al., 2015; Cheung et al., 2017). The δ^{15}N value for humans at the Jiangxifen site ranged from 5.9 to 12.4‰, indicating diverse protein sources. The shift of 5.2‰ in the mean δ^{15}N value between humans and herbivores suggested that humans may have consumed a large amount of animal protein, including fish from the Jinshajiang River. However, only one bovid collagen sample was available to assess the human consumption of animal protein in the present study; therefore, future studies should also assess herbivore δ^{15}N values to confirm our findings.

Spatial Pattern of Human Subsistence Strategies and Influencing Factors Thereof in Yunnan Province During the Bronze Age

To study the spatial pattern of human subsistence strategies in different environments of Yunnan, we compared the isotopic evidence at the Shilinggang, Jinlianshan, and Jiangxifen sites, all of which have similar chronologies (Zhang, 2011; Liu, 2016; Ren et al., 2017). The average δ^{13}C value for human bones at the Shilinggang site (-18.7 ± 0.9‰) was significantly more negative than that at the Jiangxifen site ($p = 0.000$, **Table 4**), indicating a higher consumption of C_3 foods. According to the archeobotanical studies carried out at Shilinggang (Li et al., 2016; Zhang et al., 2017), humans cultivated both rice and millets, as well as some plants with underground storage organs, such as tubers, roots, and rhizomes. The annual average temperature and precipitation at the Shilinggang site are ~21°C and 1,100–1,200 mm, respectively (Li et al., 2016); thus, the climate of this

TABLE 4 | Comparison of results of the human bone collagen isotope from archaeological sites in Yunnan.

Site	Age	Number	δ^{13}C (‰)		δ^{15}N (‰)		References
			Average	Range	Average	Range	
Jiangxifen	~900~400 BC	65	−14.2 ± 1.6‰	−18.6‰ ~ −9.4‰	9.8 ± 1.0‰	5.9‰ ~ 12.4‰	This study
Shilinggang	~950~350 BC	48	−18.7 ± 0.9‰	−20.0‰ ~ −14.9‰	9.7 ± 1.5‰	3.9‰ ~ 11.9‰	Li et al., 2016; Liu, 2016; Ren et al., 2017
Jinlianshan	~500 BC~220 AD	9	−18.8 ± 0.4‰	−19.3‰ ~ −18.2‰	9.8 ± 0.9‰	8.8‰ ~ 11.4‰	Zhang, 2011

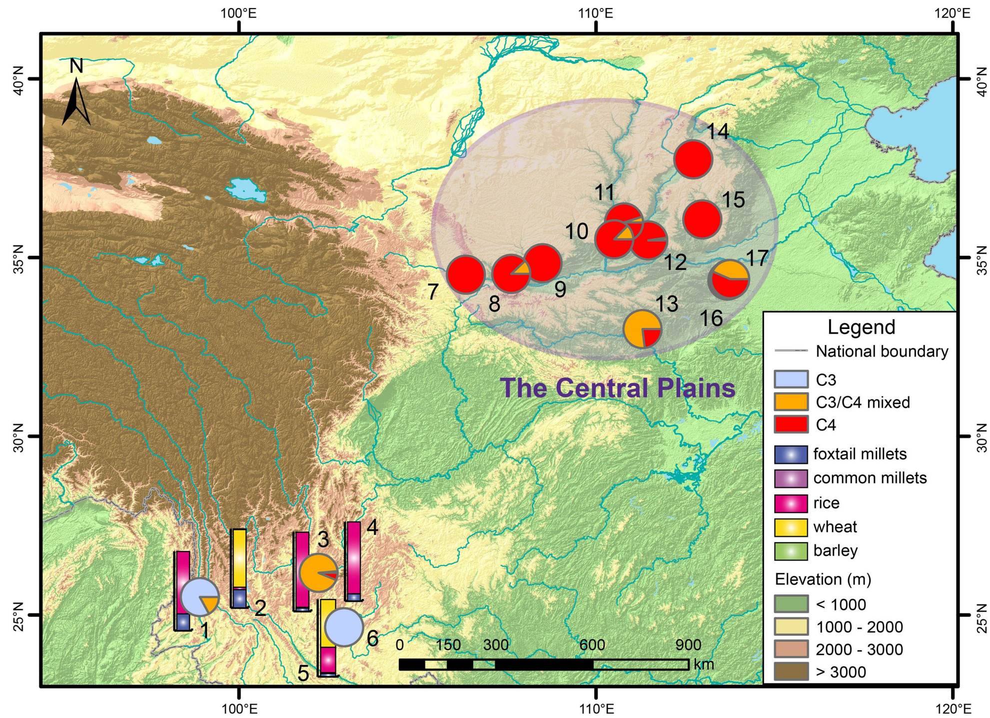

FIGURE 4 | Comparison of human C isotope values and frequency index of the crop remains at the Jiangxifen site and other contemporaneous sites in Yunnan (Xue, 2010; Zhang, 2011; Wang, 2014; Yao et al., 2015; Li and Liu, 2016; Li et al., 2016; Liu, 2016; Yang, 2016; Ren et al., 2017; Dal Martello et al., 2021) and the Central Plains (Pei et al., 2008; Ling et al., 2010a,b; Chen, 2012; Hou et al., 2012; Dong et al., 2017; Lan, 2017; Zhou et al., 2017; Tang et al., 2018; Sun, 2019; Li et al., 2020): (1) Shilinggang; (2) Haimenkou; (3) Jiangxifen; (4) Yubeidi; (5) sites around Dian and Fuxianhu Lake (including Dayingzhuang, Hebosuo, Anjiang, Xiaogucheng, Guangfentou, and Xueshan); (6) Jinlianshan; (7) Jianhe; (8) Sunjianantou; (9) Zaoshugounao; (10) Liangdaicun; (11) Neiyangyuan; (12) Hengshui; (13) Shenmingpu; (14) Xiaonanzhuang; (15) Xinancheng; (16) Changxinyuan; and (17) Xiyasi.

site is wetter and cooler than that of Jiangxifen. Accordingly, humans mainly consumed C_3 foods, with a little supplement from C_4 foods (likely millets). The age of the Jinlianshan site overlaps with that of the Jiangxifen site (Jiang and Wu, 2011). The δ^{13}C value for the human bone collagen at the Jinlianshan site was found to range from −19.3 to 18.2‰, suggesting that humans mainly consumed C_3 foods. This finding is significantly different from the findings at the Jiangxifen site (p = 0.000, **Table 4**). Unearthed plant remains from the Xueshan site (which is located near the Jinlianshan site and has a similar chronology) indicated that humans cultivated wheat, rice, barley, and millets in that area (Wang, 2014). Wheat and rice were the main crops at the Jinlianshan site. The δ^{13}C values obtained from enamel samples at the Shamaoshan site, a contemporaneous site near the Jinlianshan site, also suggested that humans mainly consumed C_3 foods in this area (Wu et al., 2019). In contrast to the hot-dry valley of the Jinshajiang River, the Jinlianshan and Shamaoshan sites are located in lake basins and are therefore more humid, indicating that there were sufficient water sources for wheat and rice cultivation.

Previous archeobotanical research has revealed differences in agricultural practices among various regions of Yunnan (**Figure 4**). The number of wheat seeds identified during the third phase of the Haimenkou site accounted for 73% of the total number of seeds from unearthed crops (Xue, 2010). In contrast, no wheat seeds were unearthed at the Jiangxifen, Shilinggang, and Yubeidi sites during the same period. Rivers and lakes with abundant water were convenient for imported wheat agriculture (Xue, 2010). Moreover, the high mountains and deep valleys in Yunnan may have hindered human migration and cultural exchanges among different regions during the Bronze Age. This may have been the main reason for the lack of wheat remains at the Jiangxifen and Shilinggang sites. Wheat and rice were the main crops in the sites around Dian and Fuxian lakes (**Figure 4**). The terrain around Dian and Fuxian lakes is flat, and the water resources are sufficient for wheat and rice cultivation.

Furthermore, tomb types and artifact assemblages unearthed from the Bronze Age sites in different regions of Yunnan Province exhibited different characteristics (Fan, 2007). These characteristics can be used to divide Yunnan into multiple cultural regions (He, 2003; Ao, 2015), further highlighting the effect of the fragmented landscape on cultural evolution (including dietary patterns) of humans during the Bronze Age. Casting processes, vessel types, and patterns of bronze ware differed among cultural regions (Fan, 2007). For example, the bronze wares unearthed in the sites around Dian Lake have complex casting techniques and diverse patterns, whereas the bronze wares from the Erhai Lake have simple casting techniques and fewer patterns. The bronze wares unearthed in northwest Yunnan have a considerable relationship with North China (Fan, 2007). In addition, the tomb type at the Wanjiaba site, which is a site near Dian Lake, is completely different from the tomb type in northwest Yunnan (He, 2003).

In contrast to the spatial heterogeneity of human livelihoods in Yunnan, the Zhou Dynasty sites in the Central Plains (∼1,046–256 BC) are revealed by isotopic evidence to have homogenous spatial characteristics in terms of human diet and subsistence (**Figure 4**). Millet crops were generally the dominant food source, whereas other crops, including wheat, rice, and soybean, were complementary food sources (Zhao, 2014; Zhou et al., 2017; Tao et al., 2020). As shown in **Figure 4**, the C isotopes of human bones from Zhou Dynasty sites in the Central Plains indicated that most individuals consumed C_4 foods (likely millets and their by-products), with only a small number of individuals consuming mixed C_4 and C_3 foods. The differences in human dietary patterns between Yunnan and the Central Plains might have been caused by the diversity of geomorphological features. Yunnan is located on the Yunnan–Guizhou Plateau; this terrain is high in the northwestern part and low in the southeastern part, with great undulations. The presence of large rivers, alternating mountains, and valleys is the reason for the high terrain fragmentation in Yunnan (Nie et al., 2008). Geomorphological features in the Central Plains are significantly different from those in Yunnan Province. Although the landform types in the Central Plains are complex, with high mountains and large plains, archeological sites are mostly distributed in the flat river valley areas (**Figure 4**). Stream networks in the middle reaches of the Yellow River facilitated human migration and cultural communication among different geographical units, and the area was controlled by a nominally unified regime (the Zhou Imperial Court). For this reason, human subsistence practice was based primarily on millet cultivation. The same social phenomenon did not occur in Yunnan until more recent historical periods; however, it is unclear whether the spatial pattern of subsistence also transformed synchronously. Therefore, this topic should be investigated further in future studies.

CONCLUSIONS

Based on C and N isotopic results and archeobotanical evidence, we concluded that humans in the Jiangxifen site consumed both C_3-based (rice and C_3 food-fed animal protein) and C_4-based food (millet and C_4 food-fed animal protein) during the period of ∼900–400 BC, with a preference for C_4-based food. The local environment in the dry-hot valley of the Jinshajiang River provided favorable conditions for millet and rice growth, which was the primary factor influencing food choice in this valley. When we compared our results with previously published isotopic data and archeobotanical evidence in contemporaneous sites of Yunnan Province, we were able to identify notable spatial discrepancies in human livelihoods in the Bronze Age in Yunnan. In this period, various crops and livestock were introduced to Yunnan Province; however, the highly fragmented geomorphological setting of the region significantly hindered trans-regional exchange. Therefore, prior to the development of a strong transportation network, local environmental settings (especially hydrothermal conditions) had a significant impact on local human diets and livelihoods in different parts of Yunnan Province.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

MM and ML: formal analysis and writing and editing. MM: funding acquisition and supervision. XL: resources. WW, YL, and LR: sample collection. ML, WW, YL, and LR: methodology. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2021.662053/full#supplementary-material

REFERENCES

Ambrose, S. H. (1990). Preparation and characterization of bone and tooth collagen for isotopic analysis. *J. Archaeol. Sci*. 17, 431–451. doi: 10.1016/0305-4403(90)90007-R

Ao, S. (2015). On early Bronze culture in Yunnan (in Chinese with English Abstract). Master's thesis Yunnan. Yunnan University.

Cao, J., Hu, J. M., and Tao, Y. (2012). An index for the interface between the Indian summer monsoon and the East Asian summer monsoon. *J. Geophys. Res. Atmos*. 117:D18108. doi: 10.1029/2012JD017841

Cao, M., and Jin, Z. Z. (1989). Classification of vegetation in Qiaojia dry-hot rier valley of Jinsha river, Yunnan (in Chinese). *Acta Botanica Yunnanica* 11, 324–336.

Chen, F. H., Dong, G. H., Zhang, D. J., Liu, X. Y., Jia, X., An, C. B., et al. (2015). Agriculture facilitated permanent human occupation of the Tibetan Plateau after 3600 BP. *Science* 347, 248–250. doi: 10.1126/science.1259172

Chen, X. (2012). Study on the bone chemistry characteristics of human bones unearthed in the Western Zhou Dynasty from Ruiguo Cemetery in Liangdai Village (in Chinese with English Abstract). [master's thesis] [Shaanxi]: Northwestern University.

Cheung, C., Jing, Z. C., Tang, J. G., Weston, D. A., and Richards, M. P. (2017). Diets, social roles, and geographical origins of sacrificial victims at the royal cemetery at Yinxu, Shang China: new evidence from stable carbon, nitrogen, and sulfur isotope analysis. *J. Anthropol. Archaeol*. 48, 28–45. doi: 10.1016/j.jaa.2017.05.006

Cheung, C., Zhang, H., Hepburn, J. C., Yang, D. Y., and Richards, M. P. (2019). Stable isotope and dental caries data reveal abrupt changes in subsistence economy in ancient China in response to global climate change. *PLoS ONE* 14:e0218943. doi: 10.1371/journal.pone.0218943

Cui, L. L., Hu, J. F., and Wang, X. (2019). Spatiotemporal evolution of C 3/C 4 vegetation and its controlling factors in southern China since the last glacial maximum. *Sci. China Earth Sci.* 62, 1256–1268. doi: 10.1007/s11430-018-9225-9

Cui, L. L., Wang, X., Shen, J., and Ding, Z. L. (2015). Changes in distribution and compound-specific carbon isotope compositions of *n*-alkanes as recorded in Lugu Lake sediments from Southwestern China since Last Glacial Maximum and implications for paleovegetation evolution (in Chinese with English Abstract). *Quat. Sci*. 35, 871–880. doi: 10.11928/j.issn.1001-7410.2015.04.09

Dal Martello, R., Li, X. R., and Fuller, D. Q. (2021). Two-season agriculture and irrigated rice during the Dian: radiocarbon dates and archaeobotanical remains from Dayingzhuang, Yunnan, Southwest China. *Archaeol. Anthropol. Sci*. 13. doi: 10.1007/s12520-020-01268-y

Dal Martello, R., Min, R., Stevens, C., Higham, C., Higham, T., and Qin, L., et al. (2018). Early agriculture at the crossroads of China and Southeast Asia: Archaeobotanical evidence and radiocarbon dates from Baiyangcun, Yunnan. *J. Archaeol. Sci. Rep*. 20, 711–721. doi: 10.1016/j.jasrep.2018.06.005

d'Alpoim Guedes, J., Lu, H. L., Li, Y. X., Spengler, R. N., Wu, X. H., and Aldenderfer, M. S. (2014). Moving agriculture onto the Tibetan plateau: the archaeobotanical evidence. *Archaeol. Anthropol. Sci*., 6, 255–269. doi: 10.1007/s12520-013-0153-4

DeNiro, M. J. (1985). Postmortem preservation and alteration of *in vivo* bone collagen isotope ratios in relation to palaeodietary reconstruction. *Nature* 317, 806–809. doi: 10.1038/317806a0

Dong, G. H., Li, R., Lu, M. X., Zhang, D. J., and James, N. (2020). Evolution of human–environmental interactions in China from the Late Paleolithic to the Bronze Age. *Prog. Phys. Geogr. Earth Environ.* 44, 233–250. doi: 10.1177/0309133319876802

Dong, G. H., Li, T., Zhang, S. J., Ren, L. L., Li, R., Li, G. Q., et al. (2021). Precipitation in surrounding mountains instead of lowlands facilitated the prosperity of ancient civilizations in the eastern Qaidam Basin of the Tibetan Plateau. *Catena* 203:105318. doi: 10.1016/j.catena.2021.105318

Dong, Y., Morgan, C., Chinenov, Y., Zhou, L. G., Fan, W. Q., and Ma, X. L., et al. (2017). Shifting diets and the rise of male-biased inequality on the Central Plains of China during Eastern Zhou. *Proc. Natl. Acad. Sci. U.S.A.* 114, 932–937. doi: 10.1073/pnas.1611742114

Fan, Y. (2007). A Study on the Floristic Types of Bronze Culture in Yunnan Province (in Chinese). Sichuan Cultural Relics, 64–73.

Gao, Y., Dong, G. H., Yang, X. Y., and Chen, F. H. (2020). A review on the spread of prehistoric agriculture from southern China to mainland Southeast Asia. *Sci. China Earth Sci.* 63, 615–625. doi: 10.1007/s11430-019-9552-5

Hanks, B., Miller, A. V., Judd, M., Epimakhov, A., Razhev, D., and Privat, K. (2018). Bronze Age diet and economy: New stable isotope data from the Central Eurasian steppes (2100-1700 BC). *J. Archaeol. Sci*. 97, 14–25. doi: 10.1016/j.jas.2018.06.006

He, J. M. (2003). A preliminary study on regional systems of Bronze cultures in Yunnan (in Chinese with English Abstract). [master's thesis] [Shaanxi]: Northwest University.

Hou, L. L., Wang, N., Lü, P., Hu, Y. W., Song, G. D., and Wang, C. S. (2012). Transition of human diets and agricultural economy in Shenmingpu Site, Henan, from the Warring States to Han Dynasties. *Sci. China Earth Sci*. 55, 975–982. doi: 10.1007/s11430-012-4409-0

Hou, Y. F., Campbell, R., Zhang, Y., and Li, S. T. (2019). Animal use in a Shang Village: the Guandimiao zooarchaeological assemblage. *Int. J. Osteoarchaeol*. 29, 335–345. doi: 10.1002/oa.2745

Hu, Y. W., Wang, S. G., Luan, F. S., Wang, C. S., and Richards, M. P. (2008). Stable isotope analysis of humans from Xiaojingshan site: implications for understanding the origin of millet agriculture in China. *J. Archaeol. Sci*. 35, 2960–2965. doi: 10.1016/j.jas.2008.06.002

Isaakidou, V., and Halstead, P. (2018). "Carcasses, ceramics and cooking in Makriyalos I: towards an integrated approach to human diet and commensality in Late Neolithic northern Greece," in *Social Dimensions of Food in the Prehistoric Balkans*, ed. Ivanova, M., Athanassov, B., Petrova, V., Takorova, D., and Stockhammer, P.W. (Oxford: Oxbow Books), 66–85. doi: 10.2307/j.ctvh1dsx3.8

Jiang, Z. L., and Wu, J. (2011). A Preliminary Research on the Jinlinshan Cemetery (in Chinese with English Abstract). *Res. China's Front. Archaeol*. 208–214.

Jin, H. T., Liu, X., Min, R., Li, X. R., and Wu, X. H. (2014). A study on flotation result of plant remains in the dadunzi site of Yuanmou, Yunan (in Chinese with English Abstract). *Jianghan Archaeol*. 132, 109–114.

Jin, Z. Z. (1999). The floristic study on seed plants in the dry-hot valleys in Yunnan and Sichuan (in Chinese). *Guihaia* 19, 1–14.

Jin, Z. Z., and Ou, X. K. (2000). Vegetation in dry-hot valleys of Yuanjiang, Nujiang, Jinshajiang, and Lancangjiang River (in Chinese). Kunming: Yunnan University Press and Yunnan Science and Technology Press.

Kohn, M. J. (1999). You are what you eat. *Science* 283, 335–336. doi: 10.1126/science.283.5400.335

Lan, D. (2017). Isotope analysis on Human and Animal's Bone Unearthed from Zaoshugounao Site in Chunhua County, Shaanxi Province (in Chinese with English Abstract). [master's thesis] [Shaanxi]: Northwestern University.

Li, H. M., Zuo, X. X., Kang, L. H., Ren, L. L., Liu, F. W., Liu, H. G., et al. (2016). Prehistoric agriculture development in the Yunnan-Guizhou Plateau, southwest China: archaeobotanical evidence. *Sci. China Earth Sci*. 59, 1562–1573. doi: 10.1007/s11430-016-5292-x

Li, P. R., Meng, G. T., Fang, X. J., and Zeng, J. M. (2009). Flora of seed plants in Wuding county, Yunnan (in Chinese with English Abstract). *J. Northeast For. Univ*. 37, 106–108.

Li, X., Zhang, S. J., Lu, M. X., Qiu, M. H., Wen, S. Q., and Ma, M. M. (2020). Dietary shift and social hierarchy from the Proto-Shang to Zhou Dynasty in the Central Plains of China. *Environ. Res. Lett*. 15:035002. doi: 10.1088/1748-9326/ab6783

Li, X. R., and Liu, X. (2016). Flotation report on the analysis on the archaeobotanical remains from the site of Guangfentou, Jiangchuan, Yunnan (in Chinese). *Agric. Archaeol*. 3, 20–27.

Ling, X., Chen, L., Tian, Y. Q., Li, Y., Zhao, C. C., and Hu, Y. W. (2010a). Carbon and nitrogen stable isotopic analysis on human bones from the qin tomb of sunjianantou site, Fengxiang, Shaanxi Province (in Chinese with English Abstract). *Acta Anthropol. Sin*. 29, 54–61.

Ling, X., Wang, W. S., Chen, L., Sun, L. J., and Hu, Y. W. (2010b). Stable Isotope Analysis of Qin Human Bones from Jianhe Cemetery in Baoji City, Shaanxi Province (in Chinese with English Abstract). Archaeol. Cultural Relics, 95–98.

Liu, H. G. (2016). Human activities and agriculture resources utilization from Paleolithic to Bronze Age in northwest Yunnan province (in Chinese with English Abstract). [dissertation thesis]. [Lanzhou]: Lanzhou University.

Ma, M., Dong, G., Liu, X., Lightfoot, E., Chen, F., Wang, H., et al. (2015). Stable isotope analysis of human and animal remains at the Qijiaping site in middle Gansu, China. *Int. J. Osteoarchaeol*. 25, 923–934. doi: 10.1002/oa.2379

Ma, M. M., Dong, G. H., Jia, X., Wang, H., Cui, Y. F., and Chen, F. H. (2016). Dietary shift after 3600 cal yr BP and its influencing factors in northwestern China: evidence from stable isotopes. *Quat. Sci. Rev*. 145, 57–70. doi: 10.1016/j.quascirev.2016.05.041

Nelson, D. M., Hu, F. S., Tian, J., Stefanova, I., and Brown, T. A. (2004). Response of C3 and C4 plants to middle-Holocene climatic variation near the prairie–forest ecotone of Minnesota. *Proc. Natl. Acad. Sci. U.S.A.* 101, 562–567. doi: 10.1073/pnas.0307450100

Nie, X., Chen, Q. H., and Wu, L. L. (2008). Method of showing the grade of terrain broken based on the DEM. *Geospatial Inf*. 6, 62–64. doi: 10.3969/j.issn.1672-4623.2008.06.020

Ou, X. K. (1994). Resource plants and their ecological characteristics in the dry- hot valley of the Jinshajiang River (in Chinese). *J. Plant Resour. Environ*. 3, 42–46.

Pei, D. M., Hu, Y. W., Yang, Y. M., Zhang, Q. C., Zhang, G. W., Tian, J. W., et al. (2008). Paleodietary analysis of humans from the neiyangyuan site of Xiangning, Shanxi Province (in Chinese with English Abstract). *Acta Anthropol. Sin*. 27, 379–384.

Ramsey, C. B. (2017). Methods for summarizing radiocarbon datasets. *Radiocarbon* 59, 1809–1833. doi: 10.1017/RDC.2017.108

Reimer, P. J., Austin, W. E., Bard, E., Bayliss, A., Blackwell, P. G., Ramsey, C. B., et al. (2020). The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon* 62, 725–757. doi: 10.1017/RDC.2020.41

Ren, L. L., Dong, G. H., Liu, F. W., d'Alpoim-Guedes, J., Flad, R. K., Ma, M. M., et al. (2020). Foraging and farming: archaeobotanical and zooarchaeological evidence for Neolithic exchange on the Tibetan Plateau. *Antiquity* 94, 637–652. doi: 10.15184/aqy.2020.35

Ren, L. L., Li, X., Kang, L. H., Brunson, K., Liu, H. G., Dong, W. M., et al. (2017). Human paleodiet and animal utilization strategies during the Bronze Age in northwest Yunnan Province, southwest China. *PLoS ONE* 12:e0177867. doi: 10.1371/journal.pone.0177867

Richards, M. P. (2015). Stable isotope analysis of bone and teeth as a means for reconstructing past human diets in Greece. *Hesperia Suppl*. 49, 15–23. Available online at: www.jstor.org/stable/24637309

Richards, M. P., and Hedges, R. E. M. (1999). Stable isotope evidence for similarities in the types of marine foods used by Late Mesolithic humans at sites along the Atlantic coast of Europe. *J. Archaeol. Sci*. 26, 717–722. doi: 10.1006/jasc.1998.0387

Shi, H. Y., and Chen, J. (2018). Characteristics of climate change and its relationship with land use/cover change in Yunnan Province, China. *Int. J. Climatol*. 38, 2520–2537. doi: 10.1002/joc.5404

Sun, W. (2019). Carbon and nitrogen stable isotope of the human and animal bones from the Hengshui cemetery (in Chinese with English Abstract). [master's thesis] [Shanxi]: Shanxi University.

Svyatko, S. V., Schulting, R. J., Mallory, J., Murphy, E. M., Reimer, P. J., Khartanovich, V. I., et al. (2013). Stable isotope dietary analysis of prehistoric populations from the Minusinsk Basin, Southern Siberia, Russia: a new chronological framework for the introduction of millet to the eastern Eurasian steppe. *J. Archaeol. Sci*. 40, 3936–3945. doi: 10.1016/j.jas.2013.05.005

Tang, M., Wang, X. Y., Hou, K., and Hou, L. L. (2018). Carbon and nitrogen stable isotope of the human bones from the Xiaonanzhuang cemetery, Jinzhong, Shanxi: A preliminary study on the expansion of wheat in ancient Shanxi, China (in Chinese with English Abstract). *Acta Anthropol. Sin.* 37, 318–330. doi: 10.16359/j.cnki.cn11-1963/q.2018.0013

Tao, D. W., Zhang, G. W., Zhou, Y. W., and Zhao, H. Z. (2020). Investigating wheat consumption based on multiple evidences: Stable isotope analysis on human bone and starch grain analysis on dental calculus of humans from the Laodaojing cemetery, Central Plains, China. *Int. J. Osteoarchaeol*. 30, 594–606. doi: 10.1002/oa.2884

Wang, Q. (2014). Plant Macrofossil Analysis of Xueshan Site in Chengjiang County of Yunnan Province (in Chinese with English Abstract). [master's thesis] [Shandong]: Shandong University.

Ward, J. K., Tissue, D. T., Thomas, R. B., and Strain, B. R. (1999). Comparative responses of model C3 and C4 plants to drought in low and elevated CO2. *Global Change Biol*. 5, 857–867. doi: 10.1046/j.1365-2486.1999.00270.x

Wu, X. T., Hein, A., Zhang, X. X., Jin, Z. Y., Wei, D., Huang, F., et al. (2019). Resettlement strategies and Han imperial expansion into southwest China: a multimethod approach to colonialism and migration. *Archaeol. Anthropol. Sci.* 11, 6751–6781. doi: 10.1007/s12520-019-00938-w

Xiao, X. Y., Haberle, S. G., Li, Y. L., Liu, E., Shen, J., Zhang, E., et al. (2018). Evidence of Holocene climatic change and human impact in northwestern Yunnan Province: High-resolution pollen and charcoal records from Chenghai Lake, southwestern China. *Holocene* 28, 127–139. doi: 10.1177/0959683617715692

Xiao, X. Y., Haberle, S. G., Shen, J., Yang, X. D., Han, Y., Zhang, E., et al. (2014). Latest Pleistocene and Holocene vegetation and climate history inferred from an alpine lacustrine record, northwestern Yunnan Province, southwestern China. *Quat. Sci. Rev*. 86, 35–48. doi: 10.1016/j.quascirev.2013.12.023

Xiao, X. Y., Yao, A., Hillman, A., Shen, J., and Haberle, S. G. (2020). Vegetation, climate and human impact since 20 ka in central Yunnan Province based on high-resolution pollen and charcoal records from Dianchi, southwestern China. *Quat. Sci. Rev*. 236:106297. doi: 10.1016/j.quascirev.2020.106297

Xue, Y. N. (2010). Pilot study of plant remains about Haimenkou site in Jianchuan County, Yunnan Province (in Chinese with English Abstract). [master's thesis] [Beijing]: Peking University.

Yang, L. X. (2006). Status Quo of Afforestation in Dry &Hot River Valley of Wudin County and Countermeasures for the Development (in Chinese with English Abstract). *For. Inventory Plann*. 31, 101–105. doi: 10.3969/j.issn.1671-3168.2006.06.024

Yang, W. (2016). The analysis of charred plant remains at Hebosuo site and Yubeidi site in Yunnan province(in Chinese with English Abstract). [master's thesis]. [Shandong]: Shandong University.

Yao, A., Jiang, Z. L., Chen, X. X., and Liang, Y. (2015). Bronze age wetland/scapes: complex political formations in the humid subtropics of southwest China, 900–100 BC. *J. Anthropol. Archaeol*. 40, 213–229. doi: 10.1016/j.jaa.2015.08.005

Yuan, J. (2015). *Zooarchaeology in China (in Chinese)*. Beijing: Cultural Relics Press.

Yunnan Institute of Cultural Relics and Archaeology (2019). Jiangxifen site, Wuding, Yunnan, China (in Chinese). Available online at: http://www.ynkgs.com/html/discover/20190828103752.htm (accessed January 1, 2021).

Zhang, G. W., Jiang, L. P., Hu, Y. W., Si, Y., Lv, P., Song, G. D., et al. (2015). C, N stable isotope analysis of human and animal bones at Tashan site in Zhejiang (in Chinese with English Abstract). *Huaxia Archaeol*. 2, 138–146. doi: 10.16143/j.cnki.1001-9928.2015.02.015

Zhang, J. Y., Xu, Y., Su, C. J., and Liu, X. L. (2005). Research progress on vegetation restoration in the dry-hot valleys of the Jinsha River (in Chinese with English Abstract). *Res. Soil Water Conserv*. 12, 101–104.

Zhang, N. M., Dong, G. H., Yang, X. Y., Zuo, X. X., Kang, L. H., Ren, L. L., et al. (2017). Diet reconstructed from an analysis of plant microfossils in human dental calculus from the Bronze Age site of Shilinggang, southwestern China. *J. Archaeol. Sci*. 83, 41–48. doi: 10.1016/j.jas.2017.06.010

Zhang, Q. C. (2011). Preliminary analysis of stable isotopes of human bones unearthed from Jinlianshan Cemetery in Chengjiang County, Yunnan (in Chinese). *Archaeology* 30–33.

Zhang, X. X., Burton, J., Jin, Z. Y., Xiao, M. H., Fan, A. C., and Xu, J. F. (2014). Isotope studies of human remains from Mayutian, Yunnan Province, China. *J. Archaeol. Sci*. 50, 414–419. doi: 10.1016/j.jas.2014.08.001

Zhao, Z. J. (2014). The process of origin of agriculture in China: Archaeological evidence from flotation results (in Chinese). *Quat. Sci.* 34, 73–84. doi: 10.3969/j.issn.1001-7410.2014.01.10

Zheng, X., Zhang, H. C., Ming, Q. Z., Chang, F. Q., Meng, H. W., Zhang, W. X., et al. (2014). Vegetational and environmental changes since 15ka B.P. recorded by lake Lugu in the southwest monsoon domain region (in Chinese with English Abstract). *Quat. Sci*. 34, 1314–2014. doi: 10.3969/j.issn.1001-7410.2014.06.21

Zhou, L. G., and Garvie-Lok, S. J. (2015). Isotopic evidence for the expansion of wheat consumption in northern China. *Archaeol. Res. Asia* 4, 25–35. doi: 10.1016/j.ara.2015.10.001

Zhou, L. G., Garvie-Lok, S. J., Fan, W. Q., and Chu, X. L. (2017). Human diets during the social transition from territorial states to empire: stable isotope analysis of human and animal remains from BCE to 220 CE on the central plains of china. *J. Archaeol. Sci. Rep*. 11, 211–223. doi: 10.1016/j.jasrep.2016.11.019

Zhou, X. Y., Li, X. Q., Dodson, J., and Zhao, K. L. (2016). Rapid agricultural transformation in the prehistoric Hexi corridor, China. *Quat. Int*. 426, 33–41. doi: 10.1016/j.quaint.2016.04.021

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Agriculture, the Environment, and Social Complexity From the Early to Late Yangshao Periods (5000–3000 BC): Insights From Macro-Botanical Remains in North-Central China

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In northern China, the Yangshao cultural period (5000–3000 BC) was a critical timespan in the establishment of agricultural economies and the emergence of social complexity. We present the results of archeobotanical analysis from 58 soil samples collected from 12 recently investigated sites located in the Luoyang Basin, and recovered 5290 carbonized plant remains from 9 sites dating to the Late Yangshao period. We compared our novel dataset with previous archeobotanical date, compiling a total of 196 samples from 58 sites in central and western Henan Province. During the Early Yangshao period (5000–4200 BC), a nascent, extensive agricultural economy based primarily on broomcorn millet, with lesser foxtail millet and rice, was developing in small settlements (<0.2 km^2) in the loess tablelands and valleys of western Henan province. However, the population pressure—rather than environmental degradation—drove the "foxtail millet-broomcorn millet substitution" during the Middle Yangshao period (4200–3500BC). The intensive agriculture based mainly on foxtail millet facilitated the development of social complexity in the region, as demonstrated by the emergence of size-graded agricultural settlements of medium (0.2–0.6 km^2) and large (> 0.6 km^2) scale. Notably, millets tend to be less ubiquitous in these larger settlements compared to smaller ones, with differences in millet ubiquity between sites increasing over time. The local surface hydrology influenced by paleoclimatic changes prompted the spread of agriculture from higher loess tablelands and valleys during the early Yangshao period into more marginal loess tablelands and plains by the Middle and Late Yangshao periods. Rice cultivation is concentrated in valley areas and appears to have been closely tied to environments with better hydrothermal conditions. Our research shows that climatic conditions during the Holocene fostered the development of agriculture during the Yangshao Culture period and that the distribution of settlements throughout this time was influenced by highly localized geomorphologic environments delimiting the distribution of crops. The rise of agriculture promoted the formation of complex and stratified economies in the Yangshao Culture period and it was the intensification and elaboration of these new economic and social systems that led to later transformation in agricultural structures and settlement sizes.

Keywords: central and western Henan Province, Yangshao Culture, foxtail millet-broomcorn millet substitution, Valley-Rice Planting, paleoenvironment, social complexity

INTRODUCTION

The emergence of social complexity—or the process by which a society transitions from relatively simple to more complex forms of economic and social organization—has long been a subject of considerable interest and debate among archaeologists. Socially complex societies are generally associated with large and dense populations, urbanism, socio-economic specialization, and the appearance of social hierarchies and inequality (Adams, 2001; Smith, 2009; Feinman, 2011). Almost simultaneously, around 3500 BC dramatic changes to social and economic organization were occurring in many regions of the world (Sandweiss et al., 1999; Brooks, 2006; Liu and Chen, 2012; Luan, 2012) and archeological evidence of pronounced cultural differentiation as well as enhanced inter-community communication and exchange (Han, 2015) attest to similar transformations underway in China, with indications of increasing social complexity becoming more and more obvious through time (Zhao, 2001; Chen et al., 2003; Liu, 2005; Liu and Chen, 2012; Dai, 2012).

Characterized by a significant increase in settlements and the advent of mature millet cultivation practices in the Loess Plateau (Barton et al., 2009), the Yangshao Culture period (5000–3000 BC) is recognized as a critical timespan for understanding the rise of complex and socially stratified agricultural societies in Neolithic northern China (Zhao, 2001; Chen et al., 2003; Liu, 2005; Dai, 2012; Luan, 2012; Wagner et al., 2013). The critical interval of rapid cultural development and population growth that marks the initial rise and expansion of the Yangshao Culture in the Neolithic is often attributed to the warm and humid climatic conditions of the mid-Holocene Megathermal period—also termed the "Yangshao Warm Period" (Shi et al., 1992; Xia et al., 2001)—which is hypothesized to have facilitated the emergence of agricultural economies at this time (Wang J. H., 2005; Wang X. G., 2005; Gao, 2009; Zhao, 2014; Han, 2015).

In Henan province, social development has been characterized as a transition from initially egalitarian organization during the Early period (5000–4200 BC) that gradually becomes more complex, eventually transforming into a stratified society by the Middle and Late Yangshao periods (4200–3000 BC) (Zhao, 2001; Dai, 2012). Concurrent with these striking social changes was a transition away from hunting and gathering and the establishment of a subsistence economy based on the cultivation of domestic crops. This transition is demonstrated by a growing number of archeobotanical studies using both macro and micro-botanical plant remains that provide evidence for increasing dependence on foxtail (*Setaria italica*) and broomcorn (*Panicum miliaceum*) millets throughout the Yangshao cultural period, culminating with these small domesticated grains becoming the foundation for Yangshao food production systems and representing the early formation of a mature agricultural system based on domestic millets (Lee et al., 2007; Zhao, 2014, 2017; Zhang et al., 2014; Wang, 2016; Zhong et al., 2020; Yang et al., 2020).

Social complexity has long been considered to be directly related to economic production systems (Tylor, 1958; Service, 1962; Mogan, 1963; Fried, 1967). For example, case studies from Southern Levant (Kuijt and Goring-Morris, 2002), Northern Negev of Israel (Winter-Livneh et al., 2010), and southwestern Asia (Algaze, 2001) have demonstrated the intimate connection between agriculture and social complexity. While the development of agriculture has been recognized as having a profound impact on complexification processes during the Yangshao Culture period (Yan, 1989; Gao, 2009; Cao, 2013; Han, 2015; Dai, 2016), discussions of how this is evinced in archeobotanical evidence from this period have been lacking in detail.

Additionally, factors constraining or facilitating the development of the agricultural practices associated with these social transformations are complex, which have been proposed by scholars as climatic changes (Dong et al., 2012; Yang et al., 2018), social complexification (Wang J. H., 2005; Gao, 2009; Zhong et al., 2020), or developments in agricultural technology (Fan, 1988; Gao, 2009; Zhao, 2018). Climate change is supposed to have a greater impact on agriculture at large spatial scales, but geomorphologic condition will be more influential at smaller, more local scales (Robert et al., 1989). Restricted by geomorphologic conditions, the distribution of prehistoric agriculture often changes with time. Studies in the Near East, for example, have shown that agriculture originates from marginal piedmont grasslands and transfers to valleys and lowlands (Binford, 1968; Flannery, 1973); Liu et al. (2009) and Ren et al. (2016) provided evidence that the distribution of both early millet in northern China and rice in southern China shifted from the foothills to the valleys. Despite a great deal of discussion surrounding the relationship between ancient agricultural developments and climate change (Jia et al., 2013; Yang et al., 2018; Zhang et al., 2018), there have been fewer studies of the relationship between agriculture and geomorphologic environments at different stages in prehistoric China (Zhang et al., 2014; Li and Zhang, 2020).

Furthermore, we know relatively little about changes regarding the agricultural economic structure or planting patterns as they occurred throughout the Yangshao period—ultimately hindering our understanding of economic conditions at this time and their relationship to cultural changes and the paleoenvironment. Situated within this gap in our understanding is ongoing debate about whether or not foxtail millet substituted broomcorn millet as the dominant staple crop across the Yangshao Culture area, and the role such a substitution would have played in the establishment of an agricultural economy (Liu et al., 2008; Han, 2015; Wang et al., 2015; Wang, 2016; Lu, 2017; Zhong et al., 2020). Foxtail millet and broomcorn millet constitute the earliest domesticated crops in northern China, dating back to more than 8,000 years ago (Zhao, 2014). Archeobotanical research has shown that initially, during the early stages of millet domestication prior to 5000 BC, broomcorn millet was the prevailing crop (Liu et al., 2008; Lu et al., 2009; Zhao, 2011, 2014). Recent evidence from charred plant remains suggests that after 5000 BC—at the onset of the Yangshao culture—foxtail millet came to replace broomcorn millet as the primary domesticated crop (Wei, 2014; Zhao, 2014, 2017; Zhong et al., 2020). This shift, however, research on phytoliths has provided evidence for the continued dominance of broomcorn millet over foxtail millet throughout the Yangshao period in northern China, complicating interpretations (Wang et al., 2015, 2019a,b; Xia et al., 2016). Why Yangshao peoples would have shifted away from broomcorn millet and focused instead on foxtail millet is a complicated question that merits further discussion and investigation. One starting point toward comprehensively addressing this question is the implementation of systematic archeobotanical research on carbonized plant macro-fossils from multiple sites representing as many temporal phases belonging to the Yangshao Culture as possible.

Based on new archeobotanical analysis of 12 sites in the Luoyang Basin, in combination with a comprehensive dataset of macro-fossil remains from central and western of Henan Province compiled from previous research, we present a comprehensive picture of agricultural development as it occurred throughout the Yangshao culture period in northern China. Using these data, we discuss structural and geographical changes in the distribution of foxtail millet, broomcorn millet, and rice as they relate to (1) paleoclimatic changes, (2) geomorphologic conditions, (3) settlement sizes, and (4) social complexity.

STUDY AREA

Environmental Settings

Our research area consists of central and western Henan Province (110°21' 114°39′ E, 33°31′ 35°05′) and is located at the transition between warm-temperate and subtropical ecozones, exhibiting a continental monsoon climate. The research area includes the Sanmenxia area, the Luoyang and Yiluo River basins, and Ying River basin (**Figure 1**).

The Sanmenxia area is located in western Henan Province, and has complex terrain consisting of mountains, loess plateaus, hills, rivers, and valleys. In addition to the Yellow River, the Luo, Hongnongjian, Qinglongjian, and Canglongjian rivers also have large tributary systems in this region. Average annual temperature is 13.9°C with annual precipitation around 550–800 mm. Soils of the Sanmenxia area are typified by obvious vertical and horizontal stratification. Fluvo-aquic soil, cinnamon soil, yellow-brown soil, and brown soil are vertically distributed sequentially from the banks of the Yellow River down to the southern mountains (LCCSC, 1997; HPICRA, 2009).

The Luoyang Basin is located in the central part of Henan Province. In terms of geomorphology, moving from north to south the Luoyang Basin consists of the loessic Mangshan Mountains and the alluvial plain of the Yiluo River Valley to the north and eroded shallow loess piedmonts to the south. The hydrological system of the Luoyang Basin is the Yi, Luo, Jian and Chan rivers. Average annual temperatures is between 12.7 and 14.6°C, with annual precipitation of about 500–650 mm (IACASS and SAACATYRV, 2019). The soils here mainly include yellow-brown soil, brown soil, cinnamon soil, carbonate cinnamon soil, fluvio-aquic soil, and mountain meadow soil (Wang, 1999).

The Ying River Basin belongs to the central part of Henan Province, which consists of mountains, hills, basins, valleys and plains. The Ying River is the largest river in this region and has a highly developed tributary system. Average annual temperature is 14°C, with average annual precipitation about 600–700 mm (HPICRA et al., 2008). The soils in this area include brown loam, leaching cinnamon, carbonate cinnamon, cinnamon, aquic cinnamon and fluvio-aquic soil (Li, 1995).

Overall, the central and western Henan Province consist of a diverse array of landforms and soil types. The climate, topography, and geomorphology of the area make it suitable for the cultivation of a variety of thermophilic crops. River terraces in this area are generally flat with abundant water resources and abundant yellow fluvio-aquic soil that is rich in organic matter, allowing for the cultivation of wheat, rice, and maize. The gently sloping loess plateau area provides for sufficient water resources and adequate drainage and consists of a porous cinnamon-colored soil that facilitates modern wheat and corn-based agriculture. In contrast, the hilly piedmont areas have limited access to water and are characterized by cinnamon-colored and carbonate soils that are nutrient poor. Modern crop production in this area consists of mainly wheat, maize, and millet (Wang, 1999).

Archeological Settings

Chinese archeology began with excavations taking place in Yangshao, Mianchi County, Henan Province in 1921 (Andersson, 2011), making this region one of the earliest centers for archeological excavations and research on Neolithic China. After several generations of archeological inquiry, the Neolithic chronology for central and western Henan province was established, beginning with the Peiligang culture, followed by theYangshao culture, and then the second phase of the Miaodigou culture—all of which made active contributions to the Neolithic archeological cultural system of Central China (Wei, 2014).

This article is concerned with agricultural developments during the Yangshao cultural period which lasted from approximately 5000 BC until 3000 BC. This can be further divided into three stages: Early Yangshao (5000–4200 BC) (Yan, 1989; Han, 2015), Middle Yangshao (4200–3500 BC) (Gao, 2009), and Late Yangshao (3500–3000 BC) (Yan, 1989; Gao, 2009; Han, 2015).

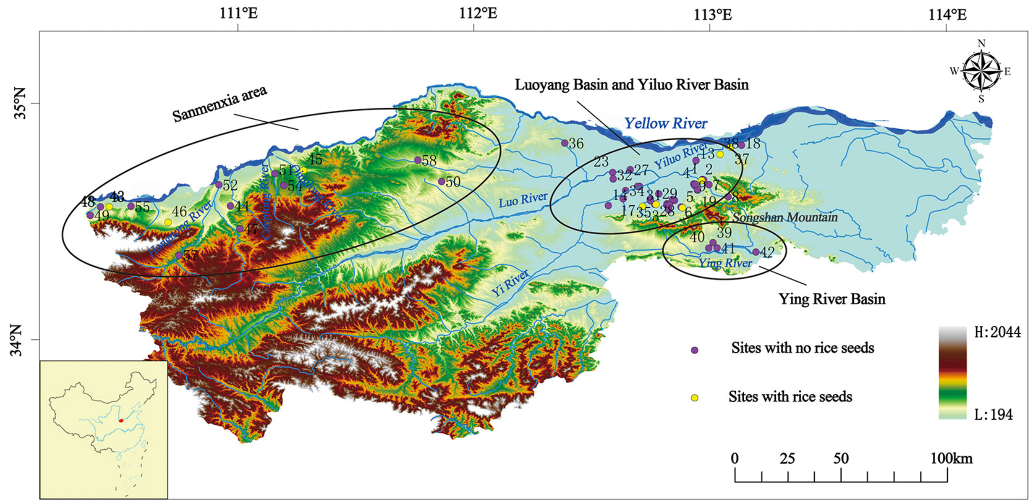

FIGURE 1 | Sites in central and western Henan Province from which remains of carbonized plants belonging to the Yangshao Culture were collected for this study. Weizhuang; 2. Weizhuang south bank of southwest River; 3. Xiqijiayao; 4. south of Yulinzhuang; 5. Zhaocheng; 6. southwest of Zhaocheng; 7. Wuluo Reservior; 8. Shangzhuang; 9. Tianpo; 10. north of Huacheng River; 11. Peicun; 12. Sanggou; 13. Nanwayao; 14. Jiuliugou Reservoir; 15. Bucun; 16. Beizhai; 17. Gongjiayao; 18. Fuxitai; 19. Tidong; 20. Longgudui; 21. Laozhouzhai; 22. Dongguanmao; 23. Xishiqiao; 24. Gaoya; 25. west of Gaoya; 26. Yulinzhuang; 27. Jingyanggang; 28. Huizui; 29. Tunzhai; 30. Waizhuang; 31. Zhaiwan; 32. Jinzhongsi; 33. Mazhai; 34. Jueshan; 35. Fujiazhai; 36. Bangou; 37. Shuanghuaishu; 38. Wanggou; 39. Yangcun; 40. Yuanqiao; 41. Yuancun; 42. Shiyangguan; 43. Didong; 44. Xiaowu; 45. Nanjiaokou; 46. Xipo; 47. Chengyan; 48. Dongqiao; 49. Dongshe; 50. Duzhong; 51. Lucun; 52. Mengcun; 53. Nanyuan; 54. Renmazhai; 55. Shangmotou; 56. Sigeda; 57. Yanzhuang; 58. Yangshao).

MATERIALS AND METHODS

Materials

In 2016, we carried out our field survey of carbonized archeobotanical remains belonging to the Yangshao period and collected samples from sites located around the Yiluo River Valley within the Luoyang Basin, including from localities near the Liujian River, Majian River, Gangou River, and other tributaries within the basin. From the exposed sections of each site, a trowel was used in the field to search for ash pits and cultural layers with a thickness of greater than 50 cm. Samples for flotation were then collected from bulk soil samples taken from these central part of ash pit deposits. On the basis of the established typology for this region, pottery recovered from these ash pits allowed us to make preliminary determinations of the cultural period that these deposits belonged to.

Our field sampling followed three principles: First, we selected as many sites as possible from different geomorphologic locations and different cultural ages. Second, in order to accurately determine where in the chronology of the Yangshao culture our samples derived from we only sampled ash pits with clear stratigraphic boundaries. Thirdly, we sampled only those pits without mixed assemblages containing material cultural remains from older or more recent periods (Zhang et al., 2014). Soil samples were taken from a total of 12 different sites: Peicun, Gaoya, Fujiazhai, Sanggou, Mazhai, Jueshan, Huizui, Zhaiwan, Jinzhongsi (**Figure 1**), Miaowan, Wutun, and Zhangcun. Altogether we sampled 28 ash pits from these sites, collecting 2–3 bags of soil samples (6–13 L/one bag) from each individual pit for a total of 58 bags of soil samples, and all used for flotation.

In addition to this original data, we also compiled the results of previous systematic archeobotanical research programs in this area (**Supplementary Table 1**), including the results of flotation studies from the Yiluo River Valley and on the regional plant remains of the Luoyang Basin (Zhang et al., 2014; IACASS and SAACATYRV, 2019). Archeological data was also extracted from previously published reports of plant remains from Yangshao sites located in Sanmenxia City (Zhao, 2011; Wei, 2014; Yang et al., 2020) as well as in the Yinghe River Basin in the Songshan region (AMPU and HPICRA, 2007; Zhong, 2016, 2018). The archeological sites discussed in this article are shown in **Figure 1**.

Methods

Flotation was performed on the collected soil samples with the use of a flotation station. Carbonized materials were collected using a 0.2 mm mesh sieve and were then set aside to dry. Once the materials were dry, they were sorted on the basis of size in the laboratory using 0.45, 0.75, 1, and 2 mm standard mesh sieves. Samples with particle sizes greater than 0.45 mm were selected and then sorted into preliminary categories with the aid of an optical stereo microscope. Carbonized samples and seeds were separated and put into sealed bags for analysis. Final taxonomic identification to the level of species of the archeobotanical samples separated at the previous step was carried out in the Archeobotany Laboratory at the Institute of Archeology, Chinese Academy of Social Sciences in Beijing. Each sample was then photographed and counted at this stage. Finally, we weighed and counted any charcoal, snail shell, and bone present in the samples.

As discussed previously, for each sample collected the relative age and archeological culture were assigned during field sampling on the basis of stratigraphic and typological material cultural evidence present in the ash pit from which the individual sample was collected. To confirm these chronological assignations nine individual charred plant seeds of foxtail millet and rice were selected and sent to Beta Analytic for direct AMS ^{14}C dating.

$$R(w) = \frac{N(bm)}{N(fm) \div 2.26} \qquad R(n) = \frac{N(bm)}{N(fm)}$$

To analyze the carbonized archeobotanical samples we calculated (1) ubiquity, (2) the ratio of broomcorn to foxtail millet, according to abundance, denoted as *R(n);* and (3) the ratio of broomcorn to foxtail millet in terms of weight, denoted as *R(w)*.

Ubiquity refers to the probability that an individual plant species will be recovered from an archeological site and reflects the distribution of plant remains (Zhao and He, 2006). The ubiquity index is calculated as a percentage of the number of samples containing specimens of a given plant species relative to the total number of samples collected. In order to compare with other sites of systematic excavation, this paper separately calculated the three regional surveys in Luoyang Basin (Zhang et al., 2014; IACASS and SAACATYRV, 2019; this study) and the regional survey in Sanmenxia (Yang et al., 2020).

The second measure, *R(n),* refers to the ratio of the absolute number of broomcorn millet specimens to the number of foxtail millet specimens. The third and final measure, *R(w)*, similarly refers to the ratio of broomcorn to foxtail millet but uses the relative weight of carbonized seeds for each species rather than the absolute number.

The average weight of 1,000 grains of broomcorn millet is 2.26 times the weight of 1000 grains of foxtail millet, meaning that the average number of individual grains in 1 g of foxtail millet is 2.26 times that of the average number of grains in 1 g of broomcorn millet (Zhang et al., 2010). The formulas for calculating both the ratio of broomcorn to foxtail millet by abundance—*R(n)*—as well as the ratio of broomcorn to foxtail millet by weight—*R(w)*—are presented below, where *N(bm)* stands for the number of broomcorn millet specimens and *N(fm)* stands for the number of foxtail millet specimens.

RESULTS

Radiocarbon Ages

The radiocarbon ages obtained are listed in **Table 1**. Huizui, Sanggou, Jinzhongsi, Mazhai, and Zhaiwan yielded corrected dates of between 3314 and 2891 cal BC, corresponding to the Late Yangshao period (3500–3000 BC). These radiocarbon dates are consistent with relative dates for the archeological cultures as determined by ceramic typologies and can thus be considered reliable. The radiocarbon ages of the Miaowan, Wutun, and Zhangcun sites are not dated to the Yangshao period. In addition, based on analysis of texture and stylistic traits of pottery sherds recovered from each site, Peicun, Gaoya, Fujiazhai, and Jueshan can also be attributed to the Late Yangshao period. So our study provides new evidence for the remains of carbonized plants from nine late Yangshao Culture sites in the Luoyang Basin.

Crop Assemblages in This Survey

We obtained a total of 40 soil samples, collected from 9 sites belonging to the Yangshao culture, which included approximately 5290 carbonized seeds (**Table 2**). In total, 4,484 foxtail millet seeds(*S. italica*), 90 broomcorn millet seeds *(P. miliaceum)*, 704 rice (*O. sativa*) seeds, and a single soybean (*Glycine max*) were identified (**Figure 2**). Remains of weedy species recovered include milkvetch (*Astragalus membranaceus*), Manchu tubergourd (*Thladiantha dubia*), and green bristlegrass (also called green or wild foxtail millet) (*Setaria viridis*).

Regarding the archeobotanical remains of domestic crop species, foxtail millet comprises the largest part of the assemblages with 84.96% and is followed by rice at 13.33%. Broomcorn millet made up only 1.7% of the domestic crop assemblage and soybeans accounted for a meager 0.01%. Furthermore, foxtail millet had the greatest ubiquity rate at 54.76%, followed by 31.25% for broomcorn millet, and 4.17% for rice.

The large number of macrobotanical remains of foxtail millet (4,424) and rice (704) form the Zhaiwan site is especially notable. Zhaiwan is the only site where rice was recovered and at all other sites where the remains of crop plants were collected totals are relatively small, never exceeding 100 grains.

Crop Assemblages From Previous Studies

The results of previous analyses on carbonized archeobotanical species from other sites in central and western Henan province are summarized in **Supplementary Table 1**. These have been included in our analysis below.

DATA ANALYSIS

Due to the very small quantity of other seeds recovered, this article focuses on changes in the quantities of foxtail millet, broomcorn millet, and rice.

Overall Characteristics and Trends in the Development of Agricultural Practices During the Yangshao Period

According to the results of this paper in combination with those from previous studies (**Table 2** and **Supplementary Table 1**), for each individual site we calculated: (1) the ubiquity of millet and rice, (2) the ratio of broomcorn to foxtail millet (in terms of ubiquity, abundance and weight) (**Supplementary Table 2**). Results of analysis are available in **Supplementary Table 2** and are shown in **Figures 3**, **4**.

In general, archeological sites with archeobotanical remains of domestic crops attributed to the Early Yangshao period (5000–4200 BC) are distributed within the Sanmenxia area (**Supplementary Table 2** and **Figure 3**). In terms of ubiquity, these Early period sites yield the highest ubiquity for broomcorn millet—ranging from 37.5 to 75%, with an overall average of 54.9%. At the Didong and North Didong sites—which belong to

TABLE 1 | Calibrated radiocarbon dates from sites investigated in Luoyang Basin (this study).

Radiocarbon Lab no.	Site	Sample	Cultural period	Conventional 14C age BC (± 1σ)	Calibrated age (cal. BC)	
					1σ (68.2%)	2σ (95.4%)
Beta–480949	Huizui East, H2-1	Foxtail millet	The late Yangshao	2371 ± 30	(54.2%) 2934–2893 (14%) 3008–2987	(95.4%) 3014–2891
Beta–480951	Sanggou southeast, H1-2	Foxtail millet	The late Yangshao	2381 ± 30	(45.9%) 2940–2899 (22.3%) 3010–2980	(95.4%) 3019–2894
Beta–480952	Jinzhongsi, H1-2	Foxtail millet	The late Yangshao	2430 ± 30	(68.2%) 3020–2926	(80.3%) 3036–2913 (15.1%) 3090–3045
Beta–480953	Mazhai, H2-2	Foxtail millet	The late Yangshao	2441 ± 30	(61.1%) 3026–2928 (7.1%) 3081–3069	(95.4%)3092–2918
Beta–480954	Zhaiwan Southeast, H1-1	Foxtail millet	The late Yangshao	2531 ± 30	(48.2%) 3329–3216 (10.9%) 3124–3097 (9.1%) 3181–3158	(90.8%) 3341–3087 (4.6%) 3059–3030
Beta–565106	Zhaiwan Southeast, H1-1	Rice	The late Yangshao	2391 ± 30	(36%) 2493–2905 (26.1%) 3011–2978 (6.1%) 2961–2951	(95.4%) 3024–2896

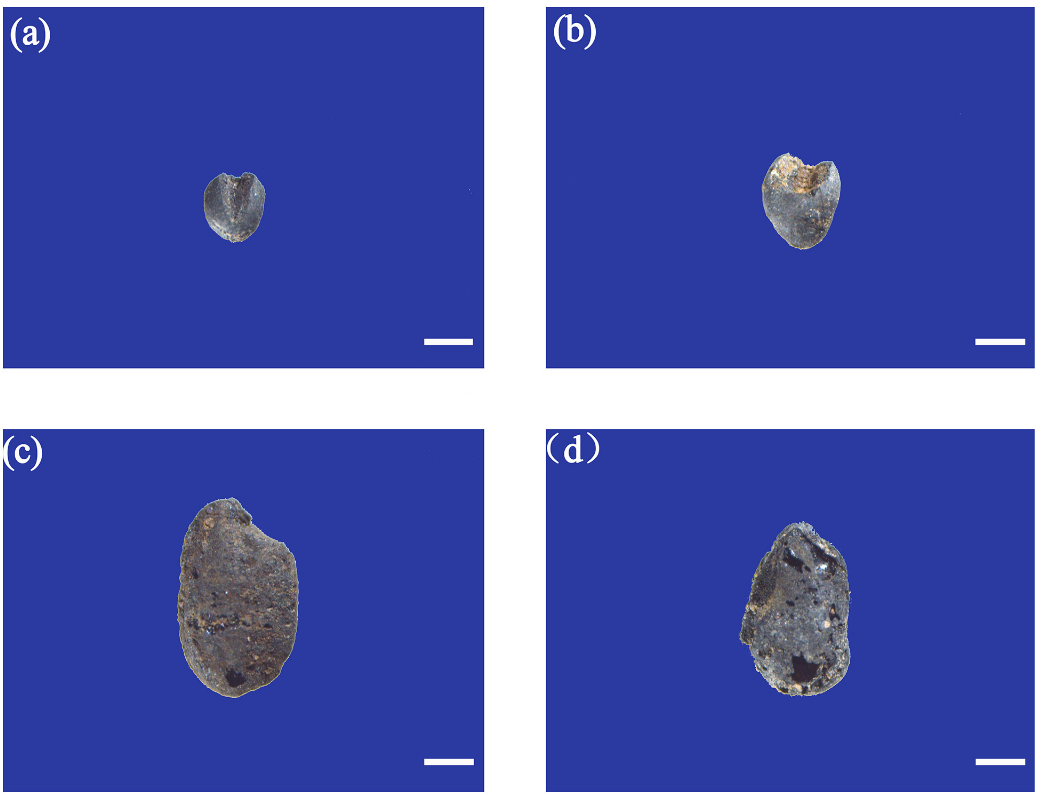

FIGURE 2 | Carbonized crop seeds recovered from Yangshao Culture sites in the Luoyang Basin (Scale bar: 1 mm). **(a)** Foxtail millet (*S. italica*) from Huizui (H2-1); **(b)** Broomcorn Millet (*P. miliaceum*) from Huizui (H2-1); **(c)** Rice (*O. sativa*) from Zhaiwan (H1-1); **(d)** Soybean (*G. max*) from Gaoya (H-1).

the first phase of the Early Yangshao period (5000–4500 BC)—the ubiquity of broomcorn millet is especially high with more than 60%. Foxtail millet is less ubiquitous at Early Yangshao sites, with an average of 36.8%. The probability of recovering foxtail, however, is never below 12.5% at any site from this period. Rice was recovered at rather high rates (ubiquity indices of around 50%) at the North Didong and Nanjiaokou sites, but was not found at any other sites at present, yielding an overall average ubiquity index of 16.7% for the Early Yangshao.

From 4200 to 3500 BC, during the Middle Yangshao period, sites with archeobotanical remains of crop species are found both in the area of Sanmenxia as well as within in Luoyang

TABLE 2 | Counts of crop seeds remains in the flotation samples from the Late Yangshao period archaeological sites in Luoyang basin (our study).

Site	Sample code	Landscape area	Volume of soil sample (L)	Foxtail millet			Broomcorn millet		Rice		Soybean	Milkvetch	Manchu tubergourd	Green bristlegrass	Unknown
				Whole	broken	agglomerate	Whole	broken	Whole	broken					
Huizui east	H1-1	Valley	10	4			3								
	H1-2		13												
	H2-1		13	22	4		9	4				1			
	H2-2		13	14	1		12	1							
	H3-1		13	3	2		3								
	H3-2		13	3	1		1								
Peicun	A southeast H1-1	Valley	6												
	A southeast H1-2		10												
	A southeast H2-1		6				2								
	A southeast H2-2		10	1			1								1
	C southeast H-1		8												
	C southeast H-2		10	1	1										
Gaoya	Northwest H-1	Plain	6												5
	Northwest H-2		6												
	Northeast H-1		6	11			1				1			1	
	Northeast H-2		6	1			1								
	East H-1		6	3			1								
Fujiazhai	North H-1	Valley	6												
	Northeast H1-1		6	4	2										
	Northeast H1-2		6												
	Northeast H2-1		10												
	Northeast H2-2		12	1											
Sanggou southeast	H1-1	Valley	8	21	5		4								
	H1-2		8	22	11		13	6							
	H2-1		10	9	4										
	H2-2		8	4	2										
Jinzhongsi	H1-1	Plain	8												
	H1-2		8	13	7	1									
	H2-1		10	1											
	H2-2		6				4	3							
Mazhai west	H1-1	Valley	8	6	1			1							
	H1-2		8												1
	H2-1		6	13	4										
	H2-2		8	56	2										
Zhaiwan	Southeast H1-1	Valley	8	1530	700		20		3	350+					3
	Southeast H1-2		8	1210	784				1	350+			1		2
	Northeast H2-1		10												
	Northeast H2-2		8												
Jueshan northeast	H-1	Valley	10												
	H-2		12												
Amount				2953	1531	1	75	15	4	700+	1	1	1	1	7

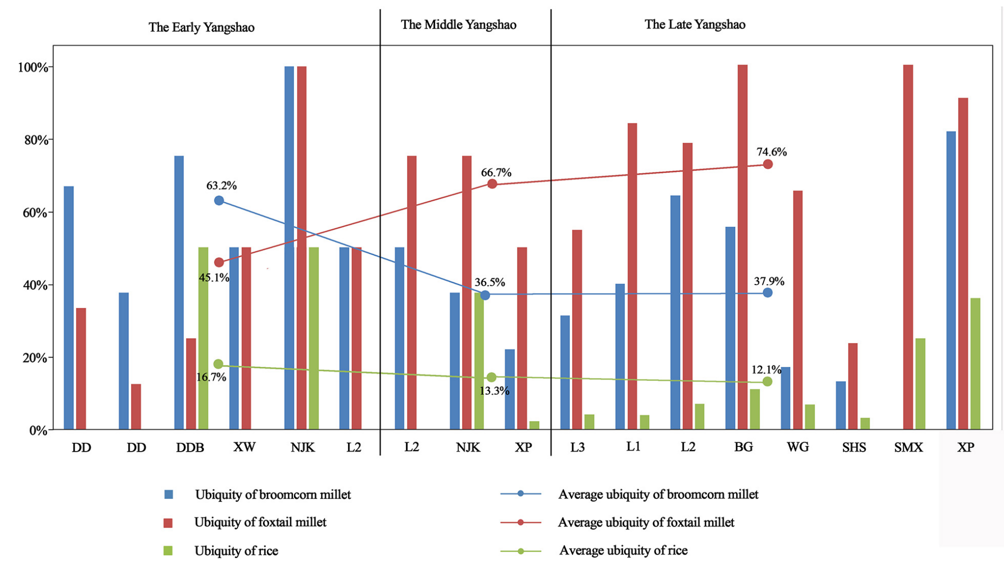

FIGURE 3 | Trends in the ubiquity of broomcorn millet and foxtail millet throughout the Yangshao Culture in eastern and western Henan Province.

Basin (**Supplementary Table 2** and **Figure 3**). At these sites, the likelihood of recovering foxtail millet was the highest of among all crop species in our analysis, having an overall average ubiquity index of 66.7% and a range of between 50 and 70%. The rate of recovery for broomcorn millet comes second with an average of 36.5% and a range of between 22 and 50%. Rice was recovered only from Middle Yangshao contexts at Nanjiaokou and Xipo, with a range of 2.3–37.5%. Overall ubiquity for rice also decreases slightly through time, going from an overall average of 16.7% in the Early Yangshao to only 13.3% in the Middle period.

By the Late Yangshao period from 3500 to 3000BC, most sites with archeobotanical remains are located in the Luoyang Basin and Songshan area (**Supplementary Table 2** and **Figure 3**). As was the case in the Middle Yangshao, foxtail millet had the highest ubiquity indices, with the site of Shuanghuaishu yielding the lowest index at 23.7% and all other sites having rates above 50% and as high 100%. Overall ubiquity indices for foxtail during the Late Yangshao are higher than they were in previous periods as well, reaching an average of 74.6%. Broomcorn millet once again occupies a secondary position with 37.9% on average and a range of 13.2–81.8%. Except for the L2 (64.2%) and BG (55.6%) sites, broomcorn millet ubiquity indices consistently fall below 40% in this period. In this period we also observe an increase in the number of sites with rice, although the average ubiquity index remains low at 12.1% and the range was between 3.2 and 36%, with only Xipo and sites from the Sanmenxia survey producing indices higher than 12%.

Analysis of Changes of Foxtail and Broomcorn Millet

In the early Yangshao ubiquity ratios are in almost all cases above 1.0, with an average of 1.83—indicating a consistently greater likelihood of recovering broomcorn over foxtail at this time (**Figure 4E**). Except for at the sites of North Didong and Nanjiakou—where foxtail millet cultivation was emphasized over broomcorn millet —this trends is echoed in the other two ratios for abundance and weight with averages of 1.67 and 3.7, respectively (**Figures 4C,D**).

Ratios of broomcorn millet to foxtail millet in terms of ubiquity, abundance, and weight for sites from the Middle and Late periods are roughly equivalent in terms of both ranges (Middle: 0.54–0.17; Late: 0.56–0.17) and averages (Middle: 0.36; Late: 0.40) (**Figures 4C–E**). Notably, all of these ratios drop to below 1.0, decreasing significantly from those calculated for the Early Yangshao and indicating the prevalence of foxtail over broomcorn millet in these later periods.

A Comparison of Crop Remains From Sites With Different Surface Areas

We also analyzed the composition of the agricultural structure—on the basis of ubiquity and abundance indices—apparent at sites of different sizes (**Figure 5**). Information was available about the size of 34 of the archeological sites examined in this study. For each period of the Yangshao Culture we divided these into (1) small sites with an area of less than 0.2 km^2, (2) medium sites with areas of between 0.2 and 0.6 km^2, and (3) large sites of over 0.6 km^2.

For sites from the Early Yangshao period with available data (**Figure 5A**), all four sites with carbonized crop seeds are classified as small. Across these four sites, broomcorn millet, foxtail millet, and rice had average ubiquity ratios of 69.45, 49.6, and 15.5%, respectively. In terms of relative abundance, broomcorn millet comprised 51.35% of assemblages on average, followed by foxtail millet (45.03%) and rice (3.62%).

For the Middle Yangshao (**Figure 5B**), the six sites with archeobotanical assemblages containing domestic crops are evenly distributed between small (n = 3) and medium (n = 3) sized sites. Average ubiquity indices and relative abundances,

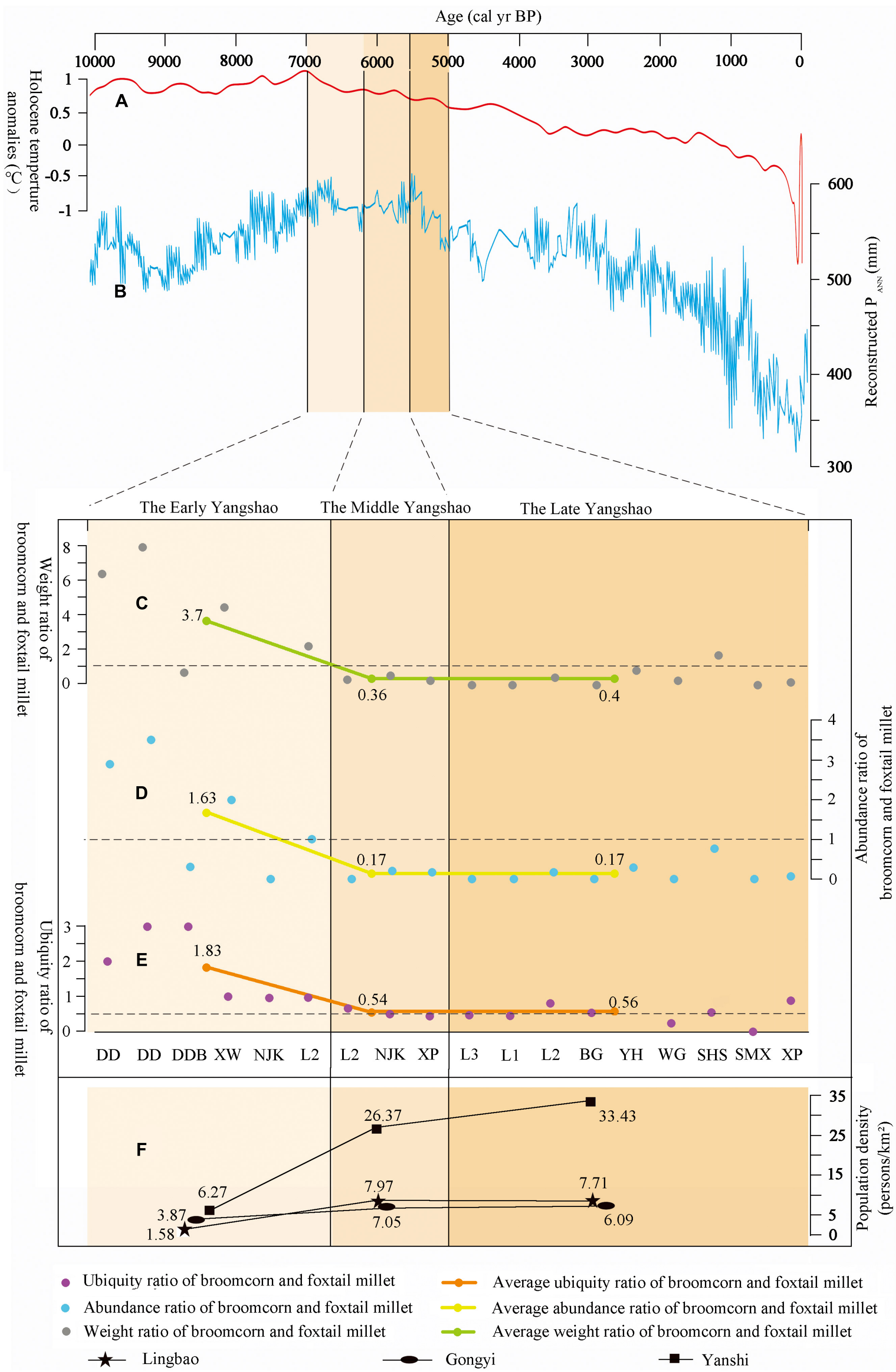

FIGURE 4 | Climate, three ratios of broomcorn millet to foxtail millet, population density curve. **(A)** Synthesized Northern Hemisphere (30°–90°N) temperature record during the Holocene55 (Shakun et al., 2012; Marcott et al., 2013). **(B)** Pollen-based annual precipitation (PANN) reconstructed from Gonghai Lake (Chen et al., 2015). **(C)** Weight ratio of broomcorn millet to foxtail millet from sites examined in this study. **(D)** Abundance ratio of broomcorn millet to foxtail millet from sites examined in this study. **(E)** Ubiquity ratio of broomcorn millet to foxtail millet from sites examined in this study. **(F)** Population density in central and western Henan Province (Wang J. H., 2005).

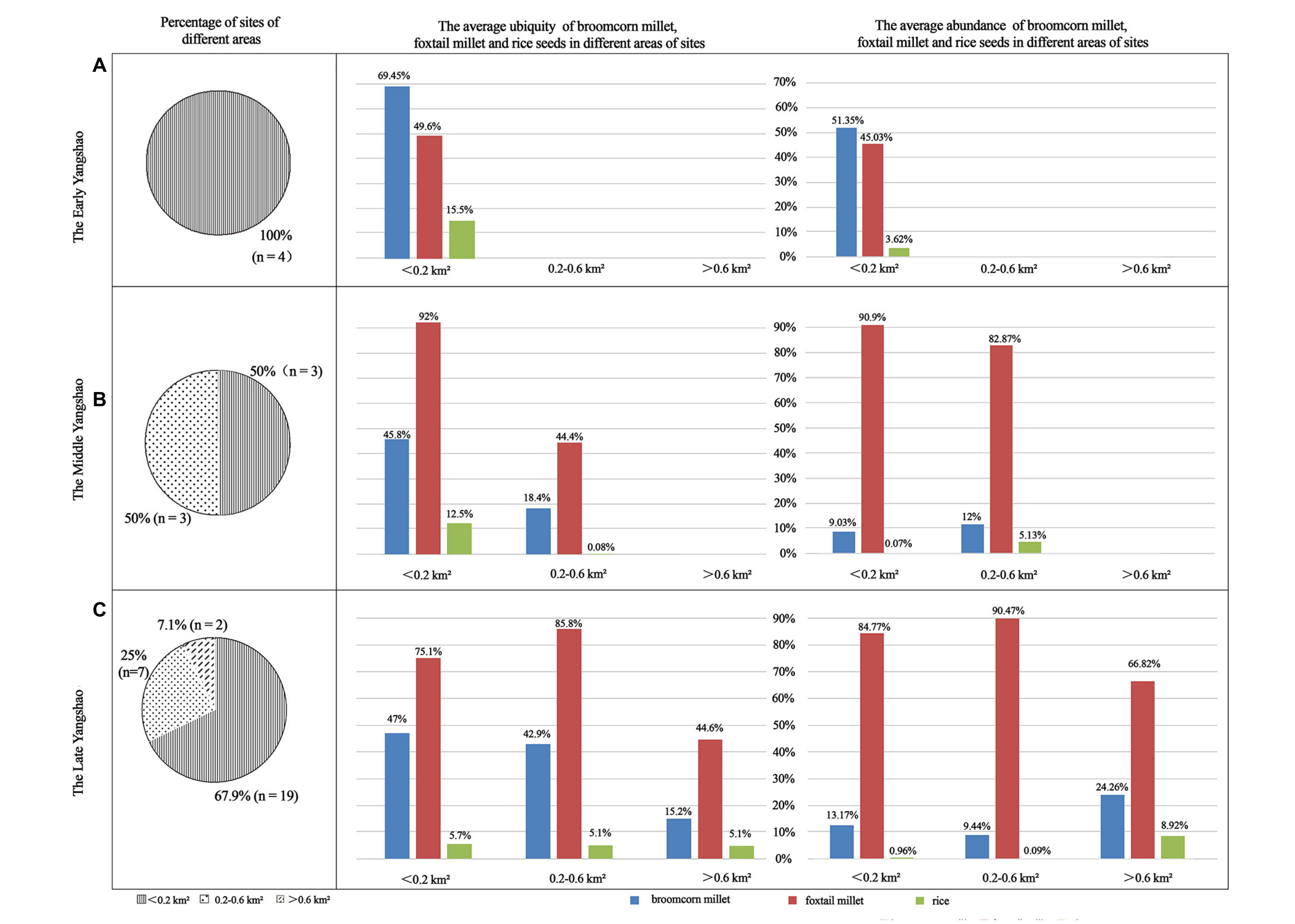

FIGURE 5 | Histograms of the ubiquity and abundance of broomcorn millet, foxtail millet, and rice according to site size in the **(A)** Early, **(B)** Middle, and **(C)** Late Yangshao.

respectively in small sites for this period were: 45.8 and 9.03% for broomcorn millet, 92 and 90.9% for foxtail millet, and 12.5 and 0.07% for rice. Average ubiquity indices and relative abundances in medium sites for this period were: 18.4 and 12% for broomcorn millet, 44.4 and 82.87% for foxtail millet, and 0.08 and 5.13% for rice.

The Late Yangshao provided the largest number of sites (n = 28) with macro-botanical remains of crops (**Figure 5C**). The majority of these (67.8%) are small sites, where broomcorn millet, foxtail millet, and rice, respectively yielded average ubiquity ratios of 47, 75.1, and 5.7%, and comprised 13.17, 84.77, and 0.96% of these assemblages, respectively, on average abundance ratios. Medium sized sites are the next most abundant making up 25% of the Late Yangshao sites for which we have data. Both ubiquity and relative abundances are fairly similar to those for small sites (average ubiquity and abundance: broomcorn: 42.9 and 9.44%, foxtail: 85.8 and 90.47%, and rice: 5.1 and 0.09%). Large sites are less abundant than either small or medium sized sites during the Late Yangshao, comprising only 7.1%. Ubiquity is similar to contemporary medium and small sized sites for rice (Large: 5.1%), but the average ubiquity as well as abundance of both broomcorn (15.2, 24.06%) and foxtail (44.6, 66.82%) millets is much smaller at the Large sized sites.

DISCUSSION

Foxtail Millet-Broomcorn Millet Substitution

Results from our analysis of archeobotanical remains from Yangshao sites in Henan demonstrate that throughout the Early Yangshao period broomcorn millet represented the primary crop within the Yangshao agricultural system, while foxtail millet made up a smaller, although not insignificant, part of Yangshao foodways at this time. In the Middle and Late Yangshao periods ubiquity, relative abundance, and relative weight measurements present an opposing trend, with foxtail millet superseding broomcorn millet for dominance in Yangshao food production systems. Our results are in line with evidence from a number of previous archeobotanical studies of Yangshao sites in the Henan province and surrounding areas where systematic flotation was conducted—including Yangguanzhai, Xipo, Didong, and

Nanjiaokou (Wei, 2014; Zhong et al., 2020)—which demonstrate a shift from broomcorn millet toward foxtail millet during these latter two periods of the Yangshao culture.

Climate change played a critical role in the selection of millet species for domestication during different periods in North China (Lu, 2017; Yang et al., 2018). However, geological records, including eolian deposits, lake sediments and soils, have shown that during the Yangshao Warm Period climatic conditions in Henan Province were much more favorable for cultivation than those seen today (Shakun et al., 2012; Marcott et al., 2013; Chen et al., 2015; **Figures 4A,B**). Environmental records from the Sihenan site in Luoyang Basin show that the lakes and marshes present during the Early and Middle Yangshao—between 5000 and 3500 BC—were less saline and supported a greater number of flora and fauna preferring warm and humid environments (Sun and Xia, 2005). Furthermore, zooarcheological studies from Xishan in Zhengzhou reporting the presence of an abundance of heat-loving terrestrial and aquatic animal species strongly suggests that a warm and wet climate continued into the Late Yangshao (Chen, 2006). Therefore, we think that climate change during the Yangshao period would not have been severe enough to result in the changes we see to agricultural systems during this time—especially because agricultural production was centered around highly adaptable, heat and drought-tolerant millets.

The Early Yangshao period represents an early stage of agricultural development in Northern China, characterized by underdeveloped crop cultivation practices and predominantly extensive production (Zhao, 2017). In this context, the dominance of broomcorn millet in the agricultural structure of the Early Yangshao was driven by a preference for this species, owing to its adaptability to various (and poor) environments, ease of cultivation, and low requirements in terms of land management and inputs (SCGR, 1994; Dong and Zheng, 2006; Zhao, 2018).

Archeological studies have shown that the Dongzhuang-Miaodigou culture type emerged in western Henan and rapidly expanded into surrounding areas during the Middle Yangshao period (Han, 2015) and the population density in the study area increased sharply during this period (Wang J. H., 2005; **Figure 4F**). In this stage, agricultural economy establishes principal position (Zhao, 2014; Li, 2018; Zhong et al., 2020). Agricultural modes of production at this time changed from "extensive" to "intensive" strategies in order to cope with ensuing resource depression brought on by population increases (Fan, 1988; Gao, 2009; Zhao, 2014, 2018; Han, 2015). Broomcorn millet can have unstable yields because its grains fall off easily after the plant reaches maturity and are difficult to harvest (Dong and Zheng, 2006; Zhang, 2016). Foxtail millet has the advantage of a short growth period along with high yields (e.g., 1950's production of foxtail millet: 750 kg/hm^2vs. broomcorn millet 670 kg/hm^2), and the grains also provide for better flavor and superior storage stability (SCGR, 1994; Dong and Zheng, 2006; Liu et al., 2008). Therefore, with investments in soil and land management strategies—including nutrient inputs, weeding, and pest controls (SCGR, 1994; Dong and Zheng, 2006; Liu et al., 2008)—Yangshao farmers would have preferred to plant foxtail millet over broomcorn, leading to the shift from broomcorn to foxtail millet evident in the Middle Yangshao period.

As such, we assert that the substitution of broomcorn millet for foxtail millet in Henan Province during the Middle Yangshao was propelled by social development and demographic expansion, rather than by environmental factors. This conclusion is also supported by research conducted at the wider regional level. Comparing the agricultural characteristics of areas surrounding Henan province, Zhong et al. (2020) proposed that foxtail millet was far more important in the agricultural systems of Henan Province than it was within other traditional dry-land farming areas in neighboring regions such as Haidai and Shanxi. He further speculates that higher numbers of sites, sites of larger size, and other evidence for higher population density within the core Miaodigou Culture area resulted in a greater demand for the higher-yielding foxtail millet (Zhong et al., 2020).

It should be noted that evidence from phytoliths is suggestive of broomcorn millet, and not foxtail, serving as the main agricultural crop in the Zhengzhou region of central Henan throughout the Yangshao Culture, with no evidence of replacement in either the Middle or Late periods (Wang et al., 2015, 2019a,b; Wang, 2016). However, remains from sites such as Lajia (Zhao, 2003; Wang et al., 2015), as well as others in the Guanzhong Basin (Zhang et al., 2010; Liu et al., 2013; Zhong et al., 2015) have shown that the results of analysis of phytoliths vs. carbonized macro-botanical remains can present conflicting results—owing to the fact that phytoliths and carbonized macrobotanical remains are studied in different ways. And the variety of preservation conditions (Renfrew, 1973) and carbonization temperature (Yang et al., 2011; Wang and Lu, 2020) both affect the carbonization rate of millet. So it is difficult to compare results based on phytoliths and carbonized remains in practice, and our study depends on examination of the latter, the discussion in this paper is mainly based on evidence from carbonized remains.

Valley-Rice Planting and Palaeogeomorphologic Evolution

Domesticated rice originated in China's Yangtze River basin (Jones and Liu, 2009; Zhao, 2014), and spread northwards into the Central Plains region to the middle reaches of the Yellow River around 8000–7000 a B.P. (Zhang et al., 2012; Wang, 2016; Lu, 2017; Wang et al., 2017), becoming an important dietary supplement to prehistoric people. The warm and humid climate of the Yangshao period was crucial for the development of rice cultivation in this region (Shi et al., 1992; Xia et al., 2001). However, the cultivation of rice in northern China relies on particular geomophologic and environmental conditions, especially in terms of water availability (Li and Zhang, 2020). Sites where rice has been observed are located near rivers and lakes, where aquatic resources were conveniently available (Zhong et al., 2020). Thus, in northern China the potential for rice cultivation at a given site was not determined by climate or latitude, but rather by proximity to an abundant water source.

Of the archeobotanical assemblages in our analysis that yielded remains of rice (**Figure 6D**), 10 sites are located in river valleys, and none were found in plains. In the Early Yangshao period, the North Didong and Nanjiaokou sites are situated on platforms along the valleys of the Xiyu and Qinglong rivers in western Henan Province. Middle Yangshao sites with rice, such as Nanjiaokou and Xipo, are similarly located within the river valleys of the Qinglong and Sha Rivers in western Henan. This trend continues into the late Yangshao period, with sites in both western and central Henan province once again found in river valleys of the Sha, Hongnong, Yihe, Luo, Yiluo, and Ying rivers.

The valley area refers to the relatively high altitude, complex and topographically variable terrain found to either side of the valley formed by the loess plateau and river terraces of the upper reaches of the Ying River (Zhang et al., 2014). For example, in the Songshan area, the western loess area experienced several fluvial deposition-erosional cycles since the terminal Late Pleistocene. A large-scale alluvial aggradation took place in the Middle Holocene, resulting in the formation of lakes, marshes and wetlands (Lu et al., 2020). And in the Luoyang Basin, during the late-middle Holocene (5300/5010∼2130/1870 BC), the loess tablelands and gullies experienced erosion of mountain slopes, resulting in increased accumulation in valleys and the formation of clay-rich and water-filled depressions. A fine sand and gravel layer from the Huizui site penetrates a layer of clay sediments, suggesting the formation of seasonal marshes and waterlogging (Rosen, 2008). This evidence indicates that during the Yangshao period, conditions in the valley areas were humid, creating an abundance of moist depressions suitable for paddy fields and providing optimal conditions for rice cultivation.

The alluvial plains area refers to the flood plain on both sides of the Yiluo River (Zhang et al., 2014) and the eastern Songshan Mountain plains, where the terrain is low and flat with less landform diversity and fertile soils. The floodplain on both sides of the Yiluo River in the central Luoyang Basin was cut down around 7,000 years ago, forming a vast area of dry and stable T1 terraces (Zhang et al., 2019). In the low-lying area the eastern Songshan plains, some of these lakes converged into large water areas and lasted throughout the Late Pleistocene and Early- Middle Holocene period (Lu et al., 2020). In short, the plain terraces of Luoyang Basin are generally dry, and the eastern Songshan plain was full of lakes and marshes, with both areas lacking stable, lowland environments allowing for rice cultivation. Therefore, we propose that the absence of rice remains from sites located in alluvial plains in central and western Henan Province dated to the Yangshao period is best explained by differences in local geomorphologic environments.

Agricultural Distribution, Paleoenvironment, and Social Complexity

A diachronic shift is evident in the distribution of sites associated with agricultural practices between the Early and Late Yangshao periods. Early period sites are primarily in the western part of Henan Province, but by the Late Yangshao sites primarily in Central Henan resulting in a more balanced representation of geomorphologic regions in site locations (**Figure 6**).

The Early Yangshao Culture Period (5000–4200 BC)

During the Early Yangshao Culture period, the Mid-Holocene Megathermal Period established a climate that was warm and humid in this region (Sun and Xia, 2005). Numerous lakes developed in the central and western areas of Henan Province (Dong et al., 2006; Zhai et al., 2011; Li et al., 2014), and in central Henan, the area around Zhengzhou especially experienced vast lake development (Li et al., 2014; Lu et al., 2020). Archeological evidence shows that settlements from this time period are mainly distributed in the areas of higher elevation, such as loess tablelands and river terraces (Zhao, 2001; HPICRA, 2009; Liao et al., 2019; Lu et al., 2020). In comparison, western Henan is generally higher in elevation than central regions, with a more diverse array of geomorphologic features. Here, ancient people similarly established settlements on the loess tablelands and terraces (HPICRA, 2009). During this period, hunting and gathering constituted a large proportion of economic and food procuring activities (Kong et al., 1998, 1999; Zhao, 2014, 2017; Li, 2018), which were facilitated in western Henan by the abundant mountainous areas rich with animal and plant resources. This situation helps to explain why sites with carbonized remains from the early Yangshao period are primarily found in western Henan Province (**Figure 6A**).

Social stratification was low or absent during the Early Yangshao period and society was likely organized around simple kin-based networks (HPICRA, 2009; Dai, 2012). Settlements from this period are small and there is no evidence for any kind of settlement hierarchy (Zhao, 2001). The lithic industry included stone spades, blades, saddle-querns, and rollers and was predominantly based on groundstone tools (ZMIA, 2001), and population densities were low (Wang J. H., 2005; **Figure 4F**). Our study provides evidence of the presence of mixed cropping systems (based on both types of millet and, in some cases, also rice) from Early Yangshao sites (**Figures 5**, **6**A), reflecting relatively undeveloped and extensive agricultural activities adapted to simple forms of social organization.

The Middle Yangshao Culture Period (4200–3500 BC)

A stable warm and wet climate during the Middle Yangshao period (Shakun et al., 2012; Marcott et al., 2013; Chen et al., 2015; Hou et al., 2019), and the presence of loess soils suitable for rain-fed dry-land farming practices in the central and western Henan Province (HPICRA, 2009), provided improved conditions for early agricultural reclamation and crop sowing. In this period, settlements increase in size and scale and can now be found at the edge of tableland areas. For example, the Nanjiaokou site is located along secondary terraces and along the slope of the middle and lower part of the southern loess tableland (HPICRA, 2009). At this time, the Dongzhuang-Miaodigou type of the Yangshao Culture emerged rapidly in western Henan and expanded vigorously into surrounding areas (Han, 2015). This expansion is also confirmed by the distribution of crop remains, which display a wider and more balanced area of distribution from sites located on terraces, in tableland areas, and along tableland edges during the Middle Yangshao (**Figure 6B**).

Although the number of carbonized seeds recovered from Middle Yangshao sites is relatively small, the dominance of

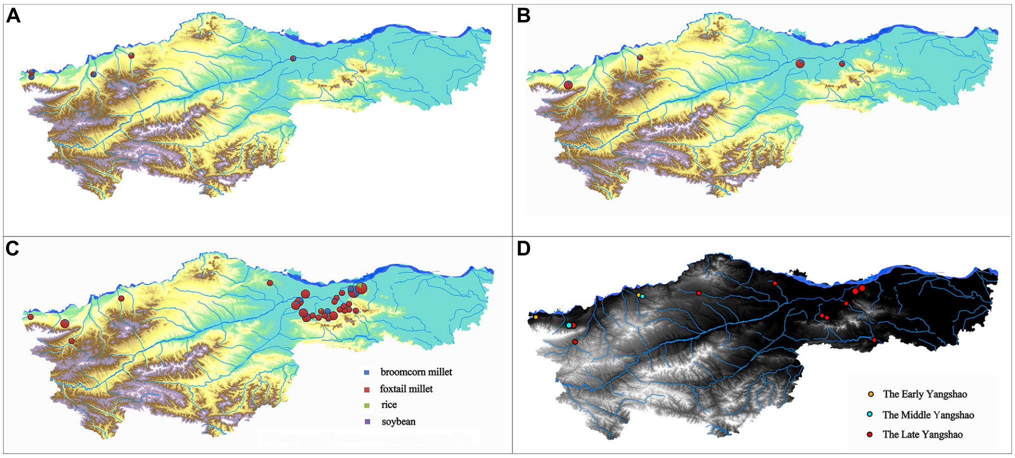

FIGURE 6 | Map of the structure of agricultural systems of the Yangshao Culture **(A)** Early Yangshao (5000–4200 BC), **(B)** Middle Yangshao (4200–3500 BC), **(C)** Late Yangshao (2500–3000 BC), **(D)** rice distribution through time). Structure of agricultural systems = are represented in pie charts including broomcorn millet, foxtail millet, and rice. Different areas of a site are shown with different circle sizes.

foxtail millet in these agricultural assemblages is obvious, with broomcorn millet and rice as secondary crops in small and medium sites in the central and western Henan Province (**Figure 5B**). We speculate that these differences between settlements of different sizes can be explained by the establishment of stratified social organization during this period. As mentioned above, the substitution of broomcorn millet for foxtail millet that occurred during the Middle Yangshao period created a new agricultural system that was now dominated by the higher yielding millet species, which in turn promoted dramatic agricultural developments. Subsequently, differentiation within and between settlements (HPICRA, 2009; Dai, 2012; Luan, 2012; Zhao, 2014; Han, 2015), distinctions between tombs and grave goods (IACASS and HPICRA, 2010) and other phenomena suggesting intensified social stratification were becoming increasingly obvious, marking a period of novel social tensions and relationships between people (Liu, 2005; Wang J. H., 2005; Dai, 2012; Han, 2015).

In this context, economic specialization resulted in the emergence of handicraft activities separate from agricultural production, including specialized lithic, ceramic, and jade working industries, as well as an increase in trade between settlements in commodities and other economic goods (Dai, 2004, 2012, 2016; Jin, 2005; Gao, 2009; Han, 2010). The small size and populations of small settlements meant they functioned primarily as agricultural settlements, whereas the larger populations and more complex economic structures of medium-sized settlements allowed for the emergence of specialized industries with a lesser emphasis on agriculture, explaining the lower probability of recovering crop remains at these sites.

The Late Yangshao Culture Period (3500–3000 BC)

Climatic conditions in these latter periods do appear to fluctuate, including a period of cooling as well as drought from 5.5 to 5 ka BP (Jiang et al., 2006; Chen et al., 2015; Dong et al., 2015; Goldsmith et al., 2017). Climatic fluctuations resulted in changes to surface hydrology, which included a decrease in surface water levels and the subsidence of lake marshes (Sun and Xia, 2005; Dong et al., 2006; Bi et al., 2016). Archeological investigation shows that settlements were being established at lower elevations in this area, with site locations expanding into the lower-lying areas such as river terraces and plains (Zhao, 2001; HPICRA, 2009; Liao et al., 2019; Lu et al., 2020).

Our data show that Late Yangshao period remains are found both along tableland valleys as well as in plains in the central and western Henan Province, with a more balanced the distribution across the landscape (**Figure 6C**). This was a result of a decline in the level of surface water runoff as well as an increase of arable land in the plains, which provided additional land suitable for agricultural production. During this period, an influx of foreign cultural influences appeared to have caused Yangshao culture in the former western core to decline; Central Henan thus became a place of cultural convergence and a unique cultural system developed in the newly populated region (Luan, 1996; Zhang, 2010; Dai, 2012; Han, 2015). Agricultural activities during this period were therefore more concentrated in central Henan than they were in western regions.

In the late Yangshao period, the average ubiquity of millet and rice, and the average abundance of foxtail millet in large sites was smaller than those in medium and small sites (**Figure 5C**). At this stage, differentiation between settlements of different scales was more obvious, and differences between settlement areas of different levels was more pronounced (Zhao, 2001; Gao, 2009; HPICRA, 2009). Massive rammed-earth wall structures and weapons found at the Xishan site in Zhengzhou (Yang, 1997) reflect a time period of violent conflict and social tension (Dai, 2012). Concentrated and intensive handicraft production at a large scale is apparent at large and central settlements of this period, and the range and amount of products evident at these sites indicates that these materials were produced to fulfill non-local demands beyond the settlement itself (Dai, 2012, 2016). It is thus likely that this resulted in the more diversified economic structure evident in larger-sized settlements, further evinced by a lower proportion of agricultural remains from these sites compared to smaller settlements.

CONCLUSION

Our study provides new evidence for the remains of carbonized plants from nine late Yangshao sites in the Luoyang Basin. In addition to millet, the hundreds of rice fragments found at the site of Zhaiwan represent the largest assemblage of rice from the Late Yangshao period found in the Luoyang Basin. Combining new data with previous evidence of carbonized plants from the Yangshao period in central and western Henan Province, this paper explores the relationship between agriculture, the environment, and social complexity.

The stable, warm and humid climate in the Mid-Holocene Warm Period provided an optimal environmental background promoting the development of agriculture in the Yangshao Culture, which subsequently became the foundation for further sustainable agricultural developments and the intensification of social complexity throughout this period. Climatic fluctuations affecting surface water levels and runoff distribution and resulting in geomorphologic changes, are associated with the spread of agricultural practices initially located in the loess tableland valley areas at higher elevations during the Early Yangshao and expanding into marginal areas and plains during the Middle and Late Yangshao periods. These low-lying lands—with better hydrothermal conditions in valley areas—meant that these areas were more suitable for rice cultivation than the plains were. Changes in the structure of crop assemblages further affected the distribution of site clusters and changes in cultural areas.

Furthermore, using carbonized macrobotanical remains we obtained key evidence of the substitution of broomcorn millet with foxtail millet by the Late Yangshao, providing a direct contrast to results from this region using phytoliths. We believe that this substitution was primarily driven by population pressure, rather than environmental degradation. The establishment of a highly efficient, foxtail millet-based agricultural system—which had its apex during the Middle Yangshao—promoted population growth, economic and social differentiation, and social stratification, resulting in a period of intensified social complexity.

Finally, our study provides an example of how processes of social complexity can affect the structure and scale of agricultural practices at different types of archeological settlements. In the Middle and Late periods, the average ubiquity and abundance of agricultural crops is lower at larger settlements than in smaller ones—Middle Yangshao period: medium < small; Later Yangshao period: large < medium and small—and this appears to be related to a reduced emphasis on agricultural production at larger settlements, due in part to their more complex economic structures and specialized handicraft production systems.

It should be noted that the imbalance of the number of sites found in western Henan and central Henan during the Yangshao period may have an effect on the distribution of foxtail millet, broomcorn millet and rice, which needs to be verified by systematic analysis of assemblages from more and newly excavated sites in this region.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

JZ designed the research. YL and JZ performed the research and completed writing. YL, JZ, and XZ analyzed the data. HZ and YL completed sampling in the field. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2021.662391/full#supplementary-material

REFERENCES

Algaze, G. (2001). Initial social complexity in southwestern Asia: The Mesopotamian Advantage. *Curr. Anthropol.* 42, 199–233. doi: 10.2307/3596412

Andersson, J. G. (2011). *An early Chinese culture*. Beijing: Cultural Relics Publishing House.

Adams, R. M. (2001). Complexity in Archaic States. *J. Anthropol. Archaeol.* 20, 345–360. doi: 10.1006/jaar.2000.0377

AMPU, and HPICRA (2007). *School of Archaeology and Museology in Peking University, and Henan Provincial Institute of Cultural Relics and Archaeology, (2007). Archaeologicla discovery and research at the Wangchenggang site in Dengfeng (2002-2005)*. Zhengzhou: Elephant Press.

Barton, L., Newsome, S. D., Chen, F. H., Wang, H., Guilderson, T. P., and Bettinger, R. L. (2009). Agricultural origins and the isotopic identity of domestication in northern china. *Proc. Natl. Acad. Sci.* 106, 5523–5528. doi: 10.1073/pnas.0809960106

Bi, S. B., Zhou, H., Yang, H. R., Shen, X., and Wang, J. (2016). Evolution of Neolithic settlement in Zhengzhou-Luoyang region and its relationship with environment. *China Sci. Paper* 011, 2479–2485. doi: 10.3969/j.issn.2095-2783.2016.21.015

Binford, L. R. (1968). *Post-pleistocene adaptations. in new perspectives in archeology*. Chicago, IL: Aldine Publishing Co.

Brooks, N. (2006). Cultural responses to aridity in the middle Holocene and increased social complexity. *Quat. Int.* 151, 29–49. doi: 10.1016/j.quaint.2006.01.013

Cao, B. W. (2013). Agriculture, Yangshao and the Formation of Chinese Civilization – A Review of Mr. Yan Wenming's Archaeological Thoughts. *Relics South* 3, 9–16. doi: 10.3969/j.issn.1004-6275.2013.03.002

Chen, F. H., Xu, Q. H., Chen, J. H., Birks, J. B., Liu, J. B., Zhang, S. R., et al. (2015). East Asian summer monsoon precipitation variability since the last deglaciation. *Sci. Rep.* 5:11186. doi: 10.1038/srep11186

Chen, Q. J. (2006). A study of the faunal remains from the Xishan Site in Zhengzhou. *Acta Archaeolog. Sin.* 3, 385–418.

Chen, X. C., Liu, L., Lee, Y. K., Wright, H. T., and Rosen, A. M. (2003). Development of social complesity in the central China: Research into the settlement pattern in the Yiluo River valley. *Acta Archaeolog. Sin.* 2, 161–218.

Dai, X. M. (2012). The formation and preliminary development of the early complex society in the Central Plains. *Archaeolog. Res.* 2012, 481–527.

Dai, X. M. (2016). Prehistoric economy in the middle Yellow River valley. *Huaxia Archaeol.* 4, 64–77.

Dai, X. M. (2004). Settlement and society of Miaodigou culture. *Ancient Civiliz.* 3, 15–40.

Dong, G. H., Xia, Z. K., Liu, D. C., and Wu, Q. L. (2006). Environmental change and its impact on human activities in Middle Holocene at Mengjin, Henan Province. *Acta Scientiar. Natural. Univ. Pekinensis* 42, 238–243. doi: 10.3321/j.issn:0479-8023.2006.02.017

Dong, G. H., Jia, X., An, C. B., Chen, F. H., Zhao, Y., Tao, S. C., et al. (2012). Mid-Holocene climate change and its effect on prehistoric cultural evolution in eastern Qinghai Province. *Quat. Res*. 77, 23–30. doi: 10.1016/j.yqres.2011.10.004

Dong, J. G., Shen, C. C., Kong, X. G., Wang, H. C., and Jiang, X. Y. (2015). Reconciliation of hydroclimate sequences from the Chinese Loess Plateau and low-latitude East Asian Summer Monsoon regions over the past 14,500 years. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 435, 127–135. doi: 10.1016/j.palaeo.2015.06.013

Dong, Y. C., and Zheng, D. S. (2006). *Chinese crops and their wild relatives (food crop)*. Beijing: China Agriculture Press.

Fan, Z. W. (1988). Agricultural tools in the Yangshao Culture Period– The evolution and application of chuploughing agricultural tools. *Agricult. History China* 3, 1–9.

Feinman, G. M. (2011). Size, Complexity, and Organizational Variation: A Comparative Approach. *Cross-Cult. Res.* 45, 37–58. doi: 10.1177/1069397110383658

Flannery, K. V. (1973). The origins of agriculture. *Ann. Rev. Anthropol.* 2, 273–310. doi: 10.1146/annurev.an.02.100173.001415

Fried, M. H. (1967). *The evolution of political society: An essay in political anthropology*. New York, NY: Random House.

Gao, J. T. (2009). *An aechaeological study of civilizing course in the Central Plains*. Beijing: Socila Sciences Academic Press.

Goldsmith, Y., Broecker, W. S., Xu, H., Polissar, P. J., de Menocal, P. B., Porat, N., et al. (2017). Northward extent of East Asian monsoon covaries with intensity on orbital and millennial timescales. *Proc. Natl. Acad. Sci. USA.* 114, 1817–1821. doi: 10.1073/pnas.1616708114

Han, J. Y. (2015). *Early China: The making of the Chinese cultural sphere*. Shanghai: Shanghai Classics Publishing House.

Han, X. H. (2010). *On the handicraft industry in Central Plains from Pregistoric to Xia and Shang periods*. Zhengzhou: Zhengzhou University. PhD dissertation.

Hou, G. L., Xu, C. J., Lu, C. Q., Chen, Q., and Lancuozhuoma. (2019). The environmental background of Yangshao culture expansion in the mid-Holocene. *Geogr. Res.* 38, 437–444. doi: 10.11821/dlyj020171214

HPICRA, DAMU, and DAWUSL (2008). *Henan Provincial Institete of Cultural Relics and Archaeology, The Department of Anthropology, Miccuri University, and The Department of Anthropology, Washington University in St. Louis. (2008) The Ying River Civilization–The archaeological investigation, excavation and research in the areas of upper Ying River*. Zhengzhou: Elephant Press.

HPICRA (2009). *Henan Provincial Institute of Cultural Relics and Archaeology. (2009) Nanjiaokou site in Sanmenxia*. Beijing: Science Press.

IACASS, and HPICRA (2010). *Institute of Archaeology, Chinese Academy of Social Sciences, and Henan Provincial Institete of Archaeology and Cultural Relics. (2010). Xipo Cemetery in Lingbao*. Beijing: Cultural Relics Press.

IACASS and SAACATYRV (2019). *Institute of Archaeology, Chinese Academy of Social Sciences, and Sino-Australian-American Collaborative Archaeological Team of the Yiluo River Valley. (2019). Pre-Qin period sites in the East and Central Luoyang Basin: The Systematic Regional Archaeology Survey Report(1997–2007)*. Beijing: Science Press.

Jia, X., Dong, G. H., Li, H., Brunson, K., Chen, F. H., Ma, M. M., et al. (2013). The development of agriculture and its impact on cultural expansion during the late neolithic in the western loess plateau, china. *Holocene* 23, 85–92. doi: 10.1177/0959683612450203

Jiang, W. Y., Guo, Z. T., Sun, X. J., Wu, H. B., Chu, G. Q., Yuan, B. Y., et al. (2006). Reconstruction of climate and vegetation changes of Lake Bayanchagan (Inner Mongolia): Holocene variability of the East Asian monsoon. *Quat. Res.* 65, 411–420. doi: 10.1016/j.yqres.2005.10.007

Jin, S. A. (2005). *The communication and merging of archaeological culture between Heluo and Haidian Regions*. PhD dissertation, Zhengzhou: Zhengzhou University.

Jones, M. K., and Liu, X. Y. (2009). Origins of agriculture in east asia. *Science* 324, 730–731. doi: 10.1126/science.1172082

Kong, Z. C., Liu, C. J., and Zhang, J. Z. (1998). Plant remains at the Bancun site, Mianchi County, Henan Province and their significance in environmental archaeology. *Q. Sci.* 3, 280–280.

Kong, Z. C., Liu, C. J., and Zhang, J. Z. (1999). Discovery of plant remains in the Neolithic site at the Bancun site, Mianchi County, Henan Province and their significance in human environment. *Acta Anthropolog. Sinica* 4, 290–295.

Kuijt, I., and Goring-Morris, N. (2002). Foraging, farming, and social complexity in the pre-pottery neolithic of the southern Levant: a review and synthesis. *J. World Prehistory* 16, 361–440. doi: 10.1023/a:1022973114090

LCCSC (1997). *The Local Chronicle Committee of the Sanmenxia City. (1997). The local chronicles of the Sanmenxia city*. Zhengzhou: Zhongzhou Ancient Books Publishing House.

Lee, G. A., Crawford, G. W., Liu, L., and Chen, X. C. (2007). Plants and people from the Early Neolithic to Shang periods in north China. *Proc. Nat. Acad. Sci*. 104, 1087–1092. doi: 10.1073/pnas.0609763104

Li, Y. C. (1995). *Land Records of Gongyi City*. Zhengzhou: Henan Science and Technology Press.

Li, Y. F., Yu, G., Li, C. H., Hu, S. Y., Shen, H. D., and Yin, G. (2014). Environment reconstruction of Mid- Holocene pa-leo- lakes in Zhengzhou and surrounding regions and the significance for human cultural development in Central China. *Mar. Geol. Q. Geol.* 34, 143–154.

Li, Y. P. (2018). *A comparative study on the subsistence of the north and south Henan Province in the period of Peiligang and Yangshao Culture*. Master dissertation, Beijing: Beijing Union University.

Li, Y. P., and Zhang, J. N. (2020). The influence of landscape evolution on rice planting in the middle-late Neolithic period to Xia-Shang dynasties in Luoyang Basin. *Q. Sci.* 40, 499–511. doi: 10.11928/j.issn.1001-7410.2020.02.19

Liao, Y. N., Lu, P., Mo, D. W., Wang, H., Storozum, M. J., Chen, P. P., et al. (2019). Landforms influence the development of ancient agriculture in the Songshan area, central China[J]. *Quat. Int.* 521, 85–89. doi: 10.1016/j.quaint.2019.07.015

Liu, C. J., Jin, G. Y., and Kong, Z. C. (2008). *Archaeobotany: research on seeds and fruits*. Beijing: Science Press.

Liu, H., Hu, S. M., Zhang, P. C., Yang, Q. H., Jiang, H. E., Wang, W. L., et al. (2013). Analysis and comparison of flotation results of two sites of Yangshao period in Shaanxi. *Archaeol. Cultural Relics* 4, 106–112. doi: 10.3969/j.issn.1000-7830.2013.04.011

Liu, L. (2005). *The Chinese Neolithic: Trajectories to Early States*. Oxford City: Cambridge University Press.

Liu, L., and Chen, X. C. (2012). *The Archaeology of China: From the Late Paleolithic to the Early Bronze Age*. Oxford City: Cambridge University Press.

Liu, X. Y., Hunt, H. V., and Jones, M. K. (2009). River valleys and foothills: changing archaeological perceptions of north china's earliest farms. *Antiquity* 83, 82–95. doi: 10.1017/S0003598X00098100

Lu, H. Y. (2017). New methods and progress in research on the origins and evolution of prehistoric agriculture in China. *Sci. China: Earth Sci.* 60, 2141–2159. doi: 10.1007/s11430-017-9145-2

Lu, H. Y., Zhang, J. P., Wu, N. Q., Liu, K. B., Xu, D. K., and Li, Q. (2009). Phytoliths Analysis for the Discrimination of Foxtail Millet (*Setaria italica*) and Common Millet (*Panicum miliaceum*). *PLoS One* 4:e4448. doi: 10.1371/journal.pone.0004448

Lu, P., Lu, J. Q., Zhuang, Y. J., Chen, P. P., Wang, H., Tian, Y., et al. (2020). Evolution of Holocene alluvial landscapes in the northeastern Songshan Region, Central China: Chronology, models and socio-economic impact. *Catena* 197:104956. doi: 10.1016/j.catena.2020.104956

Luan, F. S. (1996). On the relationship between Orient and Central Plains in Yangshao Period. *Archaeology* 4, 45–58.

Luan, F. S. (2012). Discussion on the social stratification of Middle Yangshao Period. *East Asia Archaeol.* 2012, 44–56.

Marcott, S. A., Shakun, J. D., Clark, P. U., and Mix, A. C. (2013). A reconstruction of regional and global temperature for the past 11,300 years. *Science* 339, 1198–1201. doi: 10.1126/science.1228026

Mogan, L. H. (1963). *Ancient Society*. New York,NY: World.

Renfrew, J. (1973). *Palaeoethnobany: The prehistoric food plants of the Near East and Europe*. Edinburgh: Columbia University Press.

Ren, X. L., Lemoine, X., Mo, D. W., Kidder, T. R., Guo, Y. Y., Qin, Z., et al. (2016). Foothills and intermountain basins: does china's fertile arc have 'hilly flanks'? *Quat. Int.* 426, 86–96. doi: 10.1016/j.quaint.2016.04.001

Robert, M. G., Robert, V., Gardner, H., and Bruce, T. (1989). Effects of changing spatial scale on the analysis of landscape pattern. *Landscape Ecol.* 3, 153–162. doi: 10.1007/BF00131534

Rosen, A. M. (2008). The impact of environmental change and human land use on alluvial valleys in the Loess Plateau of China during the Middle Holocene. *Geomorphology* 101, 298–307. doi: 10.1016/j.geomorph.2008.05.017

Sandweiss, D. H., Maasch, K. A., and Amderson, D. G. (1999). Climate and culture: Transitions in the Mid-Holocene. *Science* 283, 499–500. doi: 10.1126/science.283.5401.499

Service, E. R. (1962). *Primitive social organization: An evolutionary perspective*. New York,NY: Random House.

SCGR (1994). *Society of Crop Genetic Resources, Chinese associaton of agricultural science societies. (1994). Crop genetic resources in China*. Beijing: China Agriculture Press.

Shakun, J. D., Clark, P. U., Feng, H., Marcott, S. A., Mix, A. C., Liu, Z. Y., et al. (2012). Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation. *Nature* 484, 49–54. doi: 10.1038/nature10915

Shi, Y. F., Kong, Z. C., Wang, S. M., Tang, L. Y., Wang, F. B., Yao, T. D., et al. (1992). Climatic fluctuations and important events during the Holocene Mega Warm Period in China. *Science*, 1300–1308.

Smith, M. E. (2009). Gordon Childe and the urban revolution: an historical perspective on a revolution in urban studies. *Town Plann. Rev.* 80, 2–29. doi: 10.2307/27715085

Sun, X. W., and Xia, Z. K. (2005). Paleoenvi-ronment changes since Mid-Holocene revealed by a paly-nological sequence from Sihenan profile in Luoyang, Henan Province. *Acta Scientiar. Natural. Univer-sitatis Pekinensis* 41, 289–294. doi: 10.3321/j.issn:0479-8023.2005.02.016

Tylor, E. B. (1958). *Primitive culture*. New York,NY: Harper.

Wagner, M., Pavel, T., Dominic, H., Fleck, A., Ehrich, R., Chen, X. C., et al. (2013). Mapping of the spatial and temporal distribution of archaeological sites of northern China during the Neolithic and Bronze Age. *Quat. Int.* 290, 344–357. doi: 10.1016/j.quaint.2012.06.039

Wang, H. J. (1999). The local chronicles of the Luoyang city.

Wang, C., Lu, H. Y., Zhang, J. P., Ye, M. L., and Cai, L. H. (2015). Phytolith evidence of millet agriculture in the late Neolithic archaeological site of Laijia, Northwestern China. *Q. Sci.* 35, 209–217. doi: 10.11928/j.issn.1001-7410.2015.01.20

Wang, C. (2016). *Research on the early farming-human activities in the central China and their relation with climate changes*. Beijing: University of Chinese Academy of Sciences. PhD dissertation.

Wang, C., Lu, H. Y., Gu, W. F., Wu, N. Q., Zhang, J. P., Zuo, X. X., et al. (2017). The spatial pattern of farming and factors influencing it during the peiligang culture period in the middle yellow river valley, china. *Sci. Bull.* 62, 1565–1568. doi: 10.1016/j.scib.2017.10.003

Wang, C., Lu, H. Y., Gu, W. F., Wu, N. Q., Zhang, J. P., Zuo, X. X., et al. (2019a). The development of Yangshao agriculture and its interaction with social dynamics in the middle Yellow River region, China. *Holocence* 29, 173–180. doi: 10.1177/0959683618804640

Wang, C., Lu, H. Y., Gu, W. F., Wu, N. Q., Zhang, J. P., Zuo, X. X., et al. (2019b). Spatial-temporal evolution of agricultural and factors influencing it during the mid-Holocence in Zhengzhou area, China. *Quat. Sci.* 39, 108–122. doi: 10.11928/j.issn.1001-7410.2019.01.11

Wang, C., and Lu, H. Y. (2020). The carbonization temperature of common and foxtail millet and its implication in archaeobotany. *Southeast Cult.* 1, 65–74.

Wang, J. H. (2005). *Prehistoric population in the middle and lower areas of the Yellow River*. PhD dissertation, Jinan: Shandong University.

Wang, X. G. (2005). The Holocene Megathermal in China with the agricultural civilization in the middle and lower reaches of the Yellow River. *J. Histor. Sci.* 4, 5–13.

Wei, X. T. (2014). The discoveries and preliminary researches of plant remains in the region of western Henan and the southwestern Shanxi in the Neolithic Age. *East Asia Archaeol.* 343–363.

Winter-Livneh, R., Svoray, T., and Gilead, I. (2010). Settlement patterns, social complexity and agricultural strategies during the chalcolithic period in the northern Negev, Israel. *J. Archaeolog. Sci.* 37, 284–294. doi: 10.1016/j.jas.2009.09.039

Xia, Z. K., Chen, F. Y., Chen, G., Zheng, G. W., Xie, F., and Mei, H. J. (2001). Environmental background of Neo-Paleolithic culture transition in Nihewan Basin, North China. *Science* 5, 393–400. doi: 10.3321/j.issn:1006-9267.2001.05.006

Xia, X. M., Sun, Z. Y., Yang, L. P., Kang, N. W., Chen, X. L., Wang, C. S., et al. (2016). Analysis of phytoliths from the Wangyangpan archaeological site, Yulin, North Shaanxi. *Acta Anthropolog. Sinica* 35, 257–266. doi: 10.16359/j.cnki.cn11-1963/q.2016.0023

Yan, W. M. (1989). *Research on Yangshao Culture*. Beijing, China: Cultural Relics Publishing House.

Yang, L., Ma, M. M., Chen, T. T., Cui, Y. F., Chen, P. P., Zheng, L. C., et al. (2020). How did trans-Eurasian exchanges affect spatial-temporal variation in agricultural patterns during the late prehistoric period in the Yellow River valley (China)? *Holocene* 1:095968362094114. doi: 10.1177/0959683620941140

Yang, Q., Li, X. Q., Zhou, X. Y., Zhao, K. L., Ji, M., and Sun, N. (2011). Investigation of the ultrastructural characteristics of foxtail and broomcorn millet during carbonization and its application in archaeobotany. *Chinese Sci. Bull.* 56, 700–707. doi: 10.1007/s11434-011-4423-1

Yang, X. Y., Wu, W. X., Perry, L., Ma, Z. K., Bar-Yosef, O., Cohen, D. J., et al. (2018). Critical role of climate change in plant selection and millet domestication in North China[J]. *Sci. Rep.* 8:7855. doi: 10.1038/s41598-018-26218-6

Yang, Z. Q. (1997). On the nature of the late Yangshao Culture ancient city site in Xishan, Zhengzhou. *Huaxia Archaeol.* 1, 55–59.

Zhai, Q. M., Guo, Z. Y., and Shen, J. (2011). Sedimentary characteristics of lacustrine sediment profile and paleoenvironment in Mianchi Basin, Western Henan Province. *Sci. Geographica Sinica* 31, 922–928.

Zhang, J. N., Xia, Z. K., and Zhang, X. H. (2014). Research on charred plant remains from the Neolithic to the Bronze Age in Luoyang Basin. *Chin. Sci. Bull.* 59, 3388–3397. doi: 10.1360/n972013-00022

Zhang, J. N., Xia, Z. K., Zhang, X. H., Storozum, M. J., and Huang, X. Z. (2018). . *Q. Res. Inter. J.* 2018, 1–13. doi: 10.1017/qua.2017.104

Zhang, J. N., Zhang, X. H., Xia, Z. K., Xu, H., and Zhao, H. T. (2019). Geomorphic changes along the Yiluo River influenced the emergence of the first urban center at the Erlitou site, Central Plains of China. *Quat. Int.* 521, 90–103. doi: 10.1016/j.quaint.2019.06.038

Zhang, J. P., Lu, H. Y., Wu, N. Q., Li, F. J., Yang, X. Y., Wang, W. L., et al. (2010). Phytolith evidence of millet agriculture during about 6000-2100 cal. a B. P. in the Guanzhong Basin, China. *Q. Sci.* 30, 287–297.

Zhang, J. P., Lu, H. Y., Gu, W. F., Wu, N. Q., Zhou, K. S., Hu, Y. Y., et al. (2012). Early mixed farming of millet and rice 7800 years ago in the middle yellow river region, china. *PLoS One* 7:e52146. doi: 10.1371/journal.pone.0052146

Zhang, J. T. (2016). *The research on agric ulture of the Central Plains region in Shang Dynasty*. PhD dissertation, Zhengzhou: Zhengzhou University.

Zhang, X. H. (2010). *Mid-Holocence environment achaeology research in diffirent regions of Huanghe River reaches*. PhD dissertation, Beijing: Peking University.

Zhao, C. Q. (2001). *The evolution of neolithic settlements in Zhengzhou and Luoyang area*. Beijing: Peking University Press.

Zhao, Y. Y. (2018). *The reacher of primitive agricultural types and early Chinese civilization*. PhD dissertation, Yanglin: Northwest A&F University.

Zhao, Z. J., and He, N. (2006). Flotation results and analysis of Taosi city site in 2002. *Archaeology* 5, 77–86.

Zhao, Z. J. (2003). The preliminary floatation results of the Lajia site, Qinghai Province. *China Cultural Relics News* 9:19.

Zhao, Z. J. (2011). Characteristics of agricultural economy during the formation of ancient Chinese civilization. *J. Natl. Museum* 1, 19–31.

Zhao, Z. J. (2014). The process of origin of agriculture in China: Plant remains evidence from flotation results. *Q. Sci.* 34, 73–84. doi: 10.3969/j.issn.1001-7410.2014.10

Zhao, Z. J. (2017). The development of agriculture in the time of Yangshao culture and the establishment of agricultural society: An analysis on the flotation result of Yuhuazhai site. *Jianghan Archaeol.* 6, 98–108.

Zhong, H., Yang, Y. C., Shao, J., and Zhao, Z. J. (2015). Study on the remains of carbonized plants in Xinjie Site, Lantian County, Shaanxi Province. *Relics South* 3, 36–43. doi: 10.3969/j.issn.1004-6275.2015.03.008

Zhong, H. (2016). *Paleoethnobotany from Middle Yangshao to Longshan Periods in the Central Plains*. PhD dissertation, Beijing: School of Chinese Academy of Social Science.

Zhong, H. (2018). The tentative research of the spreading of rice in the Central Plain during Prehistoric Period. *Western Archaeol.* 1, 211–223.

Zhong, H., Li, X. W., Wang, W. L., Yang, L. P., and Zhao, Z. J. (2020). Preliminary research of the farming production pattern in the Central Plain area during the Miaodigou Period. *Q. Sci.* 40, 472–485. doi: 10.11928/j.issn.1001-7410.2020.02.17

ZMIA (2001). *Zhengzhou Municipal Institute of Archaeology. (2001). Dahecun*. Beijing: Science Press.

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Two Sides of the Same Coin: A Combination of Archaeometallurgy and Environmental Archaeology to Re-Examine the Hypothesis of Yunnan as the Source of Highly Radiogenic Lead in Early Dynastic China

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Bronze Age Shang China is characterized by its large-scale production system and distinctive ritual world. Both are vividly materialized by a large number of bronze ritual vessels with added lead. Whilst a remarkable amount of research effort has been channeled into the trace elemental and lead isotopic analysis of these ritual vessels, and successfully revealed some important fingerprints such as highly radiogenic lead (HRL), there is as yet no consensus on the metal source(s) which supplied the entire bronze production during the Shang period. In addition to the traditional method to look for matching and mismatching between ores and objects, we propose that environmental archaeological studies can provide crucial clues to address some long-standing questions in archaeometallurgy. In the first part of the paper, we attempt to illustrate the potential and complexity of combining these two subjects together. The second part of the paper offers a case study by reviewing the debate on Yunnan as the source of HRL. Synthesis of various lines of evidence published by most recent studies on environmental archaeology, archaeometallurgy, field reports and radiocarbon dating suggests that this hypothesis appears much less likely than previously suspected.

Keywords: environmental archaeology, archaeometallurgy, Yunnan, highly radiogenic lead, metal pollution

INTRODUCTION

Archaeometallurgy and environmental archaeology have become increasingly important in the study Bronze Age China in recent years (Xu et al., 2011; Zhang et al., 2017; Qiu et al., 2019; Storozum et al., 2020). In fact, these two subjects share a variety of research interests and objectives (Nriagu, 1972; Abbott and Wolfe, 2003; Thevenon et al., 2011; Iles, 2016; McConnell et al., 2018). Archaeometallurgy is primarily focused on all the archaeological records related to metallurgy (Rehren and Pernicka, 2008; Roberts and Thornton, 2014). Metallurgical production is a highly complex process, encompassing mining, ore crushing and selection, smelting, mould-making, casting and recycling. Each of these processes can certainly leave some markers which are detectable by environmental research. However, in the current literature we find very little attempt to correlate these two branches of archaeology in Chinese prehistoric studies. In this paper, we argue that there is great potential for archaeometallurgists and environmental scientists to work together and resolve many critical questions in both disciplines. To exemplify this, we choose to revisit the long-standing issue of highly radiogenic lead (HRL) in Chinese Bronze Age archaeology by integrating the most recent work on archaeometallurgy, environmental science and archaeological excavations. Synthesis of these various lines of information implies increasingly less possibility for Yunnan to be the source of HRL used in Bronze Age Shang China (ca. 1500–1045 BC).

Two features of metallurgical production in Bronze Age China make it particularly relevant for environmental research. The first one is the large scale of production (Ledderose, 2000; Pollard et al., 2017a; Rawson, 2017a). Since the early Shang period, especially from the upper Erligang phase (ca. 1500–1450 BC), one starts to see strong evidence of mass production of bronzes in the Central Plains (Chen, 2016; Rawson, 2017b; Xu, 2020). Although the major part of Shang Zhengzhou is still underneath the present-day Zhengzhou city, the three bronze hoards demonstrate the remarkable skills of bronze casting and the high volume of raw metal accessible to the early Shang power (Henan Institute of Archaeology, 2001). More crucially, they have also provided us with the first robust evidence for bronze ritual vessels being used in sets, which was central to ritual practice throughout the Chinese Bronze Age, and is well-documented in later Eastern Zhou period (ca. 770–256 BC) (Bagley, 1999; Rawson, 1999; Zhang, 2014). This becomes even more prominent in the Anyang period (ca. 1300–1045 BC) where thousands of elite tombs were discovered containing bronze objects. In the tomb of Fu Hao, the only intact royal tomb so far excavated at Anyang, archaeologists recovered 1.6 tonnes of bronze objects (The Institute of Archaeology, 1980; Bagley, 1999). Another good example of the large-scale of bronze production at Anyang is the famous Houmuwu Ding, containing over 830 kg of metal. Both Fu Hao's metal assemblage and the Houmuwu Ding mean that craftspeople had to process probably tens or even hundreds of tons of ores and slags, depending on the type and quality of the ores. It is important to note that although Anyang was probably the largest bronze consumer during the late Shang dynasty, it is nevertheless located in the Central Plains with the least abundant nearby metal resources (Liu and Chen, 2009; Li, 2014; Liu, 2016). The majority of metal resources in China are distributed in the middle and lower Yangtze river valley, Yunnan, the Hexi Corridor and Northeast China. Therefore, apart from the workshop practice, more labor was certainly necessary for mining, smelting and transporting metals from other places to the Central Plains. Moreover, metal production in the entire Chinese Bronze Age was based on ceramic piece-mould casting. Preparing the ceramic molds obviously required more fuel (i.e., charcoal), leading to the expectation that intensive markers would be left in various environmental records (e.g., deforestation, pollution or other anthropogenic proxies, see below).

The second feature of metal production for Bronze Age China is the addition of lead (Pollard et al., 2017a; Pollard et al., 2017b). Although metallurgy was introduced into the Central Plains from the steppe (Roberts et al., 2009; Linduff and Mei, 2014), with specific timing and route(s) still to be ascertained, the prevailing alloying recipes on the steppe are tin bronze, arsenical copper and arsenical bronze (Chernykh, 1992; Mei, 2009; Hsu, 2016). In contrast, it was only in the Central Plains that lead became a major alloying element. It is so far still impossible to illustrate when exactly lead started to be deliberately added to copper. Some evidence derives from the range of lead percentages in the objects. Since Erlitou Phase IV, one can see an increasing number of copper-alloyed objects containing lead over 5% (Jin, 2008; IA; CASS, 2014). This is undoubtedly beyond the general level of impurity in coper ores and can therefore be considered as a deliberate addition. Further evidence comes from Anyang. In the top-elite tomb M1046 (dated to Anyang Phase IV), the nine ritual vessels show a remarkably high percentage of lead, but with very narrow variation (between 30 and 35% Pb), suggesting a well-controlled alloying practice for lead (Zhao et al., 2008; Liu et al., 2020b).

Both large-scale production and the widespread use of lead could exert profound impacts on the environment. However, there is considerable complexity involved in integrating archaeometallurgy with environmental records (**Figure 1**). The most characteristic environmental marker left by metallurgical production is probably the increased levels of metallic elements, such as copper, tin, lead, arsenic, nickel, zinc in the environment. Each step of metallurgical production can significantly increase the concentrations of metallic elements in the atmosphere or biosphere. Therefore, the rise and fall of metallurgy in one region is often used as a reason to explain metal variations in the environmental records, such as ice cores, lake sediments and excavation profiles (Abbott and Wolfe, 2003; Zhang et al., 2017; McConnell et al., 2018). This is particularly true if regional metallurgical production can be linked to state expansion or warfare, when more metal objects (i.e., weapons) became widely needed. The Greenland ice core shows various rises and falls in the level of lead since ca. 1000 BC, which were ultimately sourced to the lead pollution in Europe by the atmospheric circulation modeling. Further archaeological and historical evidence back up such linkages. Based on a refined high-resolution chronology (ca. 1–10 years), McConnell et al. (2018) were able to correlate the changing levels of lead in the ice core to a variety of human factors that affected the production of silver in Europe, such as the Phoenician expansion, new silver mines being opened, along with Roman expansion and plagues that destroyed local mining industries. Silver is generally extracted from argentiferous lead ores, so the increased production of silver gives rise to increased levels of lead in the atmosphere. Similar examples can be also found in the silver extraction in Potosi, South America from the 16th century CE. The patterns of metallic elements (Pb, Sb, Ag, Bi and Sn) reveal critical information on not only the scale of local silver production (approximated by the lead spikes in the lake sediments), but also the technological changes brought about by local people or early Spanish arrival. The rapid disappearance of spikes for Ag, Bi and Sn were caused by the improved capability of local smelters to control these volatile elements. However, the new Spanish smelting technology used stone furnaces to overheat the ores, which not only failed to extract their targeted silver, but

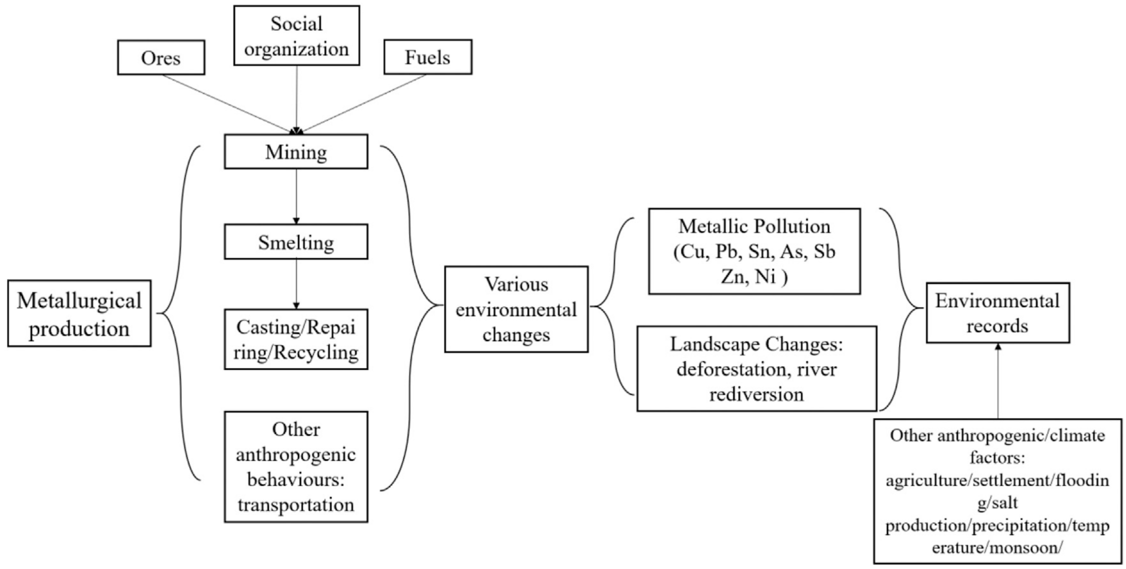

FIGURE 1 | Potential environmental changes caused by metallurgical production.

also triggered higher metallic pollution in atmosphere, which was also registered in the lake sediment. It was only in 1572 CE when mercury amalgamation was introduced into Bolivia from Mexico which allowed people to extract low-grade ores more efficiently and reduce these atmospheric fluxes (Abbott and Wolfe, 2003).

The ultimate reason for the complexity of combining archaeometallurgy and environmental data is that, apart from metallurgy, a range of different anthropogenic activities and natural factors can also result in the rise of metallic concentrations in sediments. One vivid example comes from four Neanderthal cave sites in the Iberian Peninsula. Scholars have discovered a substantial elevation in the concentrations of copper, zinc, nickel and lead in the profile of the cave sites, which were clearly unrelated to metallurgy. Copper, zinc and nickel are crucial micronutrients for plant growth, and therefore the resultant wood ash after combustion may well concentrate these metallic elements in cave deposits. For some samples, guano (bird or bat droppings) is also an important source for zinc and copper. Lead is slightly different in this case, as it is more likely to be derived from galena (or lead ornaments) leaching down from upper layers (Monge et al., 2015). The scope of catchment is another key issue in interpreting metal pollution and other environmental markers. For some environmental records such as the Greenland ice cores, the lead pollution was mainly transported from continental Europe by air movement (macro-scale) (McConnell et al., 2018). In other cases, local sources and activities can be more significant, particularly for lakes which were linked to local rivers associated with metallurgical activities (mining or smelting). Other issues are related to chronological resolution. Whilst it is sometimes possible to use isotopic analysis to source metal pollution, in most cases scholars have to rely on chronology (e.g., synchronicity) to 1) establish correlation between metallurgy and environmental changes and 2) deduce underlying causality. The exact sequence of events is therefore of uttermost importance but due to the lack of good-quality materials for dating, the chronological resolution for environmental or archaeological records could be more than one hundred years for some key periods, making it less useful to interpret potential cause and effect between different events in Bronze Age.

THE CURRENT STATE OF DEBATE

The Current State of Debate on Highly Radiogenic Lead

In Chinese archaeology, highly radiogenic lead, or HRL, refers to a specific type of lead characterized by higher values of the lead isotopic signature (e.g., $^{206}Pb/^{204}Pb > 19$, $^{207}Pb/^{204}Pb > 15.75$ and $^{208}Pb/^{204}Pb > 39.0$) (Jin, 2008; Liu et al., 2015; Jin et al., 2017). These higher isotopic ratios are ultimately derived from excessive amounts of uranium and/or thorium in the geological environment (Russell and Farquhar, 1960; Pollard et al., 2017c). It was first discovered in the bronzes at Anyang, the last capital of the Shang dynasty (ca. 1300 BC–1050 BC), by Prof Jin Zhengyao and his Chinese and Japanese colleagues (Jin, 1987). This soon rose to world-wide academic attention because HRL has to be formed through a very unique geological history, in which uranium and thorium have to be mobilized together (Prof D. Killick pers. comm). This is easier for uranium which can be dissolved in water and incorporated with other minerals. But thorium is insoluble and thus requires a different geological mechanism to be emplaced in the deposits (Chen et al., 2020; Liu et al., 2021). Several surveys of the geological literature show that the number of metallic deposits which can yield HRL is far less than those giving common lead (Jin et al., 2017; Hsu and Sabatini, 2019; Hsu et al., 2021).

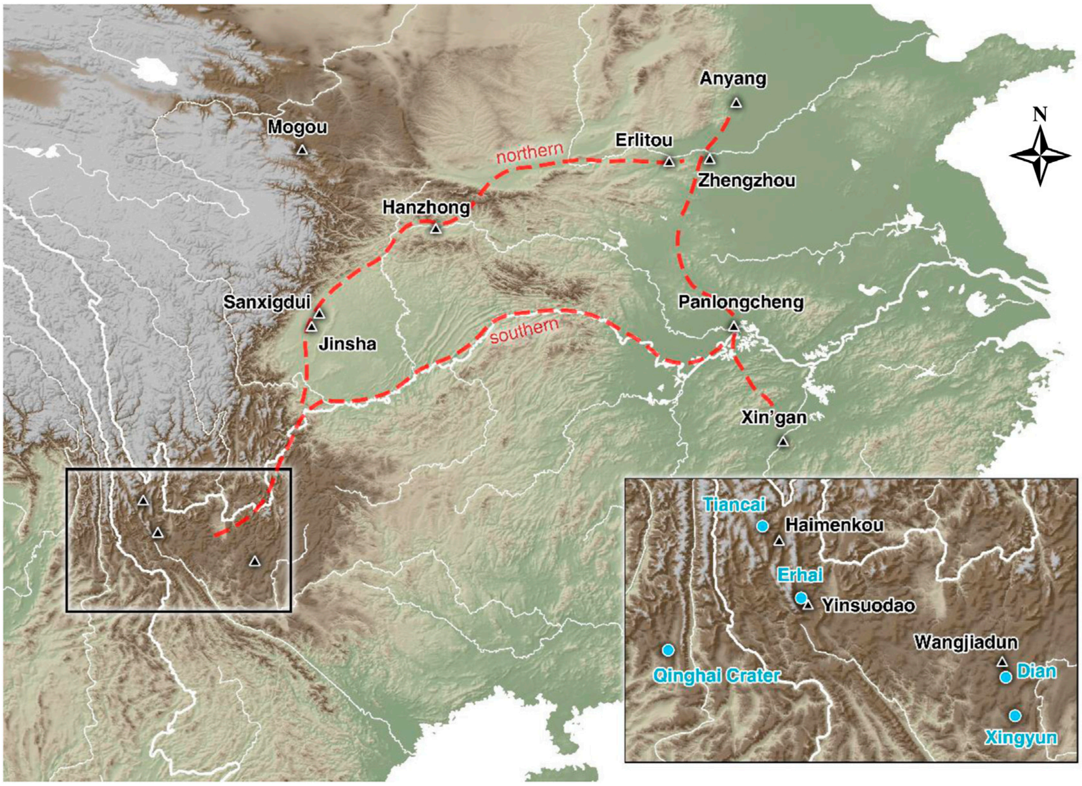

FIGURE 2 | Key archaeological sites mentioned in the text and the proposed northern and southern routes of highly radiogenic lead (HRL) from Yunnan to the Central Plains.

Decades of effort in tracking HRL have produced a comprehensive illustration of the spatial-temporal pattern of HRL during the Shang period (ca. 1500–1050 BC). The current consensus is that HRL firstly came in to use around the Erligang Lower Phase (Jin, 2008), though one bronze fragment at Erlitou is also highly radiogenic (Jin et al., 2001; Liu et al., 2021b). It soon came to dominate the supply of metal during the Erligang period. Not only at Erligang, now known as Zhengzhou, one of the capitals for the early Shang dynasty, but also at Panlongcheng along the Yangtze River, at Hanzhong along the Han River and at Mogou in the east Hexi Corridor exist a considerable number of objects been discovered with HRL. It became even more widely distributed during the Anyang period, covering northeast China, the Central Plains, middle and lower Yangtze River Valley, Hanzhong Basin and Sichuan Basin. However, the use of HRL suddenly ceased after the Shang dynasty. To be more specific, at Anyang, it once dominated over 75% of metal supply in Phase II and 50% in Phase III, but virtually disappeared in Phase IV. So far, the latest site which was heavily dependent on radiogenic lead is Jinsha in the Sichuan basin, dated to the early Western Zhou dynasty (for more details see Jin et al., 2017 and Liu et al., 2021).

The provenance of HRL has been a matter of intense debate since Jin and colleagues discovered this signal in Shang bronzes in the 1980s. It is of critical importance for reconstructing the flow of metal during the Shang period and the organization of mass bronze production that underpinned the ritual world across the Yellow and Yangtze River. Based on a comparison of lead isotopic ratios between the Shang bronzes and geological data (ores such as galena), Jin proposed that Northeast Yunnan was where the "best match can be found between the Shang bronzes and local ores", although he admitted himself that they are not completely the same (NE Yunnan is much less radiogenic than the Shang bronzes, see Jin, 2008: 21). This stimulated an extensive debate between archaeologists and geochemists. No other archaeological evidence has been found to support such long-distance communication between Yunnan and the Central Plains in the Bronze Age. Moreover, the earliest metallurgical evidence at Yunnan can only be traced to ca. 1000 BC (see below for updated chronology). The archaeological sites discovered after this pioneering isotopic work at Anyang, such as Sanxingdui, Jinsha, Xin'gan and Hanzhong, all subsequently yielded a significant proportion of bronzes with HRL. The finding of HRL at Sanxingdui and Jinshan in the Sichuan Basin, which is obviously closer to Yunnan than the other sites, seem to support the argument of a Yunnan provenance for this metal. Jin further proposed two routes via which metal could be moved from Yunnan to the Central Plains (**Figure 2**; Jin, 2008: 59–60, 147,285–289). The southern route was more favored as it takes advantage of the river system and also explains the wide distribution of HRL along the middle and lower range of the Yangtze River.

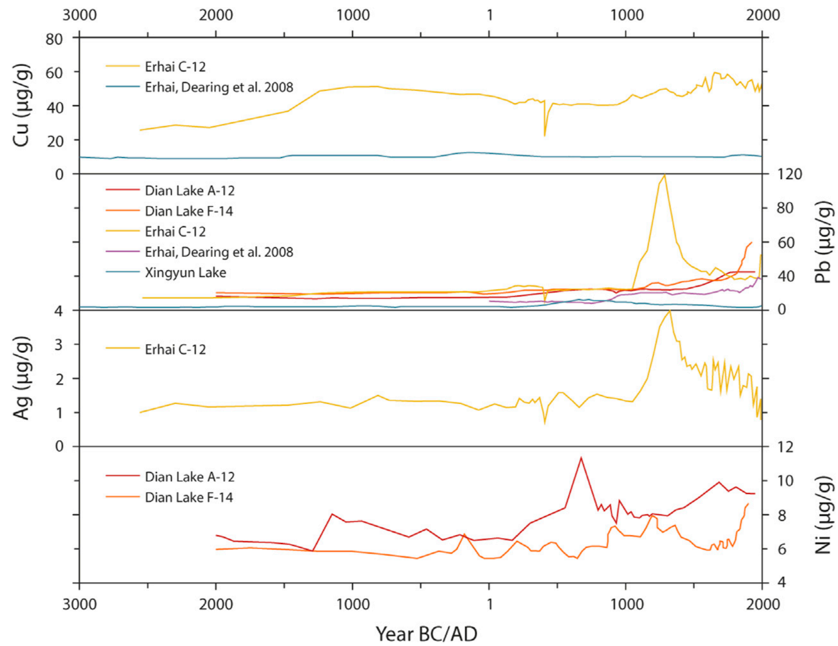

FIGURE 3 | Synthesis of metal pollution data in ancient Yunnan (modified from Hillman et al. (2019); Hillman et al. (2015); Hillman et al. (2014); Dearing et al. (2008)).

A Yunnan provenance has, however, been challenged by new data from both geologists and archaeologists. More and more lead isotopic data has been published for lead ores in China, showing that a variety of regions can produce HRL, including not only Yunnan, but also the Zhongtiao Mountains (Tong, 2012; Qin et al., 2020), the Qinling Mountains (Chen et al., 2019; Zhangsun et al., 2021), metallic deposits along the Yangtze River (Peng et al., 1999), Northeast China (Wang et al., 2020), the Hexi Corridor (Chen et al., 2020; Liu et al., 2021b: Hexi type HRL) and Xinjiang (Liu et al., 2020a). Recently, even South Africa has been listed as one potential source of HRL for Chinese bronzes (Sun et al., 2016; Liu et al., 2018b; Liu et al., 2018c; Sun et al., 2018). Liu et al. (2018a) reviewed lead isotopic data for a wider range of lead-bearing materials (e.g., copper-based objects, glaze, glass, and pigments) and pointed out that HRL sources of lead were explored across Chinese antiquity. It is highly unlikely that one specific source of HRL could have been repetitively exploited over such a long period. However, what remains uncertain is how many sources were used within the chronological range of the Shang dynasty. Sources such as Zhongtiao, the middle and lower Yangtze and Qinling are favored by archaeologists as they already showed clear evidence for a mining industry during the Shang period. Data accumulated in the last ten years from environmental archaeology, field archaeology and archaeometallurgy allows us to revisit this debate from a fresh perspective and perhaps allows us to exclude some possible sources previously discussed.

New Evidence From Environmental Archaeology

Much research effort has been devoted to reconstructing the human-environment relationship in prehistoric Yunnan. The analytical data from the cores taken from the lakes of Erhai in Northwest Yunnan, Dian and Xingyun in Central Yunnan, are particularly interesting as their environmental data include the key metal concentrations (e.g., copper, lead, silver and zinc, **Figure 3**) (Dearing et al., 2008; Hillman et al., 2014; Hillman et al., 2015; Hillman et al., 2019). Dearing et al. (2008) discovered that in the core of Erhai the copper concentration started to rise around 1400 BC, and linked this to the metallurgical production around the Erhai Lake. The earliest evidence for metallurgical production in Yunnan comes from Haimenkou and Yinsuodao, which fall in the catchment area of Erhai Lake (see *Earliest Archaeological Evidence at Yunnan Metallurgy*). However, lead in the core remained at a rather low level until AD 400. Its rapid increase in the later period was probably due to local silver production, in which cupellation was employed to extract silver from lead ores, and lead was the major by-product released into the atmosphere. Hillman et al. (2015) present similar results for Erhai, showing a clear rise in copper concentration, from 26.8 ± 1 µg/g (2500–2000 BC) to 51.1 µg/g (ca. 1500 BC) but very low levels of lead. They also confirm a synchronous rise of lead and silver starting at around AD 200, which is earlier than the period proposed by Dearing et al. (2008). The Xingyun lake is located in central Yunnan and thus represents a different area of catchment. Although the chronology of the core data only extends to 1BC/AD, it still presents some useful data to infer the earlier metallurgy. The lead

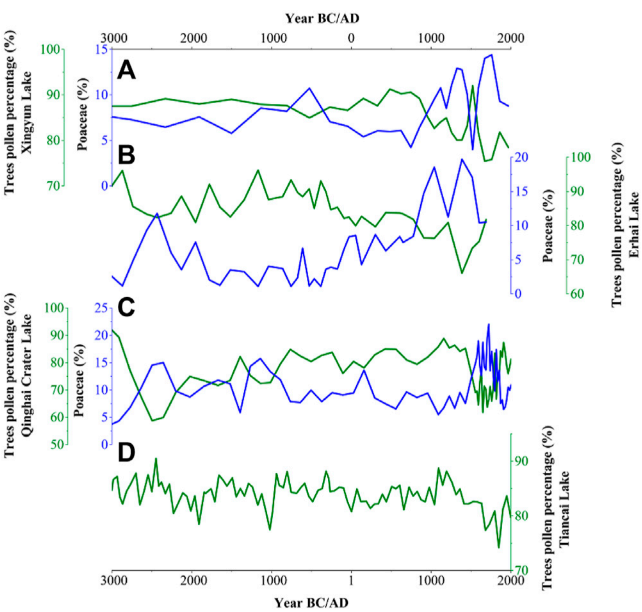

FIGURE 4 | Summary of pollen data for ancient Yunnan (Green lines: tree pollen percentage; Blue lines: poaceae pollen percentage; data source: Shen et al. (2006); Chen et al. (2014); Xiao et al. (2014); Wu et al. (2015); Xiao et al. (2015)).

concentration remains at a very low level (ca. 10 μg/g) until the rise of the Nanzhao Kingdom (AD 738–AD 902), which was probably also due to an increasing scale of silver smelting. The low level of lead pollution in the Xingyun lake in the earlier stage might suggest the absence or very limited scale of metallurgical activities around the eastern part of Yunnan. This assumption is further confirmed by the most recent data from the Dian lake, which is around 60–80 km to the northwest of the Xingyu lake. It also shows a consistently low and stable level of lead pollution (ca. 10 μg/g) between 2000–1 BC/AD (Hillman et al., 2019).

In addition to metal pollution, the other major environmental impact which could be caused by large-scale prehistoric metallurgy is deforestation, since both smelting, casting and mold-making (clay), sometimes also mining (use of fire to crack the rocks), required large amounts of charcoal as fuel. This is nevertheless not completely inevitable, depending on the scale of wood exploitation, and on the forest management practices such as coppicing. Charcoal cannot be made from large trunks, so charcoal production is usually associated with coppicing to manage the trees to produce small branches. **Figure 4** summarizes the variation of pollen data from four lake cores. There appears no evident decrease in the tree pollen data around 2000–500 BC, suggesting the absence of large-scale deforestation in Yunnan. This implies that the possibility of discovering very large-scale metallurgical production in Yunnan dating to this period is very low. The data from the Erhai lake however shows a visible decrease in tree pollen data after 500 BC as well as an increase in poaceae pollen, suggesting stronger human activities probably due to expansion of settlement and agriculture. Whilst textual records in the Eastern Zhou and later periods do testify to metallurgical activities in Yunnan, it is also important to bear in mind that settlement and agricultural production could also result in a similar pattern in the pollen record.

Earliest Archaeological Evidence at Yunnan Metallurgy

The date of the earliest metallurgical production in Yunnan has been debated for decades. Although Jianchuan Haimenkou is widely regarded as the site with the earliest metallurgical evidence, the lack of systematic excavation and high-quality radiocarbon dates has prevented scholars from engaging in further discussion. Two small-scale excavations were carried out at Haimenkou in the years 1957 and 1978, respectively, but only two radiocarbon dates were published. Moreover, a huge chronological discrepancy of 500 years is indicated by these two dates, leading to deep confusion among archaeologists as to which period the archaeological records should be assigned (Min, 2013; Li and Min, 2016).

Local archaeologists decided to perform a much larger and more systematic excavation from 2008. A series of well-defined stratigraphies and high-quality radiocarbon dates are now published, allowing a much more detailed investigation into the development of metallurgy at Haimenkou. The local metal objects are markedly different from those bronze ritual vessels in the Central Plains or the standing figures and human heads at Sanxingdui. At Haimenkou, the objects are all in small sizes, including a bell, knives, chisels, awls, arrows and bracelets. A piece of stone mold has also been discovered, indicating a different metallurgical tradition to that elsewhere in China. The new excavation identified ten stratigraphic layers in total, and the evidence of metallurgy (one bell, one copper tube, one needle, one chisel, one copper block, one awl and one knife) starts in layer VI. Surprisingly, two iron objects were also recovered from the same layer (Min, 2009).

Defining the chronology of the layer VI is however not an easy task. Li and Min (2016) argue that the metal objects in layer VI were most likely dated after the Western Zhou, with the Spring and Autumn Period (ca. 770–475 BC) as the terminus post quem and the early Warring States (ca. 475–221 BC) as the terminus ante quem. Their argument is primarily based on the iron pieces (one small iron circle and one small iron bracelet), the "alloying technology" of the copper objects and one specific radiocarbon date. Metallographic analysis shows that the iron objects were smelted iron rather than meteoritic, and a similar cast iron technology was encountered at the Guo state cemetery at Sanmenxia, which can be safely dated to the early Western Zhou at the earliest (ca.11th–10th century BC). The copper block contains 5.3% antimony, which is rare compared to the prevailing tin-bronze (Cu-Sn) or leaded bronze (Cu-Sn-Pb) elsewhere in China. They argue that such "alloying technology" is more likely to be dated to later periods such as the Warring States, with no further evidence being provided. Moreover, one millet grain discovered in layer VI is radiocarbon dated to the early Warring States (730 BC–410 BC, 68.2% probability; 760 BC–400 BC, 95.4% probability).

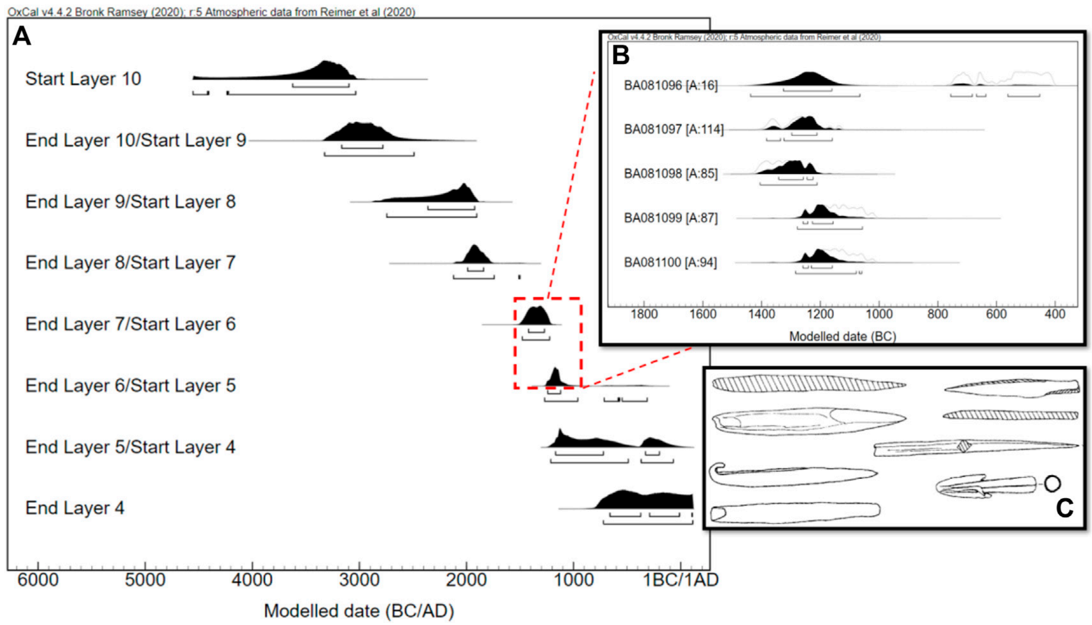

FIGURE 5 | Remodeling of the radiocarbon dates from Haimenkou (**(A)**. the modeled start and end date for each stratigraphic layer at Haimenkou; **(B)**. the four radiocarbon dates assigned to the Layer VI; **(C)**. some metal objects recovered at Haimenkou; data source: Li and Min (2016)).

The occurrence of Cu-Sb should not be considered on its own as evidence for dating. As Li and Min (2016) pointed out, smelting of some natural mixed copper ores such as tetrahedrite $Cu_{12}Sb_4S_{13}$ could also result in such an unusual chemical composition. The word "alloying technology" is sometimes used too casually in archaeometallurgical literature, which is ultimately rooted in the modern industrial metallurgy in which many archaeometallurgists were trained. It is a common assumption in the Chinese literature that any element beyond 2% in the metal can be considered as an intentional addition to copper (thus an alloying element), added in order to modify the physical properties of the finished objects. This is potentially meaningful if one is dealing with a large number of analyses, but should by no means be treated as a golden rule when applied to a single object. A similar case can be found in the early Shang metal assemblage at Hanzhong, where a variety of rare chemical combinations (Cu-As, Cu-Sb, Cu-As-Ni) can be found (Chen et al., 2009; Mei et al., 2009; Chen et al., 2016). This is almost certainly to do with local types of ores rather than artificial alloying. A more detailed discussion of alloying technology/practice can be found in Pollard et al., 2018, Pollard et al., 2019 (chapter 3 and 2019).

The radiocarbon date from the millet seems to be the most compelling evidence. However, three other radiocarbon dates from the same layer suggest a rather earlier chronology of around 1300–1100 BC. **Figure 5** shows a new Bayesian model for the Haimenkou chronology, which integrates not only the radiocarbon dates but also the stratigraphy. Given the fact that two samples are charcoal from unknown species (therefore of unknown ring position relative to the outer ring), we chose to apply Charcoal Plus Outlier Model to these samples, in order to minimize the potential effect of inbuilt-age (Dee and Bronk Ramsey, 2014). For the other samples, we have applied a General_Outlier model to reveal possible outliers due to laboratory analysis or erroneous stratigraphy (Bronk Ramsey, 2009). It is rather obvious that the posterior range of the date from the layer VI millet (BA081097) is far later than the other three dates and is completely inconsistent with the stratigraphic sequence (**Figure 5B**). Bayesian analysis also confirms that the probability for this sample to be an outlier is extremely high (ca. 88%). As all the samples followed the same analytical protocol, it is highly unlikely that this offset is due to laboratory analysis. We think it is most likely to be an intrusion from upper layers, therefore giving a much later date. In this light, it is also necessary to reconsider whether or not the two iron pieces were also intrusions.

After careful investigation into the complexity associated with chronology, it is reasonable to argue that so far the earliest metallurgical production at Haimenkou can be dated to around 1200 BC. This is still approximately three hundred years later than the first use of HRL in the Central Plains. The most recent excavation shows a scale of metallurgical activity at Haimenkou that is far from being equivalent to any major metal producers or consumers along the Yangtze or the Yellow River. All the recovered metal objects are small in size, designed for daily use or personal ornaments. No evidence of large metal production/consumption has been found. This raises the question that, if Yunnan was the producer of HRL which supported the metal production at Zhengzhou, Anyang, Sanxingdui, Hanzhong, Panlongcheng, Xin'gan and many others, why the contemporary metal production within Yunnan was still so primitive.

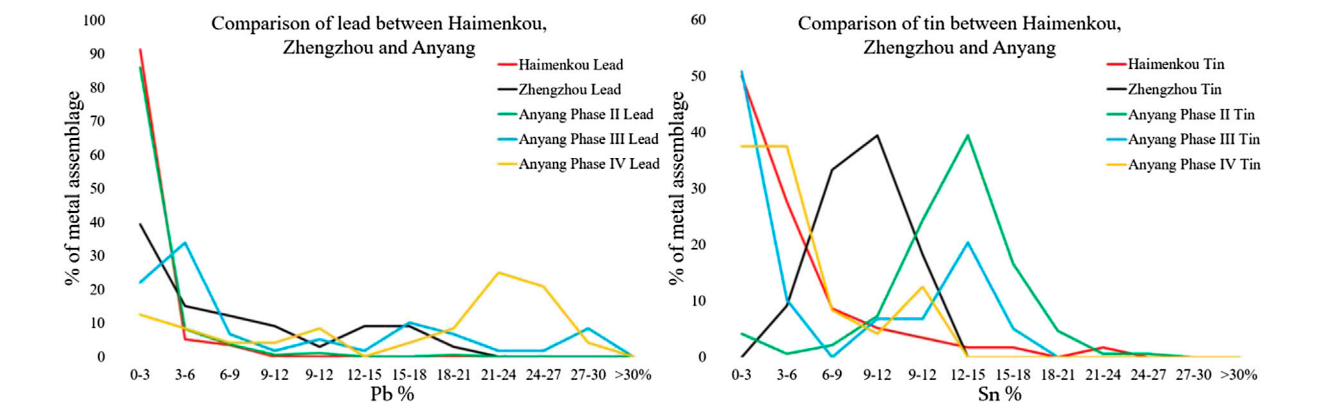

FIGURE 6 | Alloying pattern in Haimenkou, Zhengzhou and Anyang.

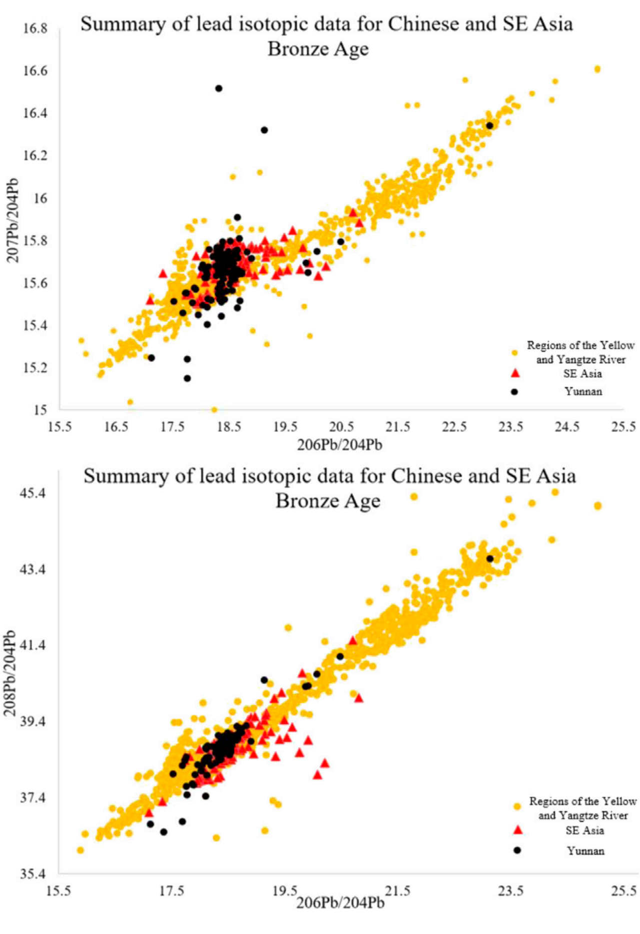

FIGURE 7 | Comparison of lead isotopic data from copper-based artifacts from Yunnan and SE Asia (data from https://flame.arch.ox.ac.uk/, see also Perucchetti et al. (2021)).

The alloying pattern can also throw some extra light on to this issue. **Figure 6** compares the distribution of lead and tin of the objects from Haimenkou (Cui and Wu, 2008; Li and Min, 2016), Zhengzhou and Anyang. Approximately 90% of Haimenkou objects (dated to all periods from ca. 1200 BC to 200 BC) contain lead at no more than 3%. The majority of objects are tin-bronzes. However, almost all the objects at Zhengzhou and Anyang are leaded bronze, except for those of Anyang Phase II, which is well-known for high-tin bronze (Zhao, 2004). There has been a long-standing question concerning the radiogenic lead, namely, whether the highly radiogenic signal derives from the lead or the copper. Some objects without added lead, for instance, less than 1–2%, do have HRL, so they may come from a copper source containing HRL lead, the majority have added lead which must be HRL (Jin, 2008; Jin et al., 2017; Liu et al., 2020c). If HRL did indeed originate from Yunnan, it is then hard to comprehend why lead was not used to alloy local objects.

Whilst a large number of publications have focused on comparative studies of lead isotopic data among various metal assemblages, there is still very little attention paid to the bronzes from Southeast Asia, which are arguably more relevant to interpret the Yunnan bronzes (Higham et al., 2011; Higham et al., 2020; Yao et al., 2020; Higham and Cawte, 2021). Yunnan and Southeast Asia bear a range of resemblances in terms of material culture. Both regions lie in the crunch area of Himalaya, which is very active in geological history, leading to many folds therefore rich metal deposits such as copper, tin and lead (Zaw et al., 2014; Cheng et al., 2016). Thanks to the decades of research made by Pryce and his colleagues (Pryce et al., 2011; Pryce et al., 2014; Pryce et al., 2018), 466 sets of lead isotopic ratios have been published for the metal assemblages excavated in Southeast Asia, ranging from 1000 BC to 700 AD. **Figure 7** summarizes almost all the lead isotopic data for bronzes from Bronze Age Southeast Asia and China, with Yunnan being highlighted. It is important to observe that Yunnan bronzes and those from Southeast Asia are directly comparable in terms of both typology and lead isotopic ratios, reflecting mutual exchange of metal and similar geological background. Nonetheless, neither of them can be matched to HRL. Intriguingly, one copper adze from the site of Wangjiadun in Yunnan (around 1200–1050 BC) shows a typical Shang HRL (Cui and Wu, 2008). Without further information, it is difficult to tell whether this was made from recycling of objects in other regions.

CONCLUSION AND FUTURE PERSPECTIVES

The discovery of HRL is one of the most crucial keys to reconstructing the supply network and management system of the metal resources during the Shang period. However, its unresolved issue of provenance makes the whole discussion like a floating chronology, which still lacks an absolute chronological point to be anchored to the real calendar years. In addition to the commonly used archaeometallurgical approaches, evidence produced by environmental archaeology can be equally thought-provoking. Metallurgical production should reshape as well as adapt to the local environment. Both environmental archaeology and archaeometallurgical research in China have made marked progress in their own field in the last two decades or so. Each discipline has produced crucial and stimulating results of interest to the other. It becomes increasingly meaningful and practical for scholars to carry out more cross-disciplinary cooperation to resolve many shared issues that combine environmental studies and archaeometallurgy. Reviewing the recent published environmental records, together with new excavation results, radiocarbon chronology and alloying practice, reveals no further evidence to support Yunnan as the source of HRL. Rather, environmental archaeology suggests no large-scale metallurgical activities at Yunnan until the historical period. Cooperation between environmental archaeology and archaeometallurgy in China is still surrounded by various issues. It is imperative to establish systematic theoretical framework in order to trigger more dynamic dialogue between the two subjects and more environmental records should be collected and analyzed for more specific questions in archaeometallurgy.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

RL design the research and wrote the whole paper; AP edited the manuscript; FL produced **Figure 4**; LH produced **Figures 2**, **3**; All the authors contributed to the discussion.

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REFERENCES

Abbott, M. B., and Wolfe, P. A. (2003). Intensive Pre-incan Metallurgy Recorded by Lake Sediments from the Bolivian Andes. *Science* 301 (5641), 1893–1895. doi:10.1126/science.1087806

Bagley, R. (1999). "Shang Archaeology," in *The Cambridge History of Ancient China: From the Origins of Civilization to 221 B.C.* Editors E. L. Shaughnessy and M. Loewe (Cambridge: Cambridge University Press), 124–231. doi:10.1017/chol9780521470308.005

Bronk Ramsey, C. (2009). Dealing with Outliers and Offsets in Radiocarbon Dating. *Radiocarbon* 51(3) 1023–1045. doi:10.1017/S0033822200034093

Cass, I. A. (2014). *Erlitou: 1999-2006*. Beijing: Wenwu press (in Chinese).

Chen, F., Chen, X., Chen, J., Zhou, A., Wu, D., Tang, L., et al. (2014). Holocene Vegetation History, Precipitation Changes and Indian Summer Monsoon Evolution Documented from Sediments of Xingyun Lake, South-West China. *J. Quat. Sci.* 29 (7), 661–674. doi:10.1002/jqs.2735

Chen, G., Cui, Y., Liu, R., Wang, H., Yang, Y., Pollard, A. M., et al. (2020). Lead Isotopic Analyses of Copper Ores in the Early Bronze Age central Hexi Corridor, north-west China. *Archaeometry* 62 (5), 952–964. doi:10.1111/arcm.12566

Chen, G. (2016). Rediscussion on the Metallurgycial Remians at Erlitou. *Zhongyuan wenwu* 3, 35–44. (in Chinese).

Chen, K., Mei, J., Rehren, T., Liu, S., Yang, W., Martinón-Torres, M., et al. (2019). Hanzhong Bronzes and Highly Radiogenic lead in Shang Period China. *J. Archaeological Sci.* 101, 131–139. doi:10.1016/j.jas.2018.11.010

Chen, K., Mei, J., Rehren, T., and Zhao, C. (2016). Indigenous Production and Interregional Exchange: Late Second-Millennium BC Bronzes from the Hanzhong basin, China. *Antiquity* 90 (351), 665–678. doi:10.15184/aqy.2016.94

Chen, K., Rehren, T., Mei, J., and Zhao, C. (2009). Special Alloys from Remote Frontiers of the Shang Kingdom: Scientific Study of the Hanzhong Bronzes from Southwest Shaanxi, China. *J. Archaeological Sci.* 36(10), 2108–2118. doi:10.1016/j.jas.2009.04.016

Cheng, Y., Mao, J., and Liu, P. (2016). Geodynamic Setting of Late Cretaceous Sn-W Mineralization in southeastern Yunnan and Northeastern Vietnam. *Solid Earth Sci.* 1, 79–88. doi:10.1016/j.sesci.2016.12.001

Chernykh, E. N. (1992). *Ancient Metallurgy in the USSR: The Early Metal Age*. Cambridge: Cambridge University Press.

Cui, J., and Wu, X. (2008). *Lead Isotopic Archaeology – Case Studies of Bronzes at Yunnan in China and Veitanam*. Beijing: Wenwu press (in Chinese).

Dearing, J. A., Jones, R. T., Shen, J., Yang, X., Boyle, J. F., Foster, G. C., et al. (2008). Using Multiple Archives to Understand Past and Present Climate-Human-Environment Interactions: the lake Erhai Catchment, Yunnan Province, China. *J. Paleolimnol* 40, 3–31. doi:10.1007/s10933-007-9182-2

Dee, M. W., and Ramsey, C. B. (2014). High-precision Bayesian Modeling of Samples Susceptible to Inbuilt Age. *Radiocarbon* 56 (1), 83–94. doi:10.2458/56.16685

Henan Institute of Archaeology (2001). *Zhengzhou Shang Site*. Beijing: Wenwu press (in Chinese).

Higham, C. F. W., and Cawte, H. (2021). Bronze Metallurgy in Southeast Asia with Particular Reference to Northeast Thailand. *J. World Prehist* 34, 1–46. doi:10.1007/s10963-020-09151-3

Higham, C., Higham, T., Ciarla, R., Douka, K., Kijngam, A., and Rispoli, F. (2011). The Origins of the Bronze Age of Southeast Asia. *J. World Prehist* 24, 227–274. doi:10.1007/s10963-011-9054-6

Higham, T. F. G., Weiss, A. D., Higham, C. F. W., Ramsey, C. B., D'Alpoim Guedes, J., Hanson, S., et al. (2020). A Prehistoric Copper-Production centre in central Thailand: Its Dating and Wider Implications. *Antiquity* 94 (376), 948–965. doi:10.15184/aqy.2020.120

Hillman, A. L., Abbott, M. B., Yu, J., Bain, D. J., and Chiou-Peng, T. (2015). Environmental Legacy of Copper Metallurgy and Mongol Silver Smelting Recorded in Yunnan Lake Sediments. *Environ. Sci. Technol.* 49, 3349–3357. doi:10.1021/es504934r

Hillman, A. L., Yao, A., Abbott, M. B., and Bain, D. J. (2019). Two Millennia of Anthropogenic Landscape Modification and Nutrient Loading at Dian Lake, Yunnan Province, China. *The Holocene* 29 (3), 505–517. doi:10.1177/0959683618816504

Hillman, A. L., Yu, J., Abbott, M. B., Cooke, C. A., Bain, D. J., and Steinman, B. A. (2014). Rapid Environmental Change during Dynastic Transitions in Yunnan Province, China. *Quat. Sci. Rev.* 98, 24–32. doi:10.1016/j.quascirev.2014.05.019

Hsu, Y.-K., O'Sullivan, R., and Li, H. (2021). Sources of Western Zhou lead: a New Understanding of Chinese Bronze Age Supply Networks. *Archaeological Anthropological Sci.* 13 (2), 1–15. doi:10.1007/s12520-021-01279-3

Hsu, Y.-K., and Sabatini, B. J. (2019). A Geochemical Characterization of lead Ores in China: An Isotope Database for Provenancing Archaeological Materials. *PLOS ONE* 14 (4), e0215973. doi:10.1371/journal.pone.0215973

Hsu, Y.-k. (2016). *The Dynamic Flow of Copper and Copper Alloys across the Prehistoric Eurasian Steppe from 2000 to 300 BCE*. PhD, University of Oxford.

Iles, L. (2016). The Role of Metallurgy in Transforming Global Forests. *J. Archaeol Method Theor.* 23, 1219–1241. doi:10.1007/s10816-015-9266-7

Jin, Z. (1987). "The Central Plain during the Late Shang Period," in *Sources of Metals for the Bronze Production in Lead Isotope Archaeology in China* (China): Press of Univeristy of Science and Technology), 292–302.Hefei

Jin, Z. (2008). *Lead Isotopic Archaeology in China*. Hefei: Press of University of Science and Technology (in Chinese).

Jin, Z., Liu, R., Rawson, J., and Pollard, A. M. (2017). Revisiting lead Isotope Data in Shang and Western Zhou Bronzes. *Antiquity* 91 (360), 1574–1587. doi:10.15184/aqy.2017.149

Jin, Z., Zheng, G., Hirao, Y., and Hayakawa, Y. (2001). "Lead Isotopic Ratios of Early Chinee Bronzes," in *Circulation of Metal in Ancient East Asia*. Editors Y. Hirao, J. Enomoto, and H. Takahama (Tokyo, Japan: Tsuruyamado), 295–304. (in Chinese).

Ledderose, L. (2000). *Ten Thousand Things: Module and Mass Production in Chinese Art*. Princeton: Princeton University Press.

Li, S., Joseph, E., and Min, Q. (2016). Remote Sensing of Ground-Level PM2.5 Combining AOD and Backscattering Profile. *Remote Sensing Environ.* 183 (3), 120–128. doi:10.1016/j.rse.2016.05.025 (in Chinese).

Li, Y. (2014). Preliminary Exploration of the Broad Organization of Metallurgy in the Central Plains and Northern China. *Zhongguo Wenwubao Wenwu Kaogu Zhoukan* 5, 1–4. (in Chinese Newspaper).

Linduff, K. M., and Mei, J. (2014). "Metallurgy in Ancient Eastern Asia: Retrospect and Prospects," in *Archaeometallurgy in Global Perspective: Methods and Syntheses*. Editors B. W. Roberts and C. P. Thornton (New York: Springer), 785–803. doi:10.1007/978-1-4614-9017-3_27

Liu, C., Liu, R., Zhou, P., Lu, C., Yang, Z., Pollard, A. M., et al. (2020a). Metallurgy at the Crossroads: New Analyses of Copper-based Objects at Tianshanbeilu, Eastern Xinjiang, China. *Acta Geologica Sinica - English Edition* 94 (3), 594–602. doi:10.1111/1755-6724.14531

Liu, L., and Chen, X. (2009). *State Formation in Early China*. London: Duckworth. doi:10.1093/oxfordhb/9780199271016.013.0020

Liu, R., Bray, P., Pollard, A. M., and Hommel, P. (2015). Chemical Analysis of Ancient Chinese Copper-Based Objects: Past, Present and Future. *Archaeological Res. Asia* 3, 1–8. doi:10.1016/j.ara.2015.04.002

Liu, R. (2016). *Capturing Changes: Applying the Oxford System to Further Understand the Movement of Metal in Shang China*. PhD, University of Oxford.

Liu, R., Hsu, Y.-K., Pollard, A. M., and Chen, G. (2021). A New Perspective towards the Debate on Highly Radiogenic lead in Chinese Archaeometallurgy. *Archaeol Anthropol. Sci.* 13 (2), 1–7. doi:10.1007/s12520-021-01280-w

Liu, R., Pollard, A. M., Cao, Q., Liu, C., Sainsbury, V., Howarth, P., et al. (2020b). Social Hierarchy and the Choice of Metal Recycling at Anyang, the Last Capital of Bronze Age Shang China. *Scientnfic Rep.* 10, 18794. doi:10.1038/s41598-020-75920-x

Liu, R., Pollard, A. M., Liu, C., and Rawson, J. (2020c). Every Cloud Has a Silver Lining: Using Silver Concentration to Identify the Number of Sources of Lead Used in Shang Dynasty Bronzes. *Acta Geologica Sinica - English Edition* 94 (3), 585–593. doi:10.1111/1755-6724.14530

Liu, R., Rawson, J., and Pollard, A. M. (2018a). Beyond Ritual Bronzes: Identifying Multiple Sources of Highly Radiogenic lead across Chinese History. *Sci. Rep.* 8, 11770. doi:10.1038/s41598-018-30275-2

Liu, S., Chen, K. L., Rehren, T., Mei, J. J., Chen, J. L., Liu, Y., et al. (2018c). Did China Import Metals from Africa in the Bronze Age? *Archaeometry* 60 (1), 105–117. doi:10.1111/arcm.12352

Liu, S. R., Chen, K. L., Rehren, T., Mei, J. J., Chen, J. L., Liu, Y., et al. (2018b). Lead isotope and metal source of Shang bronzes: a response to Sun et al .'s comments. *Archaeometry* 60 (5), 1040–1044. doi:10.1111/arcm.12411

McConnell, J. R., Wilson, A. I., Stohl, A., Arienzo, M. M., Chellman, N. J., Eckhardt, S., et al. (2018). Lead Pollution Recorded in Greenland Ice Indicates European Emissions Tracked Plagues, Wars, and imperial Expansion during Antiquity. *Proc. Natl. Acad. Sci. USA* 115 (22), 5726–5731. doi:10.1073/pnas.1721818115

Mei, J., Chen, K., and Cao, W. (2009). Scientific Examination of Shang-Dynasty Bronzes from Hanzhong, Shaanxi Province, China. *J. Archaeological Sci.* 36(9), 1881–1891. doi:10.1016/j.jas.2009.04.017

Mei, J. (2009). "Early Metallurgy and Socio-Cultural Complexity: Archaeological Discoveries in Northwest China," in *Social Complexity in Prehistoric Eurasia: Monuments, Metals, and Mobility*. Editors B. K. Hanks and K. M. Linduff (Cambridge: Cambridge University Press), 2108–2118.

Min, R. (2013). Synthesis of Archaeological Excavations at Haimenkou Jianchuan. *Xuyuan* (15), 6–9. (in Chinese).

Min, R. (2009). The Third Excavation at Haimenkou, Jianchuan, Yunnan. *Kaogu* (8), 3–22. (in Chinese).

Monge, G., Jimenez-Espejo, F. J., García-Alix, A., Martínez-Ruiz, F., Mattielli, N., Finlayson, C., et al. (2015). Earliest Evidence of Pollution by Heavy Metals in Archaeological Sites. *Scientific Rep.* 5, 14252. doi:10.1038/srep14252

Nriagu, J. O. (1972). A Hisotry of Global Metal Pollution. *Science* 272, 223. doi:10.2475/ajs.272.5.476

Peng, Z., Liu, Y., Liu, S., and Hua, J. (1999). Preliminary of the Provenance of Bronzes and Raw Copper and lead Materials in Southern China. *Ziran kexueshi yanjiu* 18 (3), 241–249. (in Chinese).

Perucchetti, L., Bray, P., Felicetti, A., Sainsbury, V., Howarth, P., Saunders, M. K., et al. (2021). FLAME-D Database: An Integrated System for the Study of Archaeometallurgy. *Archaeometry* 63 (3), 651–667. doi:10.1111/arcm.12616

Pollard, A. M., Bray, P., Hommel, P., Hsu, Y.-K., Liu, R., and Rawson, J. (2017a). Bronze Age Metal Circulation in China. *Antiquity* 91 (357), 674–687. doi:10.15184/aqy.2017.45

Pollard, A. M., Bray, P., Hommel, P., Hsu, Y.-K., Liu, R., and Rawson, J. (2017b). Further Understanding of Chinese Bronzes by the Oxford System. *Kaogu* (1), 95–106.

Pollard, A. M., Bray, P., Hommel, P., Liu, R., Pouncett, J., Saunders, M., et al. (2018). *Beyond Provenance : New Approaches to Interpreting the Chemistry of Archaeological Copper Alloys*. Belgium, Leuven: Leuven University Press. doi:10.2307/j.ctv7xbs5r

Pollard, A. M., Heron, C., and Armitage, R. A. (2017c). *Archaeological Chemistry*. London, United Kingdom: Royal Society of Chemistry: Royal Society of Chemistry.

Pollard, A. M., Liu, R., Rawson, J., and Tang, X. (2019). From Alloy Composition to Alloying Practice: Chinese Bronzes. *Archaeometry* 61 (1), 70–82. doi:10.1111/arcm.12415

Pryce, T. O., Baron, S., Bellina, B. H. M., Bellwood, P. S., Chang, N., Chattopadhyay, P., et al. (2014). More Questions Than Answers: the Southeast Asian Lead Isotope Project 2009-2012. *J. archaeological Sci.* 42, 273–294. doi:10.1016/j.jas.2013.08.024

Pryce, T. O., Htwe, K. M. M., Georgakopoulou, M., Martin, T., Vega, E., Rehren, T., et al. (2018). Metallurgical Traditions and Metal Exchange Networks in Late Prehistoric central Myanmar, C. 1000 BC to C. AD 500. *Archaeol Anthropol. Sci.* 10 (5), 1087–1109. doi:10.1007/s12520-016-0436-7

Pryce, T. O., Pollard, M., Martinón-torres, M., Pigott, V. C., and Pernicka, E. (2011). Southeast Asia's First Isotopically Defined Prehistoric Copper Production System: when Did Extractive Metallurgy Begin in the Khao Wong Prachan Valley of Central Thailand? *Archaeometry* 53 (1), 146–163. doi:10.1111/j.1475-4754.2010.00527.x

Qin, Y., Wei, G., and HUang, Q. (2020). The Provenance of Yin-Shang Bronzes with Highly Radiogenic lead Isotopes. *Archaeological Anthropological Sci.* 12, 1–10.

Qiu, L., Zhuang, X., HUang, X., Liu, P., and Zhao, X. (2019). Study on Heavy Metals' Influence on Buried Cultural Relics in Soil of an Archaeological Site*Environ. Tech.* 42. Environmental Technology Online available (12), 1955–1966. doi:10.1080/09593330.2019.1684569

Rawson, J. (2017a). China and the Steppe: Reception and Resistance. *Antiquity* 91 (356), 375–388. doi:10.15184/aqy.2016.276

Rawson, J. (2017b). Shimao and Erlitou: New Perspectives on the Origins of the Bronze Industry in Central China. *Antiquity Project Gallery* 91. doi:10.15184/aqy.2016.234

Rawson, J. (1999). "Western Zhou Archaeology," in *Western Zhou Archaeology " in* the Cambridge History of Ancient China : From the Origins of Civilization to 221 B.C. Editors E. L. Shaughnessy and M. Loewe (Cambridge: Cambridge University Press), 352–449. doi:10.1017/chol9780521470308.008

Rehren, T., and Pernicka, E. (2008). Coins, Artefacts and Isotopes-Archaeometallurgy and Archaeometry. *Archaeometry* 50 (2), 232–248. doi:10.1111/j.1475-4754.2008.00389.x

Roberts, B. W., and Thornton, C. P. (2014). *Archaeometallurgy in Global Perspective: Methods and Syntheses*. Springer Science & Business Media.

Roberts, B. W., Thornton, C. P., and Pigott, V. C. (2009). Development of Metallurgy in Eurasia. *Antiquity* 83 (322), 1012–1022. doi:10.1017/s0003598x00099312

Russell, R. D., and Farquhar, R. M. (1960). *Lead Isotopes in Geology*. New York: Interscience Publishers.

Shen, J., Jones, R. T., Yang, X., Dearing, J. A., and Wang, S. (2006). The Holocene Vegetation History of Lake Erhai, Yunnan Province Southwestern China: the Role of Climate and Human Forcings. *The Holocene* 16 (2), 265–276. doi:10.1191/0959683606hl923rp

Storozum, M. J., Qin, Z., Wang, Y., and Liu, H. (2020). Buried Soils as Archives of Paleo-Pollution in the North China Plain. *Anthropocene* 31, 1–16. doi:10.1016/j.ancene.2020.100251

Sun, W.-d., Zhang, L.-p., Guo, J., Li, C.-y., Jiang, Y.-h., Zartman, R. E., et al. (2016). Origin of the Mysterious Yin-Shang Bronzes in China Indicated by lead Isotopes. *Sci. Rep.* 6, 23304. doi:10.1038/srep23304

Sun, W.-D., Zhang, L.-P., Guo, J., Li, C.-Y., Jiang, Y.-H., and Zhang, Z.-F. (2018). Comment on 'Did China Import Metals from Africa in the Bronze Age?' *Archaeometry* 60 (5), 1036–1039. doi:10.1111/arcm.12412

The Institute of Archaeology, C. (1980). *Yinxu Fuhao Tomb*. Beijing: Cultural Relics Publishing House (in Chinese).

Thevenon, F., Guedron, S., Chiaradia, M., Loizeau, J.-L., and Pote, J. (2011). (Pre-) Historic Changes in Natural and Anthropogenic Heavy Metals Deposition Inferred from Two Contrasting Swiss Alpine Lakes. *Quat. Sci. Rev.* 30 (1-2), 224–233. doi:10.1016/j.quascirev.2010.10.013

Tong, W. (2012). "Yuanqu Shang Site and the Copper Resources in the Zhongtiao Mountains," in *Kaoguxue Yanjiu (jiu)*. Editor B.U. School of Archaeology and Museology (Beijing: Science Press), 346–361. ((in Chinese).

Wang, Y., Mei, J., Li, Y., Chen, K., Cao, J. e., and Dang, Y. (2020). Research on the Ore Sources of Some Bronze Objects from the Lower Xiajiadian Culture Sites. *Sci. Conservation Archaeology* 3, 1–7. (in Chinese).

Wu, D., Zhou, A., Liu, J., Chen, X., Wei, H., Sun, H., et al. (2015). Changing Intensity of Human Activity over the Last 2,000 Years Recorded by the Magnetic Characteristics of Sediments from Xingyun Lake, Yunnan, China. *J. Paleolimnol* 53 (1), 47–60. doi:10.1007/s10933-014-9806-2

Xiao, X., Haberle, S. G., Shen, J., Yang, X., Han, Y., Zhang, E., et al. (2014). Latest Pleistocene and Holocene Vegetation and Climate History Inferred from an alpine Lacustrine Record, Northwestern Yunnan Province, Southwestern China. *Quat. Sci. Rev.* 86, 35–48. doi:10.1016/j.quascirev.2013.12.023

Xiao, X., Shen, J. I., Haberle, S. G., Han, Y., Xue, B., Zhang, E., et al. (2015). Vegetation, Fire, and Climate History during the Last 18 500 Cal a BP in South-Western Yunnan Province, China. *J. Quat. Sci.* 30 (8), 859–869. doi:10.1002/jqs.2824

Xu, H. (2020). Two Great Ritual Changes at Erlitou. *Nanfang wenwu* (02), 8–16. (in Chinese).

Xu, M. X., H, W. S., Zhou, S. L., Liao, F. Q., Ma, C. M., and Zhu, C. (2011). Hyperspectral Reflectance Models for Retrieving Heavy Metal Content: Application in the Archaeological Soil. *J. Infrared Millimeter Waves* 30 (2), 109–114. (in Chinese with English abstract).

Yao, A., Darre, V., Jiang, Z., Lam, W., and Wei, Y. (2020). Bridging the Time gap in the Bronze Age of Southeast Asia and Southwest China. *Archaeological Res. Asia* 22, 1–19. doi:10.1016/j.ara.2020.100189

Zaw, K., Meffre, S., Lai, C. K., Burrett, C., Santosh, M., Graham, I., et al. (2014). Tectonics and Metallogeny of mainland Southeast Asia—A Review and Contribution. *Gondwana Res.* 26 (1), 5–30.

Zhang, C. (2014). "Erligang a Perepctive from Panlongcheng," in *Art and Archaeology of the Erligang Civilization*. Editors K. Steinke and D. C. Y. Ching (Princeton: Princeton University Press), 51–63.

Zhang, S., Yang, Y., Storozum, M. J., Li, H., Cui, Y., and Dong, G. (2017). Copper Smelting and Sediment Pollution in Bronze Age China: a Case Study in the Hexi Corridor, Northwest China. *Catena* 156, 92–101. doi:10.1016/j.catena.2017.04.001

Zhangsun, Y. Z., Jin, Z. Y., Feng, F. Z., Tian, J. H., Wang, H. G., Zhao, C. C., et al. (2021). Revisiting the lead Isotopic Compositions of the Shang Bronzes at Hanzhong and the New Hypothesis of Qinling as the Source of Highly Radiogenic lead. *Archaeometry* 63 (1), 122–141. doi:10.1111/arcm.12630

Zhao, C. (2004). Chemical Analysis of Bronzes at Anyang. *Kaoguxue jikan* (15), 243–268. (in Chinese).

Zhao, C., Yue, Z., and Xu, G. (2008). The Chemical Analysis of Bronzes from M1046 at Anyang. *Wenwu* (1), 92–94. (in Chinese).

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The Spatiotemporal Pattern of Cultural Evolution Response to Agricultural Development and Climate Change From Yangshao Culture to Bronze Age in the Yellow River Basin and Surrounding Regions, North China

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The processes and mechanisms of cultural evolution provide helpful insights into the origin and development of civilizations. This study analyses data from the national archaeological survey using kernel density analysis, a geospatial tool provided by ArcGIS10 software, to explore the spatiotemporal pattern of cultural evolution from the beginning of the Yangshao cultural period to the Bronze Age in the Yellow River basin. Agricultural development and the environmental background of this region were reconstructed using published flotation materials and high-resolution paleoclimate records. The results indicate that cultural expansion and differentiation from Yangshao (7000–5000 BP) to Longshan period (4600–4000 BP) are responding to the establishment and strengthening of millet-based agriculture and the appearance of multiple subsistence strategies in the context of environmental deterioration. To the Bronze Age, the center of sites accumulates to the Central Plains and Shandong, in contrast to the continuous cultural expansion and differentiation. The opposite circumstance may result from early urbanization along with the formation of a social system with high centralization of power.

Keywords: cultural evolution, agricultural development, climate change, kernel density analysis, urbanization, Yellow River basin

INTRODUCTION

The process and influencing factors of cultural evolution have been widely studied (Weiss et al., 1993; DeMenocal et al., 2001; Dong et al., 2012; Dong et al.2013; Kennett et al., 2012; Medina-Elizalde and Rohling, 2012; Cui et al., 2018). The Neolithic is one of the most pivotal periods to examine cultural evolution because of the major changes associated with the development of food-producing economies and growing population unseen in prior periods. By studying the spatiotemporal pattern of cultural evolution and its influencing factors, we can better understand the origin and changing mechanisms of a civilization.

Much attention is given to the study of Chinese civilization. The Yellow River basin is the cradle of Chinese civilization. The earliest Neolithic sites are distributed along the Yellow River basin from east

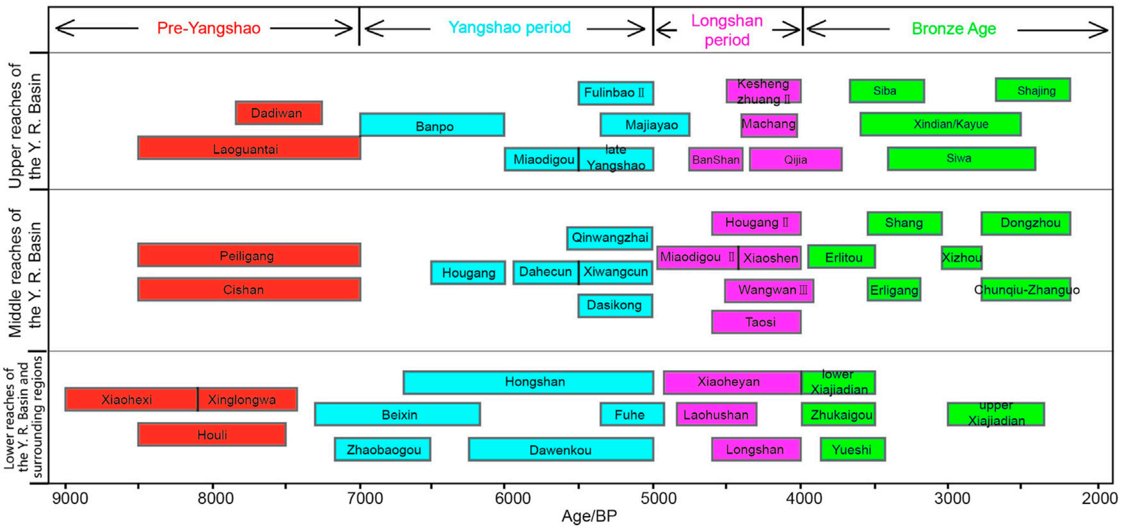

FIGURE 1 | Culture sequence in the Yellow River basin and surrounding regions.

to west, including the Houli site in Shandong Province, the Donghulin site in Beijing, the Cishan site in Hebei Province, the Peiligang site in Henan Province, the Laoguantai site in Shaanxi Province, and the Dadiwan site in Gansu Province. The modern Chinese civilization however was established during the Bronze Age as seen by the founding of several dynasties during this period, including the Xia, Shang, and Zhou. These dynasties were centered in the middle and lower reaches of the Yellow River basin.

Neolithic culture in the Yellow River basin (**Figure 1**) can be broadly divided into three periods: pre-Yangshao period (9000–7000 BP), Yangshao period (7000–5000 BP), and post-Yangshao period (5000–4000 BP). During pre-Yangshao period, cultural groups include, Xiaohexi culture (9000–8200 BP), Houli culture (8500–7500 BP), Xinglongwa culture (8200–7400 BP), Cishan culture (8000–7000 BP), Peiligang culture (8500–7000 BP), Laoguantai culture (8200–7000 BP),and Dadiwan culture (7800–7300 BP). Several cultures including Banpo (7000–5900 BP), Miaodigou (6000–5500 BP), Xiwangcun (5600–5000 BP), Qinwangzhai (5600–5000 BP), early Dahecun (5900–5500 BP), Beixin (7300–6200 BP), early to mid Dawenkou (6300–5000 BP), and early Majiayao (5300–4800 BP) belong to the Yangshao period. The post-Yangshao period in the Neolithic is also known as the Longshan period and includes the Shandong Longshan (4600–4000 BP), Miaodigou Ⅱ (4900–4300 BP), Wangwan Ⅲ (4500–3900 BP), Keshengzhuang Ⅱ (4500–4000 BP), Hougang Ⅱ (4600–4000 BP), Taosi (4600–400 BP), Caiyuan (4800–4200 BP), and early Qijia (4300–4000 BP) cultural sites which are found in a different area of the Yellow River basin during this period. Different cultural sites of the Bronze Age have begun to be parsed in other parts of the Yellow River basin. Several cultural sites such as Siba (3700–3200 BP), Xindian (3600–2500 BP), Kayue (3600–2500 BP), Siwa (3400–2400 BP), and Shajing (2700–2100 BP) have been discovered in the upper Yellow River basin. Other Bronze Age cultural sites including Erlitou–Erligang (3900–3000 BP), Yueshi (3800–3400 BP), and Lower Xiajiadian (4300–3600 BP) are found in the middle and lower reaches of the Yellow River basin. At the same time, many archaeological remains associated with the Shang and Zhou dynasties have been found in this area. It should be noted that cultures what we talked about are material culture complexes and not genetic groups or political formations.

According to the second national relic survey (Bureau of National Cultural Relics, 1991; Bureau of National Cultural Relics, 1996; Bureau of National Cultural Relics, 1998; Bureau of National Cultural Relics, 2002; Bureau of National Cultural Relics, 2003; Bureau of National Cultural Relics, 2006; Bureau of National Cultural Relics, 2009; Bureau of National Cultural Relics, 2010; Bureau of National Cultural Relics, 2011a; Bureau of National Cultural Relics, 2011b; Bureau of National Cultural Relics, 2013; Mei and Kong, 2008), approximately 147 pre-Yangshao period sites have been identified in the Yellow River basin and its surrounding region. These sites are relatively small and usually consist of less than a 1000 square meters. Most of these sites appear to be dispersed and exhibit mutual independence from each other, although there may be some evidence of faint links among the Peiligang, Laoguantai, Cishan, and Houli cultures, as shown by Han (2015). This study examines the spatiotemporal pattern of sites from the Yangshao period, Longshan period, and Bronze Age in the Yellow River basin with the use of kernel density analysis, a geospatial software tool. In addition, this study simultaneously compares two methods of inputting data into this analysis tool and the usefulness of the results. These results are discussed by reviewing previous evidence from archaeological excavations in the region to highlight the results' potential connection to agricultural development and geopolitics.

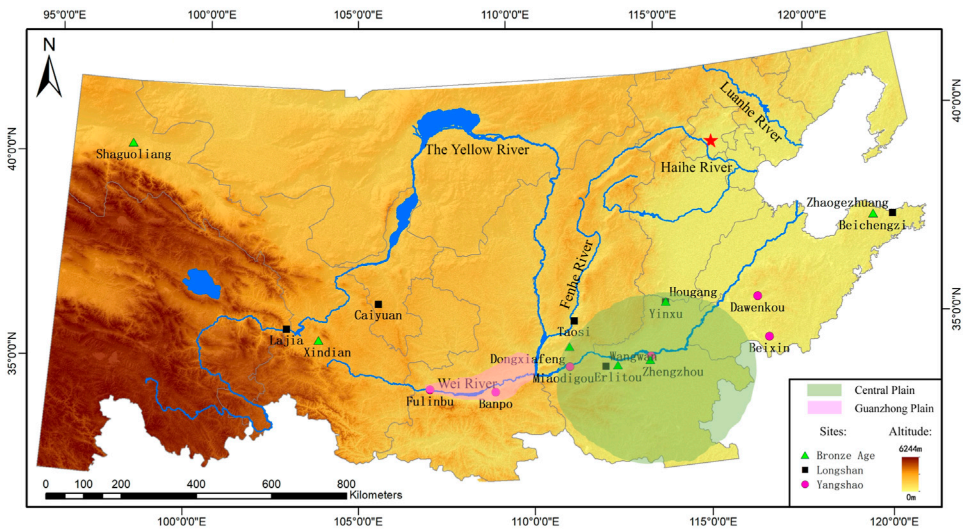

FIGURE 2 | Study area.

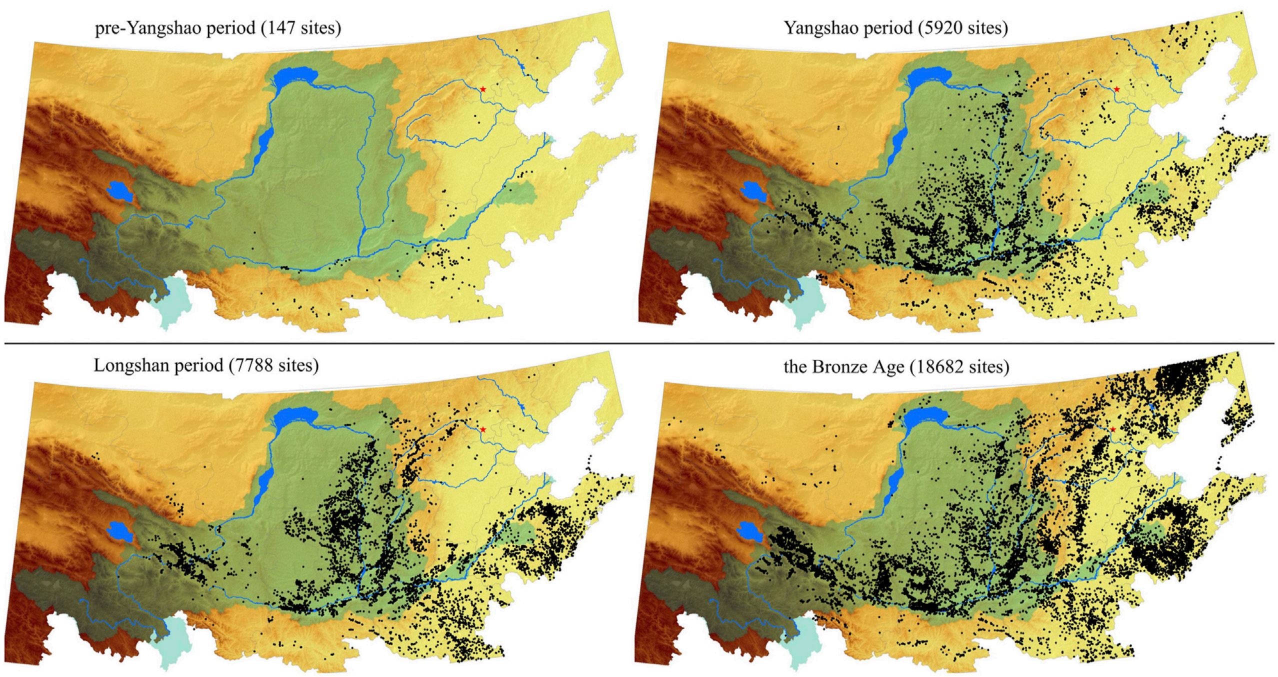

FIGURE 3 | Distribution of sites from pre-Yangshao period to the Bronze Age in the Yellow River basin and surrounding regions.

STUDY AREA

The study area (95.8°E–122.7°E, 32.1°N–41.8°N) covers the Yellow River drainage basin and its surrounding regions in northern China, stretching approximately 2300 km from the Hexi Corridor in the west to the Shandong Peninsula in the east. This area encompasses all of Ningxia, Shaanxi, Shanxi, Henan, Tianjin, Beijing, and Shandong provinces and part of Qinghai, Gansu, Inner Mongolia, Hebei, and Liaoning provinces. The Yellow River and its two main tributaries (the Weihe River and the Fenhe River), the Luanhe River, and the Haihe River flow through these regions (**Figure 2**). The Yellow River is approximately 5464 km long, with its drainage basin covering 795,000 km^2 and its altitude decreasing 4480 m from west to east. The mean annual temperature ranges from −4 to 14°C, and the mean annual precipitation ranges from 80 to 1200 mm. As the cradle of Chinese civilization, the Yellow River basin was the cultural and economic center of ancient China until the dynasties of South Song and Yuan. Several prehistoric sites are distributed within this study area, including 5920 Yangshao sites, 7788 Longshan sites, and 18682 Bronze Age sites (**Figure 3**, Bureau of National Cultural Relics, 1991; Bureau of National Cultural Relics, 1996; Bureau of National Cultural Relics, 1998; Bureau of National Cultural Relics, 2002; Bureau of National Cultural Relics, 2003; Bureau of National Cultural Relics, 2006; Bureau of National Cultural Relics, 2009; Bureau of National Cultural Relics, 2010; Bureau of National Cultural Relics, 2011a; Bureau of National Cultural Relics, 2011b; Bureau of National Cultural Relics, 2013; Mei and Kong, 2008). Several typical sites belonging to these three cultural periods display along the Yellow River basin and surrounding regions; among them, Beixin, Dawenkou, Miaodigou, Banpo, Fulinbu are classified as Yangshao period sites (**Figure2**, pink points); Zhaogezhuang, Hougang, Wangwan, Taosi, Caiyuan, and Lajia belong to Longshan period sites (**Figure2**, dark squares); and Beichengzi, Yinxu, Zhengzhou Shang, Dongxiafeng, Xindian, and Shaguoliang are considered as Bronze Age sites (**Figure2**, green triangles).

MATERIAL AND METHODS

Material

The archaeological site information is collected from published "Atlas of Chinese Relics" of 10 provinces and two municipalities (Bureau of National Cultural Relics, 1991; Bureau of National Cultural Relics, 1996; Bureau of National Cultural Relics, 1998; Bureau of National Cultural Relics, 2002; Bureau of National Cultural Relics, 2003; Bureau of National Cultural Relics, 2006; Bureau of National Cultural Relics, 2009; Bureau of National Cultural Relics, 2010; Bureau of National Cultural Relics, 2011a; Bureau of National Cultural Relics, 2011b; Bureau of National Cultural Relics, 2013; Mei and Kong, 2008). The information (including site location, area, and cultural attribute) is used to indicate the distributional pattern of site in north China. This "Atlas of Chinese Relics" was published after the second national archaeological survey conducted in 1981–1985, which was organized by the Provincial Administration for Cultural Heritage. The data shown in the "Atlas of Chinese Relics" use a unified format and mapping standard. We digitized these atlases to collect the geographic coordinates, cultural attributes, and site size data in order to investigate kernel density.

Methods

By using the kernel density tool provided by ArcGIS10, the site distribution patterns of the three phases are tested and compared. As a method of converting a group of points into gratings, kernel density calculates the density of point elements around each output grating cell. In this process, a smooth surface is fitted at each point. The surface value is highest at the point and decreases as the distance from the point gets larger. It reaches zero at the distance from the search radius of the point. The kernel function is used to determine how the curvature decreases. In this case, we use the quartic kernel function. The volume under the surface is equal to the fill field value of the point, or 1 if no value is specified. Then, the density of each output grating cell is calculated by adding the values of all the core surfaces covering the center of the grating cell. In our example, the population field is specified by the site size to reasonably increase the weight of large sites. Without considering the influence of the site size, we also generate the kernel density without specifying the population field representing the distribution pattern. Conceptually, each site is like a hilltop surrounded by decreasing altitude values, and the nuclear density is used to restore a continuous surface. The search radius (or bandwidth) determines the smoothness of the surface: the larger the search radius, the wider the accumulation on the smooth surface; the smaller the search radius, the narrower the accumulation on the concave convex surface. The default search radius recommended by ArcGIS is calculated by dividing the smaller of the width or height of the input range by 30, which in our case is about 35 km. Considering the large sample area, the method of twice the default value of 70 km is used to distinguish the three-phase distribution pattern. To ensure the comparability of the final results, the uniform search radius is specified to analyze all the nuclear densities, and the highest peak value is adjusted reasonably to keep the high consistency of the results represented by ArcScene (**Figure 4**).

$$K_2(x) = \begin{cases} 3\pi^{-1}(1 - x'x)^2 & \textit{if } x'x < 1 \\ 0 & \textit{otherwise} \end{cases} \quad (1)$$

(Silverman, 1986)

RESULT

Kernel Density Analyses Without Specifying Weight (or Site Number Density)

A spatial pattern of the relative site density for each period was created using kernel density analysis without specifying a weight (or in this case without considering site size). These results are shown in **Figure 4**. Most Yangshao sites are distributed in the valleys of the upper and middle Yellow River and its main tributaries including, the Weihe River, the Fenhe River, the Taohe River, and the Huangshui River. The largest clustering of sites appears to be centered in the Guanzhong basin, Shaanxi Province (**Figure 4A**).

During the Longshan period, site density on the landscape changes and expands to several regions along the Yellow River basin. Numerous Qijia cultural sites dating to this period are found in the Huangshui River and Taohe River valleys. Miaodigou II, Wangwan III, Keshengzhuang II, Hougang II, Taosi, and Caiyuan cultural sites have been found widely distributed on both sides of the middle Yellow River. Shandong Longshan cultural sites are known from the region downstream of the Yellow River. In addition to being distributed along the river valley, Longshan period sites are also found in higher elevations among the foothills and mountains surrounding the Yellow River basin including sites found in north Shaanxi, northeast Henan, southwest Shandong, and

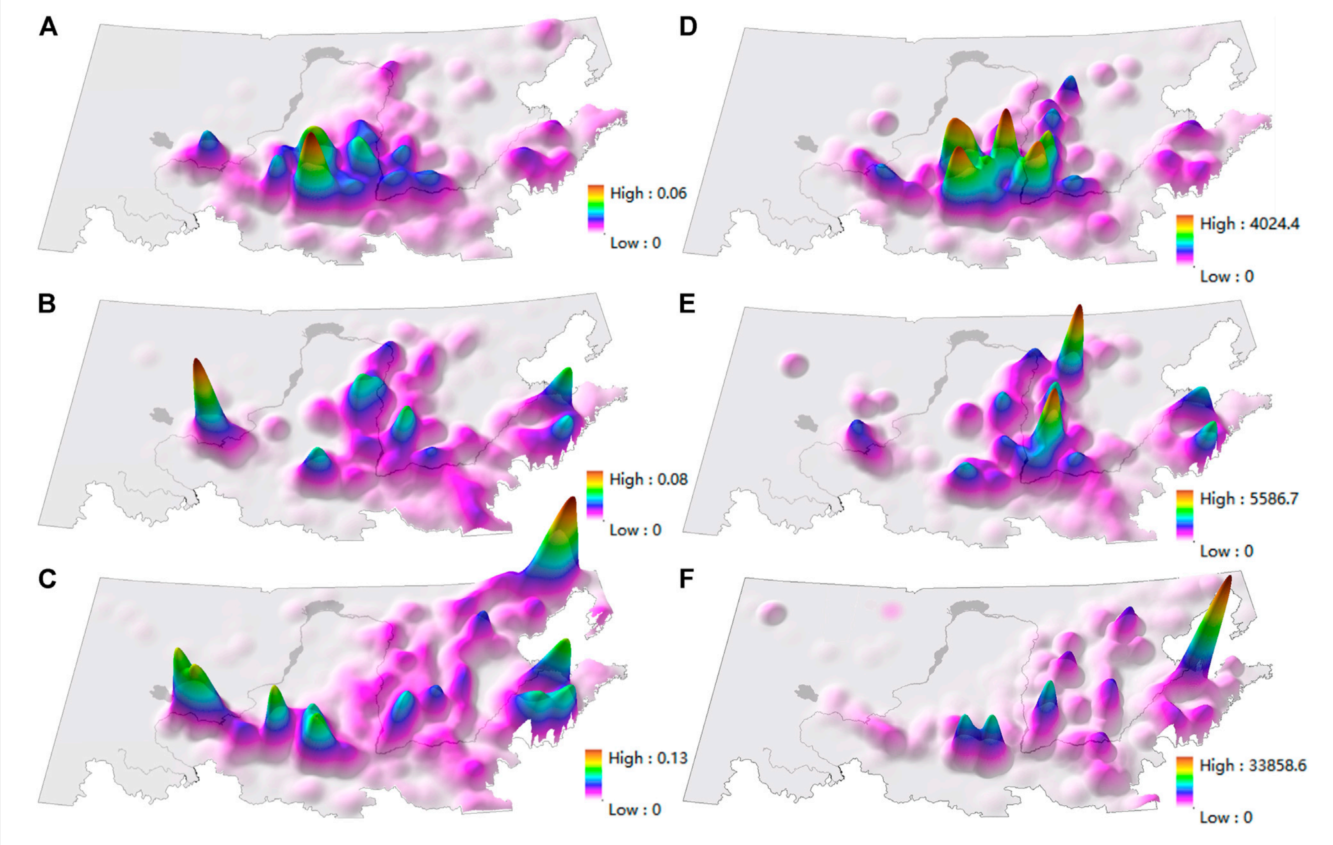

FIGURE 4 | Results of kernel density (with and without specifying weight). **(A)** Site number density of Yangshao sites. **(B)** Site number density of Longshan sites. **(C)** Site number density of the Bronze Age site. **(D)** Area density of Yangshao sites. **(E)** Area density of Longshan sites. **(F)** Area density of Bronze Age sites.

north Shanxi provinces (Bureau of National Cultural Relics, 1991; Bureau of National Cultural Relics, 1998; Bureau of National Cultural Relics, 2006; Bureau of National Cultural Relics, 2011a; Bureau of National Cultural Relics, 2013). Site density during the Longshan period differs from the Yangshao period, instead of high site density being found in one central location on the landscape, and multiple centers begin to appear located in east Gansu, south and central Shaanxi, south Shanxi, and west Shandong provinces (**Figure 4B**).

The number of sites in this region continues to expand during the Bronze Age. While site densities are higher, they appear to aggregate in many of the same locations as they did during the Longshan period, with the exception of new clusters found in the Haihe and Luanhe River valleys (**Figure 4C**).

Kernel Density Analyses With Specified Weight (or Area Density)

The results of kernel density with specified weight (or area density) show practical unanimity. A spatial pattern of relative site density was again created for each time period but utilizing the second method, kernel density with specified weight (taking into consideration site size using total area).

In the Yangshao period, the result of size density shows practical unanimity with that of site number density. The center of gravity located in the valleys of the upper and middle Yellow River and its main tributaries (**Figure 4D**).To the Longshan period, the center of gravity has an eastward and northward transfer to west Henan and north Shanxi provinces, when compared with the Yangshao period. And several sites with a large area appeared in west Shandong Province during this period (**Figure 4E**).During the Bronze Age, this is what the map shows very different when compared with the Longshan period. The gravity in the middle reach of the Yellow River has a southward transfer to Henan Province, the same as the Yangshao period. Othewise, there are sites with a huge area distributed in west Shandong Province, and it makes a really high peak lift in there (**Figure 4F**).

DISCUSSION

Limitations of Using Atlas of Cultural Relics as Data Source

As we mentioned before, the archaeological site information is collected from published "Atlas of Chinese Relics" of 10 provinces and two municipalities (Bureau of National Cultural Relics, 1991; Bureau of National Cultural Relics, 1996; Bureau of National Cultural Relics, 1998; Bureau of National Cultural Relics, 2002; Bureau of National Cultural Relics, 2003; Bureau of National

Cultural Relics, 2006; Bureau of National Cultural Relics, 2009; Bureau of National Cultural Relics, 2010; Bureau of National Cultural Relics, 2011a; Bureau of National Cultural Relics, 2011b; Bureau of National Cultural Relics, 2013). The survey was conducted in 1981–1985, and in the process of investigation, the criteria for judging the basic information of the site are not detailed in the publications, which will cause some doubts about the scientific validity of the data sources (Jaffe et al., 2020). For example, the Shimao site, which is a super large center settlement site that has been continuously excavated in recent years. The site area on the cultural relics atlas is 900000 square meters, and the latest information shows that the site area is more than four million square meters (Sun et al., 2020). In the process of digitizing, we also recorded some abnormal data possibly due to clerical errors in Atlas of Cultural Relics. For example, there are more than 10 sites in Shandong Province, each covering an area of more than 10 million square meters in the Bronze Age. Among them, there are even two sites with an area over 48 million square meters (Goutou site with 78 million square meters and Xigeng site with 48 million square meters). Meanwhile, in the Central Plains, there are only two sites with an area of more than 10 million square meters (Yinxu ruin with 30 million square meters and a Zhenghangucheng site with 23 million square meters). When verifying the accuracy of the site area information, we found that the two aforementioned sites with an extremely large size in Shandong Province were resurveyed in 2009, and the sizes were only recorded as 2400 and 15000 square meters on the website of Dongying Museum (http://www.dymuseum.cn/). Therefore, the abnormal peak of area density of Bronze Age sites observed in Shandong Province may be biased due to those clerical errors (**Figure 4F**). To avoid biased data revision and keep the standard unified, we kept all the records from the original Atlas of Cultural Relics when mapping them. The settlement distribution characteristics in problematic area like Shandong can be further discussed when the latest and more accurate data of the third cultural relics census are published in the future.

Despite the existing accuracy problems, our work based on enormous samples (more than 30,000) is still meaningful. Different from other smaller scale regional studies, our work focuses on summarizing the evolutional site distributional pattern from a macroscopic spatiotemporal scale. Considering topics like agricultural diversification and climate change also happens in a similar spatiotemporal scale, and the corresponding cultural response is more suitable to be examined from a macroscopic perspective. Meanwhile, other regional studies could be more accurate on dataset and superior in manifesting cultural response to regional events like micro-landform change and rapid environmental incidents (e.g., An et al., 2005; Li et al., 2017; Liu et al., 2019; Drennan et al., 2014).

A Comparison of the Results Between Site Number Density and Area Density Analyses

If we consider that large peaks on the map equal core areas of occupation, we believe the comparison of the two results (with or without the population field specified by the site size) will indicate when and where significant site size hierarchy (or early urbanization) appears through intuitive cartographic representation.

Using the first method, we see that there is one core area located there (east Shaanxi and Henan provinces) with occupation, and it becomes less dense as we spread outward during Yangshao period. This single core area shifts to two core areas in the Longshan period, and we see core areas in the east (west Shandong Province) and west (east Gansu Province), while the previous core area shifts to a less dense occupation. During the Bronze Age, we find an expansion of core areas across the landscape ("multi-core" distribution along the Yellow River basin from west to east).

Using the second method, we see that there is one core area located there (east Shaanxi, Henan Provinces) with occupation, and it becomes less dense as we spread outward during the Yangshao period. This is similar to what we saw in the first method. This single core area shifts to two core areas in the Longshan period, similar to what we saw with first method, but the location of the core areas are different (Henan and Shanxi provinces) and the core area from the previous period appears to shift northeast. The Bronze Age shows a vastly different core area using this model. There are two main core areas, one is located in the Central Plains and the other one located in the east (west Shandong Province), and other previous core areas of occupations show a less dense occupation.

Considering model 1 through time, it shows a single core which shifts to two different cores at opposite ends of the landscape and then results in many core areas of occupation during the Bronze Age. Conversely, model 2 through time suggests a single core area shift to multiple core areas in the same region and then results in one center of occupation in the east, demonstrating an eastward propagation toward Shanxi Province through the periods. When comparing the two models, the results correspond to the Yangshao period (**Figures 4A,D**). While considering the Longshan period, the results changed and centralization trend strengthened in the Central Plains, and many marginal small peaks appear in **Figure 4E** when compared with those in **Figure 4B**. Considering the Bronze Age, several marginal high peaks replaced by small peaks and a more strong center appeared when ignoring the abnormal peak in Shandong Province (the reason behind appearance of this abnormal peak is discussed in the previous part).

By taking into consideration the size information (or area) of sites, area density analysis not only represents the distribution of sites but is able to reveal the regional settlement pattern (Liu, 2007; Ma et al., 2012), further adding to our understanding of social complexity (Drennan and Uribe, 1987). Large settlement sites with areas larger than a million square meters corresponding to town sites have been found, during both the Yangshao and Longshan periods; however, the ratio of large settlements and town sites is still very low when compared to the number of smaller sites (Qian, 2001). Using the site number density analysis obscures this information because it does not consider where larger sites are on the landscape. During the Bronze Age, several large town sites appeared in the Central Plains of China, of them Yinxu ruin is the most famous town site. This transfers the center of sites from west and east sides to the central part of the study area. The appearance of many large town sites has consanguineous relationship with the establishment of Shang and Zhou dynasties in the Central Plains of China. The establishment of dynasties reflects the formation of a social system with high centralization of power and leads to the Central Plains becoming the core area of north China.

Possible Influencing Factors to the Spatiotemporal Pattern of Cultural Evolution From the Yangshao Period to the Bronze Age in the Yellow River Basin

The results of the site number density analysis and area density analysis provide a clearer picture of the spatiotemporal pattern of cultural evolution during the Yangshao, Longshan, and Bronze Age periods in the Yellow River basin. The number of sites and their density on the landscape expand through time, while the core areas of occupation change from a single location to multiple locations after the Yangshao period.

The strengthening of agriculture is considered as the most important impetus of cultural expansions during the prehistoric period (Diamond and Bellwood, 2003; An et al., 2005, An et al., 2010; Barton et al., 2009; Kennett et al., 2012; Dong et al., 2016a), and it provides convenience for prehistoric people to expand their active area (Chen F. H. et al., 2015a). Archaeobotanical studies of macro- and micro-plant remains found in several pre-Yangshao sites indicate that millet-based agriculture originated in the Yellow River around 10,000 BP (Lee et al., 2007; Lu et al., 2009; Yang et al., 2012; Zhao, 2011; Zhao, 2014) and dated the establishment of millet-based agriculture in the Loess Plateau (Zhao, 2011; Zhao, 2014) to the early Yangshao period and Shandong area to the Beixin period (8200–7800 BP). After this time period, millet-based agriculture rapidly expanded to the Yellow River basin (Zhao, 2014; Chen F. H. et al., 2015a; Han, 2015). A small number of charred rice seeds were identified using flotation at the Yuhuazhai site which dates to the early Yangshao period (Zhao, 2014). The number of recovered rice remains increased in several late Yangshao sites, including Nanjiaokou, Xinjie, and Baligang (Wei et al., 2000; Deng and Gao, 2012; Zhong et al., 2015). Millet is a type of a dry farming crop, whose output is highly influenced by precipitation (Yang and Li, 2015). The Yangshao period experienced a relatively wet climate according to the reconstructed mean annual precipitation determined using Gonghai Lake sediments (Chen F. et al., 2015b). Suitable climate conditions can provide a wider space for human survival, which is conducive to increase the yield of crop cultivation, and also increase population and promote the prosperity of culture (Dong et al., 2012). The warm and humid climate of the Yangshao culture ensured the broad and flat loess platform in the Yellow River Valley, which was suitable for millet agriculture. Millet-based agriculture became the most important subsistence strategy in most areas of the Yellow River basin in the Yangshao period, which promoted the Yangshao culture to become the most influential mainstream culture in the Neolithic Age of north China (Dong et al., 2016b).

During the Longshan period, obvious regional differentiation of culture is demonstrated by the appearance of multi-core zones of sites densities (**Figures 2**, **4**). Archaeobotanical evidence from the flotation at 31 Longshan period sites allows for a greater understanding of plant utilization during this period (**Supplementary Table S1**). Millet-based agriculture was still the main subsistence strategy, and rice agriculture is further developed. Wheat also appeared in a few late Longshan period sites including Dongpan, Liangchengzhen, Xijincheng, and Yuhuicun. The temperature and precipitation during the early Longshan period (5000–4500 BP) decreased significantly according to the northern hemisphere (30–90°N) temperature record compared to 1961–1990 instrumental mean temperature (Marcott et al., 2013) and reconstructed mean annual precipitation based on Gonghai Lake sediments (Chen F. et al., 2015b). The development of rice agriculture, further strengthening of millet-based agriculture, and the appearance of wheat during the late Longshan period indicate that agriculture subsistence strategies diversified to confront the deteriorating climate. The deterioration of climate compelled the farmers to change their subsistence strategies (Dong et al., 2013). The transformation of human diets from simplification to diversification is reflected in the results of stable carbon isotope studies in human bones as well (Ma et al., 2014).

Regional differentiation of culture and areas of occupation continue to expand into the Bronze Age according to the site number density analysis. (**Figure 4C**). However, the area density analysis suggests that the core of Bronze Age sites are concentrated in the Central Plains because of the appearance of several large town sites (**Figure 4F**). Influenced by the long-distance exchange of plants across Eurasia during the second millennium BC (Dodson et al., 2013; Spengler et al., 2014; Dong et al., 2017), agriculture subsistence strategies diversified in local contexts. With the introduction of wheat, domesticated in Southwest Asia, reliance on millet-based changed to a greater reliance on wheat, barley, and millet or a mixed agriculture in the upper Yellow River valley and its adjacent areas during the Bronze Age (Liu et al., 2014; Miller et al., 2014; Ma et al., 2016). However, there is also evidence for increasing reliance on animal husbandry during this period (An et al., 2003; An et al., 2005). On the Central Plains, millet-based agriculture was still the main subsistence strategy of farmers during Erlitou, Erligang, Shang, and Zhou periods. Archaeobotanical evidence suggests that there was a decrease in the use of rice, and wheat-based agriculture increased (Chen et al., 2012; An et al., 2014; Wu et al., 2014; Yang et al., 2017). The climate became much colder and drier after 4000 BP (Cai et al., 2010; Zhou et al., 2010; Duan et al., 2012; Marcott et al., 2013), which may suggest that the adjustment of subsistence strategies in different regions are in response to the further deteriorating climate. The changing location of core occupation on the landscape may not relate directly to climate change during this period. It is possible that the changing core concentrations of occupation through the three periods indicates the beginning of urbanization in north China as vast numbers of large town sites emerged along with the formation of dynasties or social systems with high centralization of power.

CONCLUSION

In the past, the study of settlement evolution mostly used the method of site number density analysis. In this study, by comparing site number density and area density made possible by the kernel density tool and by placing the results in context of the archaeological evidence, we can provide preliminary insights into the spatiotemporal pattern of cultural evolution taking place in China during its formative periods. Comprehensive consideration of the number and area of sites can better express the characteristics of settlement evolution. Conducive climate and the establishment and strengthening of millet-based agriculture contributed to the success of Yangshao cultures in the Yellow River basin. During the Longshan period, climatic conditions deteriorated. Differential cultural responses were found to be regionally based and subsistence strategies appear to have diversified. Site numbers on the landscape continue to expand, yet the number of larger sites become increasingly centered in the Central Plains and Shandong during the Bronze Age. This transition to a more centralize core area with larger sites seen in the results of the area density analysis may be highlighting the beginning of urbanization in China that is linked to this period.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, and further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2021.657179/full#supplementary-material

REFERENCES

An, C.-B., Tang, L., Barton, L., and Chen, F.-H. (2005). Climate Change and Cultural Response Around 4000 Cal Yr B.P. In the Western Part of Chinese Loess Plateau. *Quat. Res.* 63 (3), 347–352. doi:10.1016/j.yqres.2005.02.004

An, C. B., Feng, Z. D., and Tang, L. Y. (2010). Environmental Change and Cultural Response between 8000 and 4000 Cak Yr BP in the Western Loess Plateau, Northwest China. *J. Quat. Sci.* 19 (6), 529–535.

An, C., Feng, Z., Tang, L., and Chen, F. (2003). Environmental Changes and Cultural Transition at 4 Cal. Ka BP in Central Gansu. *J. Geographical Sci.* 58 (5), 743–748. (In Chinese).

An, J. P., Dong, W. B., Guo, R. Z., and Jin, G. Y. (2014). Analysis of Carbonized Plant Residues in the Tangye Site of Jinan, Shandong Province. *Nongyekaogu* 6, 7–21. (In Chinese).

Barton, L., Newsome, S. D., Chen, F.-H., Wang, H., Guilderson, T. P., and Bettinger, R. L. (2009). Agricultural Origins and the Isotopic Identity of Domestication in Northern china. *Proc. Natl. Acad. Sci.* 106 (14), 5523–5528. doi:10.1073/pnas.0809960106

Bureau of National Cultural Relics (2011b). *Atlas of Chinese Cultural Relics-Fascicule of Gansu Province*. Beijing: Surveying and Mapping Publishing House. (In Chinese).

Bureau of National Cultural Relics (2013). *Atlas of Chinese Cultural Relics-Fascicule of Hebei Province*. Beijing: Cultural Relics Press. (In Chinese).

Bureau of National Cultural Relics (1991). *Atlas of Chinese Cultural Relics-Fascicule of Henan Province*. Beijing: Sinomap press. (In Chinese).

Bureau of National Cultural Relics (2003). *Atlas of Chinese Cultural Relics-Fascicule of Inner Mongolia Autonomous Region*. Xi'an: Xi'an Cartographic Publishing House. (In Chinese).

Bureau of National Cultural Relics (2009). *Atlas of Chinese Cultural Relics-Fascicule of Liaoning Province*. Xi'an: Xi'an Cartograghic Publishing House. (In Chinese).

Bureau of National Cultural Relics (2010). *Atlas of Chinese Cultural Relics-Fascicule of Ningxia Hui Autonomous Region*. Beijing: Cultural Relics Press. (In Chinese).

Bureau of National Cultural Relics (1996). *Atlas of Chinese Cultural Relics-Fascicule of Qinghai Province*. Beijing: Sinomap press. (In Chinese).

Bureau of National Cultural Relics (2011a). *Atlas of Chinese Cultural Relics-Fascicule of Shandong Province*. Beijing: Surveying and Mapping Publishing House. (In Chinese).

Bureau of National Cultural Relics (1998). *Atlas of Chinese Cultural Relics-Fascicule of Shaanxi Province*. Xi'an: Xi'an Cartographic Publishing House. (In Chinese).

Bureau of National Cultural Relics (2006). *Atlas of Chinese Cultural Relics-Fascicule of Shanxi Province*. Beijing: Sinomap press. (In Chinese).

Bureau of National Cultural Relics (2002). *Atlas of Chinese Cultural Relics-Fascicule of Tianjin*. Beijing: Encyclopedia of China Publishing House. (In Chinese).

Cai, Y., Tan, L., Cheng, H., An, Z., Edwards, R. L., Kelly, M. J., et al. (2010). The Variation of Summer Monsoon Precipitation in central china since the Last Deglaciation. *Earth Planet. Sci. Lett.* 291 (1-4), 21–31. doi:10.1016/j.epsl.2009.12.039

Chen, F. H., Dong, G. H., Zhang, D. J., Liu, X. Y., Jia, X., An, C. B., et al. (2015a). Agriculture Facilitated Permanent Human Occupation of the Tibetan Plateau after 3600 B.P. *Science* 347, 248–250. doi:10.1126/science.1259172

Chen, F., Xu, Q., Chen, J., Birks, H., Liu, J., Zhang, S., et al. (2015b). East Asian Summer Monsoon Precipitation Variability since the Last Deglaciation. *Scientific Rep.* 5, 11186. doi:10.1038/srep11186

Chen, W. W., Zhang, J. Z., and Cai, Q. F. (2012). Analysis of Carbonized Plant Residues in the Guchengzhai City Site in Xinmi, Henan Province. *Huaxiakaogu* 1, 54–62. (In Chinese).

Cui, Y., Liu, Y., and Ma, M. (2018). Spatiotemporal Evolution of Prehistoric Neolithic-Bronze Age Settlements and Influencing Factors in the Guanting Basin, Northeast Tibetan Plateau. *Sci. China Earth Sci.* 61 (02), 31–44. doi:10.1007/s11430-017-9138-8

Demenocal, P. B. (2001). Cultural Responses to Climate Change during the Late Holocene. *Science* 292, 667–673. doi:10.1126/science.1059827

Deng, Z., and Gao, Y. (2012). Analysis of Plant Remains Unearthed from Baligang Site in Dengzhou. *Henan Province* 1, 156–163. (In Chinese).

Diamond, J., and Bellwood, P. (2003). Farmers and Their Languages: the First Expansions. *Science* 300 (5619), 597–603. doi:10.1126/science.1078208

Dodson, J. R., Li, X., Zhou, X., Zhao, K., Sun, N., and Atahan, P. (2013). Origin and Spread of Wheat in china. *Quat. Sci. Rev.* 72 (2), 108–111. doi:10.1016/j.quascirev.2013.04.021

Dong, G., Jia, X., An, C., Chen, F., Zhao, Y., Tao, S., et al. (2012). Mid-holocene Climate Change and its Effect on Prehistoric Cultural Evolution in Eastern Qinghai Province, China. *Quat. Res.* 77 (1), 23–30. doi:10.1016/j.yqres.2011.10.004

Dong, G., Jia, X., Elston, R., Chen, F., Li, S., Wang, L., et al. (2013). Spatial and Temporal Variety of Prehistoric Human Settlement and its Influencing Factors in the Upper Yellow River valley, Qinghai Province, China. *J. Archaeological Sci.* 40 (5), 2538–2546. doi:10.1016/j.jas.2012.10.002

Dong, G., Liu, F., Yang, Y., Wang, L., and Chen, F. (2016a). Cultural Expansion and its Influencing Factors during Neolithic Period in the Yellow River valley, Northern China. *Chin. J. Nat.* 38 (4), 248–252. (In Chinese).

Dong, G., Yang, Y., Han, J., Wang, H., and Chen, F. (2017). Eastern and Western Cultural Exchange from the Perspective of Crops. *Sci. China Earth Sci.* 47 (5), 530–543. (In Chinese).

Dong, G., Zhang, S., Yang, Y., Chen, J., and Chen, F. (2016b). Agricultural Intensification and its Impact on Environment during Neolithic Age in Northern China. *Chin. Sci. Bull.* 61, 2913–2925. (In Chinese). doi:10.1360/n972016-00547

Drennan, R., Peterson, C., Lv, X., Zhu, D., and Hou, S. (2014). Settlement and Social Dynamics in the Upper Daling and Chifeng Regions of Northeast China. *Asian Archaeology* 2, 50–76.

Drennan, R., and Uribe, C. (1987). Chiefdoms in the Americas. *Am. Indian Q.* 13 (1).

Duan, K., Yao, T., Wang, N., Xu, B., and Thompson, L. (2012). The Unstable Holocene Climatic Change Recorded in an Ice Core from the central Tibetan Plateau. *Sci. China Earth Sci.* 42, 1441–1449. (In Chinese).

Han, J. (2015). Early China: The Making of the Chinese Cultural Sphere. Shanghai: Shanghai Classics Publishing House, 282. (In Chinese).

Jaffe, Y., Castellano, L., Shelach-Lavi, G., and Campbell, R. (2020). Mismatches of Scale in the Application of Paleoclimatic Research to Chinese Archaeology[J]. *Quat. Res.* 99, 1–20. doi:10.1017/qua.2020.60

Kennett, D. J., Breitenbach, S. F. M., Aquino, V. V., Asmerom, Y., Awe, J., Baldini, J. U. L., et al. (2012). Development and Disintegration of Maya Political Systems in Response to Climate Change. *Science* 338 (6108), 788–791. doi:10.1126/science.1226299

Lee, G.-A., Crawford, G. W., Liu, L., and Chen, X. (2007). Plants and People from the Early Neolithic to Shang Periods in north china. *Pnas* 104 (3), 1087–1092. doi:10.1073/pnas.0609763104

Li, H., Liu, F., Cui, Y., Ren, L., Storozum, M. J., Qin, Z., et al. (2017). Human Settlement and its Influencing Factors during the Historical Period in an Oasis-Desert Transition Zone of Dunhuang, Hexi Corridor, Northwest china. *Quat. Int.* 458 (6), 113–122. doi:10.1016/j.quaint.2016.11.044

Liu, L., Chen, X., Wright, H., Xu, H., Li, Y., Chen, G., et al. (2019). Rise and Fall of Complex Societies in the Yiluo Region, North China: The Spatial and Temporal Changes. *Quat. Int.* 521, 4–15. doi:10.1016/j.quaint.2019.05.025

Liu, L. (2007). *China's Neolithic Age - the Road to the Early Country*. Beijing: Cultural relics publishing house. (In Chinese).

Liu, X., Lightfoot, E., O'Connell, T. C., Wang, H., Li, S., Zhou, L., et al. (2014). From Necessity to Choice: Dietary Revolutions in West China in the Second Millennium BC. *World Archaeology* 46 (5), 661–680. doi:10.1080/00438243.2014.953706

Lu, H., Zhang, J., Liu, K.-b., Wu, N., Li, Y., Zhou, K., et al. (2009). Earliest Domestication of Common Millet (panicum Miliaceum) in East Asia Extended to 10,000 Years Ago. *Proc. Natl. Acad. Sci.* 106 (18), 7367–7372. doi:10.1073/pnas.0900158106

Ma, M., Dong, G., Jia, X., Wang, H., Cui, Y., and Chen, F. (2016). Dietary Shift after 3600 Cal Yr BP and its Influencing Factors in Northwestern china: Evidence from Stable Isotopes. *Quat. Sci. Rev.* 145, 57–70. doi:10.1016/j.quascirev.2016.05.041

Ma, M., Dong, G., Jia, X., and Zhang, Z. (2012). Analysis on the Settlement Pattern and its Influencing Factors of Neolithic-Bronze Age in Hualong County, Qinghai Province. *Quat. Res.* 32, 209–218. (In Chinese).

Ma, M. M., Dong, G. H., Lightfoot, E., Wang, H., Liu, X. Y., Jia, X., et al. (2014). Stable Isotope Analysis of Human and Faunal Remains in the Western Loess Plateau, Approximately 2000 Calbc. *Archaeometry* 56, 237–255. doi:10.1111/arcm.12071

Marcott, S. A., Shakun, J. D., Clark, P. U., and Mix, A. C. (2013). A Reconstruction of Regional and Global Temperature for the Past 11,300 Years. *Science* 339 (6124), 1198–1201. doi:10.1126/science.1228026

Medina-Elizalde, M., and Rohling, E. J. (2012). Collapse of Classic Maya Civilization Related to Modest Reduction in Precipitation. *Science* 335, 956–959. doi:10.1126/science.1216629

Mei, N., and Kong, F. (2008). *Atlas of Chinese Cultural Relics-Fascicule of Beijing*. Beijing: Science Press. (In Chinese).

Miller, A., Usmanova, E., Logvin, V., Kalieva, S., Shevnina, I., Logvin, A., et al. (2014). Subsistence and Social Change in central Eurasia: Stable Isotope Analysis of Populations Spanning the Bronze Age Transition. *J. Archaeological Sci.* 42 (1), 525–538.

Qian, Y. (2001). *Research on Prehistoric City Sites and Civilization Origins in China*. Xi'an: Northwest University Press. (In Chinese).

Silverman, B. W. (1986). *Density Estimation for Statistics and Data Analysis*. New York: Chapman & Hall. doi:10.1007/978-1-4899-3324-9

Spengler, R., Frachetti, M., Doumani, P., Rouse, L., Cerasetti, B., Bullion, E., et al. (2014). Early Agriculture and Crop Transmission Among Bronze Age mobile Pastoralists of central Eurasia. *Proc. R. Soc. B.* 281 (1783), 20133382. doi:10.1098/rspb.2013.3382

Sun, Z., Shao, J., and Di, N. (2020). New Archaeological Discoveries of Huangchengtai Location of Shimao Site in 2016-2019. *Kaoguyuwenwu* 04, 3–11.

Wei, P., Kong, Z., and Liu, C. (2000). "Large in Size and a High Degree of Government Administration" Should Not Be the Direction of Higher Educational Reform (Part II). *Chin. Education Soc.* 33, 77–83. (In Chinese). doi:10.2753/ced1061-1932330177

Weiss, H., Courty, M.-A., Wetterstrom, W., Guichard, F., Senior, L., Meadow, R., et al. (1993). The Genesis and Collapse of Third Millennium north Mesopotamian Civilization. *Science* 261 (5124), 995–1004. doi:10.1126/science.261.5124.995

Wu, W., Zhang, J., and Jin, G. (2014). Archaeobotanical Evidence from Erlitou to Han Dynasty in Nanwa Site, Dengfeng, Henan Province. *Zhongyuanwenwu* 1, 109–117. (In Chinese).

Yang, Q., and Li, X. (2015). Carbon Isotope Characteristics of Millets in the Loess Plateau and its Influencing Factors. *Org. Geochem.* 11, 1683–1697. (In Chinese).

Yang, X., Wan, Z., Perry, L., Lu, H., Wang, Q., Zhao, C., et al. (2012). Early Millet Use in Northern china. *Proc. Natl. Acad. Sci.* 109 (10), 3726–3730. doi:10.1073/pnas.1115430109

Yang, Y., Yuan, Z., Zhang, J., Chen, Z., Jian, L., and Fang, F. (2017). Agricultural Characteristics and Development Process of Carboniferous Plant Remains in Zhengzhou Dongzhao Site during Xia and Shang Period. *J. Anthropol.* 36 (1), 119–130. (In Chinese).

Zhao, Z. (2011). New Archaeobotanic Data for the Study of the Origins of Agriculture in china. *Curr. Anthropol.* 52 (S4), S295–S306. doi:10.1086/659308

Zhao, Z. (2014). The Formation Process of Ancient Chinese Agriculture- Evidence of Surviving Plants in Flotation. *Quat. Res.* 34 (1), 73–84. (In Chinese).

Zhong, H., Yang, Y., Shao, J., and Zhao, Z. (2015). Study on the Remains of Carbonized Plants in Xinjie Site, Lantian County, Shaanxi Province. *Nanfangwenwu* 3, 36–43. (In Chinese).

Zhou, A., Sun, H., Chen, F., Zhao, Y., An, C., Dong, G., et al. (2010). High-resolution Climate Change in Mid-late Holocene on Tianchi lake, Liupan Mountain in the Loess Plateau in central china and its Significance. *Chin. Sci. Bull.* 55 (20), 2118–2121. doi:10.1007/s11434-010-3226-0

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Agricultural Transformations and Their Influential Factors Revealed by Archaeobotanical Evidence in Holocene Jiangsu Province, Eastern China

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The development and adoption of agriculture has been investigated for decades, and remains a central topic within archaeology. However, most previous studies focus on the crop's domestication centers, leading to gaps in knowledge, particularly in transitional zones between these centers. This paper reviews published archaeobotanical evidence and historical documents to reconstruct the trajectory of agricultural systems in Holocene Jiangsu Province. Comparing these new results to paleoclimate information, historical documents, and archaeological data enables us to better understand the underlying influences of past agricultural development. Our results indicate that a warm and wet climate may have promoted ancient peoples to first settle in Jiangsu between 8,500 and 6,000 BP and adopt rice farming. The continuous warm and wet climate may have facilitated the rapid development and expansion of rice agriculture, ultimately contributing to large-scale human settlement in 6,000–4,000 BP in Jiangsu Province. Between 4,000 and 2,300 BP during a cooler and drier climate millet agriculture diffused southward, facilitating a mixed rice and millet agricultural system. This mixed farming supported a continuesd widespread settlement and population growth in Jiangsu. After 2,300 BP, political instability in north China resulted in further southeastward migration, advanced planting technology was brought about to south China, facilitating highly developed agricultural systems and rapid population expansion in Jiangsu. Population growth led to the establishment of Jiangnan as the regional economic center, where people chose high-yielding rice and wheat rather than millet.

Keywords: archaeobotany, rice, millet, wheat, Yangtze River, Huai River, climate change

INTRODUCTION

The transition to entrenched agricultural systems is a critical topic relevant to modern economics, politics, international security, and climate change and adaptation. Environmental factors such as climate, landform, hydrology, and soil are critical variables impacting changing agricultural systems (Zhang et al., 2014; Chen et al., 2015; Ren et al., 2016; Wang et al., 2017; Liao et al., 2019). Climactic change is regarded as a key factor for prehistoric agriculture changes and cultural evolution (e.g., Dalfes et al., 1997; Bawden and Reycraft, 2002; Staubwasser et al., 2003; An et al., 2005; Jia et al., 2013, Jia et al., 2016; Dong et al., 2019, Dong et al., 2021). It is argued that a warm and humid climate was critical in promoting the large-scale development of millet farming on the Loess Plateau after 6,000 BP (An et al., 2004; Sheng et al., 2018; Dong et al., 2019). While a cold and dry climate supported the widespread cultivation of barley and wheat in the Hexi Corridor and northeast Tibetan Plateau around 4,000 BP (Chen et al., 2015; Zhou et al., 2016; Li and Dong, 2018). Other researchers have argued that geomorphic and hydrological conditions constrained agricultural systems (Wang et al., 2017). Wang et al. (2017) posit that two modes of farming existed along the middle reaches of the Yellow River Basin during the Peiligang period (8,500–7,000 BP): millet-based agriculture in hilly areas and mixed rice-millet farming on the plains. In addition to human innovation and adaptation, cultural and political factors played pivotal roles in subsistence systems (Kearns, 2010; Zhang et al., 2015; Pei et al., 2019), as did people's preference for certain crops change agricultural systems (Zhou et al., 2016; Xhauflair et al., 2017; Overton and Barry, 2018). To anticipate potential future agricultural risks, it is necessary to understand the many complex variables impacting changing ancient agricultural systems, particularly in transitional areas between regions.

The widespread adoption of agriculture is regarded as one of the most significant events in human history (Zohary et al., 2012; Barker and Goucher, 2015). Around 10,000 BP, crops were almost simultaneously domesticated in six discrete centers across the world (Mannion, 1999; Lev–Yadun et al., 2000; Zohary and Hopf, 2000; Diamond and Bellwood, 2003; Nakamura, 2010; Price and Bar-Yosef, 2011). This strategy has improved the ability of human beings to adapt to their surrounding environment, increasing worldwide population dramatically (Gignoux et al., 2011). Newly domesticated crops spread from centers of domestication alongside Neolithic peoples, initiating agricultural production in new areas (Gignoux et al., 2011). Many scholars have conducted studies of agricultural exchanges between centers of domestication, including the spread of wheat and barley from Western Asia to China, and of millet from the Yellow River basin to Western Asia (Sherratt, 2006; Frachetti et al., 2010; d'Alpoim Guedes, 2011; Jones et al., 2011; Spengler et al., 2014; Jones et al., 2016; Stevens et al., 2016; Dong et al., 2017, Dong et al., 2018; Liu et al., 2019; Dai et al., 2021). However, the spread of agricultural systems is often ignored in the transitional areas between adjacent centers of domestication. This is likely due to the complexity and difficulty of understanding the relationships within these processes.

In East Asia, millets and rice were domesticated in the Yellow River Basin and the mid-lower reaches of the Yangtze river around 10,000 BP, changing human lifeways and subsistence in these two areas, then spreading (Fuller et al., 2009; Lu et al., 2009; Zhao Y., 2011, Qin, 2012; Zhao, 2014; Yang et al., 2012). Located in the center of Eastern China, Jiangsu Province lies between a center of dry-land agriculture, Shandong Province to the north and a center of rice agriculture, Zhejiang Province to the south (Fuller et al., 2009; Crawford et al., 2016; Jin et al., 2016; Zhao, 2020). Therefore, Jiangsu Province is a transitional area where the north dry-land agriculture spread southward and the southern wet rice agriculture spread northward. However, the changing impact of these agricultural systems on local people's subsistence strategies in Jiangsu remain unclear. Sporadic archaeobotanical data indicates that rice farming first appeared in Jiangsu Province around 8,500 BP (Lin et al., 2014; Yang et al., 2016; Qiu et al., 2018), with millet farming introduced around 6,000 BP (Cheng et al., 2020), and wheat and soybean identified after 4,000 BP (Wu et al., 2019). These studies indicate the timeline and potential routes of millet and rice agriculture into Jiangsu Province, but have not paid much attention to the transformations in agricultural systems after their introduction. Further complicating our understanding is that Jiangsu is densely covered with lakes and rivers, with a variety of landforms, with a complex and changeable ecology.

To address these complications, this paper reconstructs the trajectories of agricultural systems in Holocene Jiangsu through published prehistoric archaeobotanical data and historical agricultural records. In addition, paleoclimate information, historical documents, and other archaeological data influences on agricultural change in Jiangsu Province are also explored. This study contributes to our understanding of changes in areas of converging agricultural systems and human adaptation within those ecologically diverse regions.

Regional Settings and Data Sources

Jiangsu Province (30°45'–35°20' N, 116°18'–121°57' E) is located in the center of Eastern China between Shandong Province in the north and Zhejiang Province in the south (**Figure 1**). Its total land area is 10.72×10^4 km, accounting for 1.12% of China's total. The primary landforms include low hills, alluvial plains, and water areas. Easily traversable flat terrain spans most of the plains area of Jiangsu Province, providing convenient communication and access between the north and south of the province. The Yangtze River runs across the south of Jiangsu, while the Huai River runs through central Jiangsu. These two rivers divide Jiangsu into three areas, from north to south: the northern Jiangsu Plain, the Jianghuai area and the southern Jiangsu area (Zhou and Han, 2008; Zhao Z., 2011). There are significant environmental differences between the southern Jiangsu area and the northern Jiangsu Plain, with the Jianghuai region transitioning between them. The climate of Jiangsu province is impacted by a transitional monsoon climate, and is split between a subtropical humid monsoon climate in the south and warm temperate humid monsoon climate in the north (Jiang et al., 2006; Xia et al., 2015). The average annual precipitation in Jiangsu Province is 660–1,617 mm (Xu, 2016), and the average annual

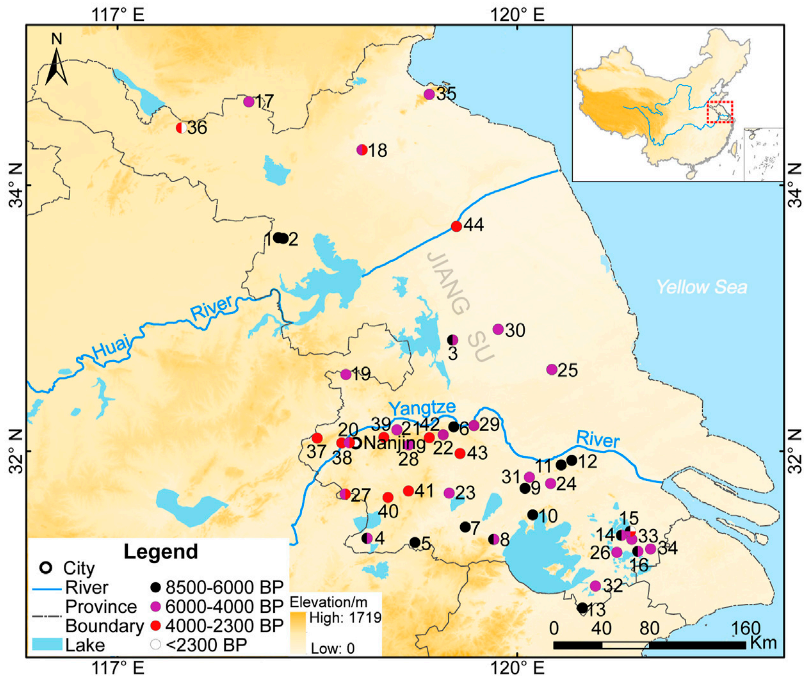

FIGURE 1 | Map of Jiangsu and sites mentioned in this study. 1) Shunshanji; 2) Hanjing; 3) Longqiuzhuang; 4) Xuecheng; 5) Shendun; 6) Zuohu; 7) Xixi; 8) Luotuodun; 9) Weidun; 10) Yangjia; 11) Qitoushan; 12) Dongshancun; 13) Guangfucun; 14) Caoxieshan; 15) Chuodun; 16) Jiangli; 17) Dadunzi; 18) Wanbei; 19) Miaoshan; 20) Beiyinyangying; 21) Dingshadi; 22) Sijiaodun; 23) Sanxingcun; 24) Nanlou; 25) Qingdun; 26) Chenghu; 27) Xiaodanyang; 28) Chengtoushan; 29) Mopanshan; 30) Jiangzhuang; 31) Sidun; 32) Longnan; 33) Zhumucun; 34) Shaoqingshan; 35) Tenghualuo; 36) Miaotaizi; 37) Niutougang; 38) Longshan; 39) Dianjiangtai; 40) Lishuixian; 41) Fushanguoyuan; 42) Dingjiacun; 43) Fenghuangshan; 44) Luzhuang.

temperature is 13–14°C in the north, 14–15°C in the Jianghuai, and 15–16 C in the south. The principle modern crops in the region are rice, wheat, corn, and potatoes, and the main livestock are pigs, cattle, and sheep.

Forty-five published archaeobotanical records from Jiangsu are presented here, including macrobotanical seeds, phytoliths, and starch grains samples. Information from twenty historical documents about crops in Jiangsu are summarized and presented. For the presented chronology, we used direct radiocarbon dating on macrobotanical crop remains when available, followed by carbonized charcoal from the related contexts. Four relative chronological intervals were selected based on artifact assemblage and are combined with prehistorical archaeological culture and historical periods: 8,500–6,000, 6,000–4,000, 4,000–2,300 BP, and <2,300 BP. The locations of these sites are shown in **Figure 1**, and detailed information can be obtained from published archives (**Table 1** and **Supplementary Table S1**).

RESULTS AND DISCUSSION

The History of Agricultural Processes in Holocene Jiangsu Province

Based on previous archaeobotanical studies, rice farming appeared around 8,500 BP in Jiangsu Province. Starch grains and phytoliths of rice were identified from the Shunshanji and Hanjing sites, respectively, from the Shunshanji Culture (8,500–7,000 BP) in Suqian, northern Jiangsu Plain (Yang et al., 2016; Qiu et al., 2018). Charred rice was also recovered at the Shunshanji and Hanjing sites, and directly radiocarbon dated to 7,869 ± 74 and 8,284 ± 88 cal yr BP, respectively, (Lin et al., 2014; National Museum of China et al., 2018). While rice remains were identified from thirteen Majiabang cultural (7,000–6,000 BP) sites in southern Jiangsu (**Figure 1**; **Table 1**). Rice agriculture was clearly present in Jiangsu Province around 8,500–6,000, however, there are differences in the timing of appearance. Rice farming appeared earlier on the northern Jiangsu plains than in southern Jiangsu (**Table 1**; **Figure 1**). It must be emphasized that it is very possible that rice management was a supplement to a primarily hunting and gathering economy. For example, the ubiquity and proportion of wild plant remains such as *Coix lacryma-jobi* and *Trichosanthes kirilowii* dominate the microfossil assemblages (phytoliths and starch grains) at the Shunshanji and Hanjing sites (Yang et al., 2016; Wu et al., 2017a; Qiu et al., 2018). Further wild plant remains such as Euryale ferox and water chestnut account for more than 80% of the macrofossil remains (charred seeds) in the Longqiuzhuang site in Gaoyou (Tang and Zhang, 1996; Tang, 1999; Wang, 1999), 93.33% in the Jiangli site in Kunshan (Qiu et al., 2013), and 71.6% in the Yangjia site in Wuxi (Qiu et al., 2016). While rice was planted by people in Jiangsu Province between 8,500 and 6,000 BP, it was likely a supplementary component of hunting and gathering subsistence.

Rice agriculture was established and developed rapidly between 6,000 and 4,000 BP. The number of archaeological

TABLE 1 | Botanical evidence of major crops in Holocene in Jiangsu Province, Eastern China.

Sites/region	Rice	Millets	Wheat	Culture	References
				Phase I (8,500–6,000 BP)	
Shunshanji	PSC	—	—	Shunshanji (8,500–7,500 BP)	Lin et al. (2014); Yang et al. (2016); Luo et al. (2016)
Hanjing	PCD	—	—	Shunshanji (8,500–7,500 BP)	National Museum of China et al. (2018); Qiu et al. (2018)
Longqiuzhuang	PC	—	—	Early Longqiuzhuang (7,000–6300 BP)	Tang and Zhang, (1996); Tang, (1999); Wang, (1982)
Zuohu	P	—	—	Majiabang (7,000–6,000 BP)	Lin and Wang, (2000)
Dongshancun	PC	—	—	Majiabang (7,000–6000 BP)	Wang and Ding, (1999); Qin, (2016)
Qitoushan	D	—	—	Majiabang (7,000–6,000 BP)	Zhu et al. (2003)
Weidun	D	—	—	Majiabang (7,000–6,000 BP)	You, (2001); Chen, (1995)
Xuecheng	P	—	—	Majiabang (7,000–6,000 BP)	Wang et al. (2013)
Shendun	PD	—	—	Majiabang (7,000–6,000 BP)	Wang, (2007); Tang, (2016)
Xixi	CD	—	—	Majiabang (7,000–6,000 BP)	Tian et al. (2009)
Yangjia	PC	—	—	Majiabang (7,000–6000 BP)	Qiu et al. (2016)
Luotuodun	D	—	—	Majiabang (7,000–6,000 BP)	Lin et al. (2003); Lin and Tian, (2009); Zhang and Lin, (2008); Li et al. (2008)
Chuodun	PCD	—	—	Majiabang (7,000–6,000 BP)	Ding, (2004); Qin, (2011); Fuller, (2011) Cao et al. (2007)
Caoxieshan	PC	—	—	Majiabang (7,000–6,000 BP)	Gu et al. (1998); Udatsu et al. (1998); Tang et al. (1999)
Jiangli	PC	—	—	Majiabang (7,000–6,000 BP)	Qiu et al. (2013), Qiu et al. (2014a)
Guangfucun	P	—	—	Majiabang (7,000–6,000 BP)	Wang and Ding, (2001)
				Phase II (6,000–4,000 BP)	
Longqiuzhuang	PC	—	—	Late Longqiuzhuang (6,300–5500 BP)	Tang and Zhang, (1996); Tang, (1999); Wang, (1982)
Wanbei	C	C	—	Early Dawenkou (6,200–5600 BP)	Cheng et al. (2020)
Dadunzi	D	D	—	Dawenkou (6,200–4600 BP)	Yin et al. (1964)
Qingdun	PD	—	—	Songze (6,000–5300 BP)	Guo, (2000)
Miaoshan	D	—	—	Beiyinyangying (6,000–5300 BP)	Chen, (2013)
Dingshadi	PD	—	—	Beiyinyangying (6,000–5,300 BP)	Chen, (2013)
Sijiaodun	P	—	—	Beiyinyangying (6,000–5,300 BP)	Chen, (2013)
Beiyinyangying	P	—	—	Beiyinyangying (6,000–5,300 BP)	Chen, (2013)
Nanlou	D	—	—	Songze (6,000–5,300 BP)	Fan, (2011); Wang, (2007)
Sanxingcun	D	—	—	Beiyinyangying (6,000–5,300 BP)	Wang and Zhang, (2004)
Chuodun	PC	—	—	Songze (6,000–5,300 BP)	Ding, (2004); Qin, (2011) Fuller, (2011)
Caoxieshan	PC	—	—	Songze (6,000–5,300 BP)	Gu et al. (1998); Udatsu et al. (1998); Tang et al. (1999)
Xuecheng	P	—	—	Songze (6,000–5,300 BP)	Wang et al. (2013)
Luotuodun	CD	—	—	Songze (6,000–5,300 BP)	Lin et al. (2003); Lin and Tian, (2009); Zhang and Lin, (2009); Li et al. (2008)
Jiangli	PC	—		Songze (6,000–5,300 BP)	Qiu et al. (2013), Qiu et al., 2014a
Chenghu	PC	—	—	Songze (6,000–5,300 BP)	Qin, (2011) Fuller, (2011); Ding and Zhang, (2004)
Wanbei	C	C	—	Middle and late Dawenkou (5,600–4,600 BP)	Cheng et al. (2020)
Jiangzhuang	C	C	—	Liangzhu (5,300–4,000 BP)	Wu et al. (2019)
Mopandun	D	—	—	Liangzhu (5,300–4,000 BP)	Chen, (2013)
Chengtoushan	D	—	—	Liangzhu (5,300–4,000 BP)	Min, (1986)
Sidun	D	—	—	Liangzhu (5,300–4,000 BP)	Wang et al. (1984)
Xiaodanyang	D	—	—	Liangzhu (5,300–4,000 BP)	Yi, (1988); Chen, (2013)
Zhumucun	PC	—	—	Liangzhu (5,300–4,000 BP)	Qiu et al. (2014b)
Shaoqingshan	PD	—	—	Liangzhu (5,300–4,000 BP)	Xi, (2003); Wang and Ding, (2000)
Jiangli	PC	—	—	Liangzhu (5,300–4,000 BP)	Qiu et al., 2013, Qiu et al. (2014a)
Tenghualuo	PC	—	—	Longshan (4,500–4,000 BP)	Lin and Zhang, (2005); Nanjing Museum and Lianyungang Museum, (2015)
Longnan	PD	—	—	Liangzhu (5,300–4,000 BP)	Zheng and Chen, (2006); Qian et al. (2006); Zheng et al. (1994); Tang et al. (1992)
				Phase III (4,000–2300 BP)	
Chuodun	P	—	—	Maqiao (4,000–3,400 BP)	Ding, (2004); Qin, (2011) Fuller, (2011) Cao et al. (2007)
Miaotaizi	C	C	C	Shang and Zhou (3,600–2,256 BP)	Wu et al. (2021), in press
Wanbei	C	C	C	Shang and Zhou (3,600–2,256 BP)	Cheng et al. (2020)
Beiyinyangying	P	—	—	Shang and Zhou (3,600–2,256 BP)	Chen, (2013)
Luzhuang	D	—	—	Hushu (3,600–2,400 BP)	Shen, (2009)
Dianjiangtai	D	—	—	Hushu (3,600–2,400 BP)	Zhong, (1987)
Dingjiacun	C	C	C	Hushu (3,600–2,400 BP)	Wu et al. (2017a)
Niutougang	D	—	—	Hushu (3,600–2,400 BP)	Han, (1997)
Longshan	D	—	—	Hushu (3,600–2,400 BP)	Chen, (2013)
Fenghuangshan	D	—	—	Hushu (3,600–2,400 BP)	Wang et al. (2002)

(Continued on following page)

TABLE 1 | (*Continued*) Botanical evidence of major crops in Holocene in Jiangsu Province, Eastern China.

Sites/region	Rice	Millets	Wheat	Culture	References
Fushanguoyuan	D	—	—	Hushu (3,600–2,400 BP)	Zhenjiang Museum, (1979)
Xiaodanyang	D	—	—	Hushu (3,600–2,400 BP)	Yi, (1988); Chen, (2013)
Lishuixian	D	—	—	Hushu (3,600–2,400 BP)	Han, (1997)
Phase IV (<2,300 BP)					
Miaotaizi	C	C	C	Han dynasty (202 BC–220 AD)	Wu et al. (2021), in press
Chu and Yue	+	—	—	Qin and Han dynasties (221 BC–AD 202)	Shi Ji, Shihuozhi
Jiangnan	+	—	—	Qin and Han dynasties (221 BC–AD 202)	The Geographical Records of the Han Shu
Wu Country	+	—	—	Three Kingdoms (AD 220–AD 280)	Records of the Three Kingdoms, Wu shu
Dongjing Jun	—	—	+	Wei, Jin and the southern and northern dynasties (AD 220–AD 589)	Song Shu, Biography of Emperor Xiaowu
Hailingxian	+	—	—	Wei, Jin and the southern and northern dynasties (AD 220–AD 589)	Naturalis Historia
Xiaoxian and Suqian	+	—	—	Wei, Jin and the southern and northern dynasties (AD 220–AD 589)	Records of the Three Kingdoms, Wei shu
Jianghuai	+	—	—	Sui and Tang dynasties (AD 581–AD 907)	Xin Tang Shu, Monograph on Food and Currency
Yangzhou	+	—	—	Sui and Tang dynasties (AD 581–AD 907)	Xin Tang Shu, Biography of Emperor Xuanzong
Zhenjiang	—	—	+	Sui and Tang dynasties (AD 581–AD 907)	Pentasyllabic regulated verse Xian Ju Meng Xia Ji Shi
Chuodun	P	—	—	Song dynasty (AD 960–AD 1279)	Ding, (2004); Qin, (2011) Fuller, (2011) Cao et al. (2007)
Jiangbei	+	—	+	Song and Yuan dynasties (AD 960–AD 1368)	Song History, Monograph on Food and Currency
Jiangnan	+	—	—	Song and Yuan dynasties (AD 960–AD 1368)	Song History, Monograph on Food and Currency
Jianghuai	+	—	—	Song and Yuan dynasties (AD 960–AD 1368)	Song History, Monograph on Food and Currency
Liangzhe	+	—	—	Song and Yuan dynasties (AD 960–AD 1368)	Song History, Monograph on Food and Currency
Kunshan	+	—	+	Song and Yuan dynasties (AD 960–AD 1368)	Wu Jun Zhi Tao Shan Ji
Hailing	+	—	+	Song and Yuan dynasties (AD 960–AD 1368)	Wu Jun Tu Jing Xu Ji
Wuzhong	+	—	+	North Song dynasty (AD 960–AD 1127)	Dao Pin
Suzhou	+	—	+	Ming dynasty (AD 1,368–AD 1,644)	Bu Nong Shu Jiao Shi
Jiangnan	+	—	+	Ming dynasty (AD 1,368–AD 1,644)	Jiang Nan Cui Geng Ke Dao Bian
Wujun	+	—	+	Qing dynasty (AD 1,636–AD 1,912)	Jiang Nan Cui Geng Ke Dao Bian
Jiangnan	+	—	+	Qing dynasty (AD 1,636–AD 1,912)	

P, phytolith; C, charred seeds collected by system archaeobotanical work; D, discovered plant remians during the archaeological excavation; S, starch grains; " + " represent the crop was recorded in historical documents. See ESM 1 for more detailed information.

sites with rice remains (25) nearly doubled during this time (**Table 1**; **Figure 1**). Systematic archaeobotanical work demonstrates that charred rice dominates the macrobotanical seed assemblages between 6,000 and 4,000 BP. For example, the proportion of rice grains increases from 20% in 7,000–6,300 BP to 80% in 6,300–5,500 BP at the Longqiuchuang site, while proportions of the Euryale ferox and water caltrop fell from more than 80% to around 20% (Tang, 1999; Tang and Zhang, 1996; Wang, 1999). Next, the number of rice grains was also much higher than that of other weeds in the subsequent Liangzhu period (5,300–4,000 BP), including the Jiangzhuang site in Taizhou (Wu et al., 2019), Jiangli site in Wuxi (Qiu et al., 2013; Qiu Z. W. et al., 2014), and Zhumucun site in Kunshan (Qiu Z. et al., 2014). Extensive cultivation of rice was also confirmed by excavated rice paddy fields at many Liangzhu period sites, including the Tenghualuo site in Lianyungang (Lin and Zhang, 2005), the Jiangli site in Wuxi (Qiu et al., 2013; Qiu Z. W. et al., 2014), the Zhumucun and Chuodun sites in Kunshan (Cao et al., 2007; Qiu Z. et al., 2014), the Chenghu site in Suzhou (Fuller, 2011; Qin, 2011), and the Luotuodun site in Yixin (Lin et al., 2003). During this time, millet farming also spread southeastward from the Haidai or Central Plains culture area to the northern Jiangsu Plain. 19 carbonized foxtail millets, 17 carbonized broomcorn millets, and 407 carbonized rice seeds were identified at the Wanbei site in Shuyang during the Dawenkou period (6,000–4,600 BP) (Cheng et al., 2020). However, millet agriculture seems to be blocked by the Huai River as there are no millet remains in the Jianghuai and southern Jiangsu area. We conclude that between 6,000 and 4,000 BP rice agriculture developed rapidly and was firmly established in Jiangsu Province, while millet agriculture was introduced on the northern Jiangsu plain.

Millet farming began to expand southward to the Jianghuai and southern Jiangsu areas between 4,000 and 2,300 BP. Simultaneously wheat crops originating in western Asia were introduced to southern China. Between 4,000 and 2,300 BP a mixed agricultural system had formed in Jiangsu Province including the integrated farming of millets, rice, wheat, barley, and soybean. Charred foxtail millet, broomcorn millet, wheat, rice, and soybean seeds were found together in the Shang and Zhou cultural layers (3,600–2,256 BP) at Miaotaizi site in Xuzhou (Wu et al., 2021, in press). Charred foxtail millet, broomcorn millet, rice, wheat, and barley were also unearthed from the Shang cultural layers (3,600–3,046 BP) at Wanbei site in Shuyang (Cheng et al., 2020). The co-existence of foxtail millet, broomcorn millet, wheat, rice, and soybean were also recovered from the Hushu culture layer (3,600–2,400 BP) at Dingjiacun site in Zhengjiang (Wu et al., 2017b). Notably, in spite of the integration, the most ubiquitous crops were different at these three sites. The ratio and ubiquity of crop remains reveal that foxtail millet, rice, and wheat were the dominant crops in the Miaotaizi site, Wanbei site, and Dingjiacun site, respectively, (Wu et al., 2017b; Cheng et al., 2020; Wu et al., 2021, in press).

Agricultural systems shifted in Jiangsu Province once more after 2300 BP. Due to little archaeobotanical research covering this period (Li et al., 2006; Wu et al., 2021, in press), we draw on historical documents to inform agricultural systems during the imperial period. Particular crops were often recorded by multiple historic documents in the region, indicating that it was widespread and common. The Chinese character "稻" (rice plant body) and "米" (rice caryopsis) were recorded in many Jiangsu historical documents, such as the "*Shi Ji, Huo Zhi Biography*", "*Records of the Three Kingdoms, Wei shu*", "*Jiang Nan Cui Geng Ke Dao Bian*" etc (**Table 1**; **Supplementary Table S1**). These records indicate that rice was common in Jiangsu Province from the Qin (221–207 BC) to Qing (AD 1636–AD 1912) dynasties (**Table 1**).The Chinese character "麦" (wheat) was also recorded in many historical documents in Jiangsu, such as the "*Song Shu, Biography of Emperor Xiaowu*", "*Song History, Monograph on Food and Currency*", "*Tao Shan Ji*" etc (**Table 1**; **Supplementary Table S1**), suggesting that wheat was also commonly found in Jiangsu Province. Millet and soybean had withdrawn from much of Jiangsu Province, and only were planted in some relatively dry areas in Jiangnan, Zhejiang, Jinghu and similar areas, recorded by the "*Song History, Monograph on Food and Currency*". From this evidence, after 2,300 BP people were primarily engaged in the production of rice and wheat after in Jiangsu, and millet and soybeans only planted sporadically in some drylands.

In summary, rice farming first emerged in Jiangsu Province around 8,500 BP, and dominated subsistence strategies between 6,000 and 4,000 BP. With the introduction of millet, mixed agriculture was practiced between 4,000 and 2,300 BP, including rice, millet, wheat and soybean. Agricultural practices shifted after 2,300 BP, when rice and wheat were predominately grown, while sporadic millet agriculture remained in a few dry areas. It is worth noting that the existence of differences in subsistence from the north and south of the Huai River. Rice agriculture emerged around 8,500 BP in the north of the Huai River, which was 1,500 years earlier than its appearance south of the Huai River. Millet was introduced north of the Huai River between 6,000 and 4,000 BP, and was introduced with wheat south of the Huai River only between 4,000 and 2,300 BP. After 2,300 BP, a mixed cropping pattern continued north of the Huai River in Jiangsu Province including rice, foxtail millet, broomcorn millet, wheat, and soybean, while millet farming disappeared. South of the Huai river, rice, and wheat agriculture remained the dominant agricultural subsistence.

Influential Factors on Human Settlement and Agricultural Systems in Holocene in Jiangsu Province

The beginning of plant domestication is often argued to be related to the warm climate transformations of the early Holocene (Zeder, 2008; Willcox et al., 2009; d'Alpoim Guedes and Bocinsky, 2018). Similarly, the emergence of agriculture is also often argued to be a result of a warm climate during the Holocene Optimum (Richerson et al., 2001; Feynman and Ruzmaikin, 2007; Atahan et al., 2008). Many previous paleoclimate studies indicated that a warmer and wetter climate was present between 8,500 and 4,000 BP in the lower Yangtze River (Wang et al., 1996; Qu et al., 2000; Wang and Gong, 2000; Hori et al., 2001; Tao et al., 2006; Atahan et al., 2008; Chen et al., 2009; Ma et al., 2009; Qiu et al., 2020). The emergence of rice farming likely benefited from the warm climate between 8,500 and 6,000 BP in its original centers of domestication. A recent study showed that the increase of rice pollen in the Tai Lake Basin may be related to the emergence of rice agriculture during the warm and wet climate between 8,500 and 6,000 BP (Qiu et al., 2020). Similarly, the warm and wet climate potentially supported the emergence and adoption of rice farming in Jiangsu between 8,500 and 6,000 BP, with increasing food production facilitating a growing population. In this time people settled far from the current coastline of Yellow Sea (**Figure 2A**) owing to the amount of land covered by the sea during this period (Li et al., 2008; Li et al., 2009).

Formal agriculture was established in China by 6,500–6,000 BP, likely benefiting from the warm and wet Holocene Optimum (Fuller et al., 2009; Zhao Y., 2011; Qin, 2012; Zhao, 2014). The favorable climate conditions likely promoted the adoption of agriculture with a resulting population expansion in northern China in this time. The population expansion on the Central Plains of China is likely mirrored, the migration and expansion of the Yangshao culture southeastward (An et al., 2004). Southeastward migration brought millet farming to the northern Jiangsu plain, verified by archaeobotanical evidence (36 charred millets) at Wanbei site in Shuyang County during the Dawenkou period (6,000–4,600 BP) (Cheng et al., 2020). Therefore, the warm and wet climate promoted the establishment of rice agriculture in Jiangsu between 6,000 and 4,000 BP, and indirectly facilitated the development of millet agriculture on the northern Jiangsu plain. Some scholars have argued that the marine regression process increased available land for human activities in the Liangzhu cultural period. This would further encourage rapid development and establishment of rice agriculture in Jiangsu Province (Zhang et al., 2004; Zhang, 2005; Li et al., 2008, Li et al., 2009). The establishment of agricultural systems likely led to populations increasing in Jiangsu Province during 6,000–4,000 BP, where the number of archaeological sites increased from 86 in 8,500–6,000 BP to 213 in 6,000–4,000 BP (**Figures 2A,B**).

Around 4,200 BP, the "Holocene Event 3", an extreme cold and dry climate event, commenced, impacting climate across the world (Bond et al., 1993; Bond et al., 2001; DeMenocal, 2001). This event has been argued to lead to the demise of some ancient states, such as the Akkad Empire and the Harappa civilization (Weiss et al., 1993; Kerr, 1998; Cullen et al., 2000; Staubwasser et al., 2003). This event also played a significant impact on the transformation of civilization in China (Wu and Liu, 2001, Wu and Liu, 2004; Sun et al., 2019), and is argued to have led to significant culture change and transformations of subsistence strategies in China (Wu and Liu, 2001, Wu and Liu, 2004; Wang, 2004; Chen et al., 2015; Jia et al.,

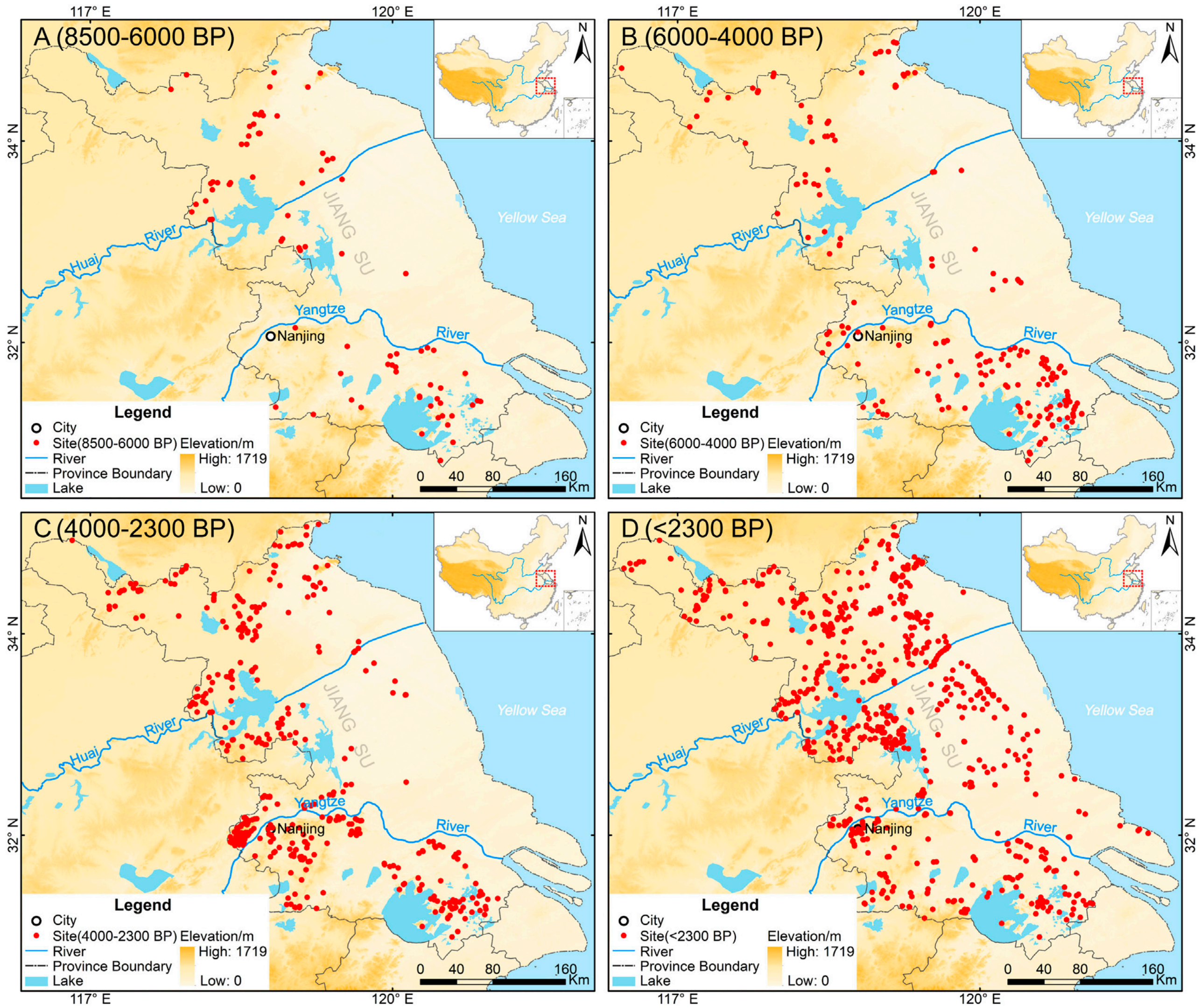

FIGURE 2 | The distribution of archaeological sites since in Holocene in Jiangsu Province.

2016). In particular, the collapse of the Liangzhu Culture is considered a result of this event in southeastern China (Stanley et al., 1999; Li et al., 2010; Sun et al., 2019). This climate event potentially caused southward human migration, bringing millet and wheat dry-land farming to Jiangsu Province. During this time mixed agriculture was prevalent in Jiangsu Province, verified by the archaeobotanical evidence from the Miaotaizi site in Xuzhou (Wu et al., 2021, in press), the Wanbei site in Suqian (Cheng et al., 2020), the Datongpu site in Yancheng (Liu et al., 2021; Under review) and the Dingjiacun site in Zhenjiang (Wu et al., 2017b) (**Table 1**). Mixed agriculture potentially increased food production, and indirectly improved the human ability to respond the environmental risks. Concurrent with these changes between 4,000 and 2,300 BP is the transition in Chinese societies from the late Neolithic, to Bronze Age, and to the Iron Age. This transformation is confirmed by bronze-iron implements obtained from the archaeological excavation in various cemeteries during 4,000–2,300 BP in Jiangsu Province (Liao, 1982; Liang, 1986; Wu, 2011). Productivity and grain production were greatly improved by the widespread utilization of bronze-iron implements. Therefore, mixed agriculture and the revolutionary implements jointly increased food resources in Jiangsu Province, leading to widespread population growth between 4,000 and 2,300 BP, illustrated by multiple archaeological sites (616) (**Figure 2C**).

Human settlement peaked after 2,300 BP in Jiangsu Province (**Figure 2D**). According to the "*Zizhi Tongjian*", "*Xin Tang Shu*", and "*Song Shi*", the increasing population was considered a result of the shifting of the provincial economic center from the Central Plain to the Jiangnan area (southern Jiangsu) (Zheng, 2003; Cheng, 2004). Over time recurrent wars in northern China led to a large scale of migration southward, such as the Yongjia rebellion (AD 311), the rebellion of An Lushan (AD 757), and the Jingkang rebellion (AD 1127) (Zhang, 2008; Sun and Liu, 2011; You, 2018). Some scholars further argue that two cold climatic events compelled human migration southward from northern China during the Tang Dynasty (AD 710–750 and AD 780–860) (Fang, 1989; Man, 2009; Ge et al., 2014). With the human migration southward, revolutionary tools and technology were introduced into southern China. A variety of advanced agricultural tools such as "lóu chē" (a sowing tool), two advanced crop planting techniques such as "lí–pá–lóu" (a kind of soil preparation technology) and "sōu zhòng fǎ" (a sowing technology) (Min, 1986; Zeng, 2005; Wang et al., 2019). According to the "*Leisi Jing*," the advanced farming tools and techniques were introduced from the northern China into the southern Jiangsu Province during the late Tang dynasty, and led to people discarding extensive farming practices, leading to the era of intensive farming. With the introduction of new tools and technologies, larger areas of land were cultivated in southern China, leading to agricultural production increasing and a doubling of income. According to the *Xin Tang Shu*, *Song Shi, Nung Sang Chi Yao*, and *Agricultural Administration book*, the government also carried out a series of policies to increase agricultural production in south China, such as draining lakes, building terraces, and "wéi tián" (low-lying paddy fields surrounded with dikes). The state's economic center gradually shifted to the Jiangnan Area (southern Jiangsu area) after the dredging on Beijing-Hangzhou Grand Canal in the Sui-Dynasty (AD 581–AD 618). With an increasing population, crops with higher productive yields were preferred in Jiangsu Province after 2,300 BP, such as rice and wheat, while millet and other crops were gradually abandoned owing to their relatively low yield.

In summary, the warm and wet climate encouraged the emergence of rice agriculture after 8,500 BP, facilitating human settlement in Jiangsu Province. Between 6,000 and 4,000 BP rice agriculture was firmly established, encouraged by the continuous warm and humid climate and marine regression process, and ultimately contributing to large-scale human settlement in Jiangsu. Millet agriculture was also brought into northern Jiangsu plains in this time. This is indirectly attributed to the warm and humid climate conditions in northern China, increasing food production supported by a favorable climate led to greater population growth and migration. Dry-farming was introduced into Jiangsu after 4,000 BP, which was likely the result of human migration southeastward from northern China from the "Holocene event 3". Mixed agriculture and the revolutionary implements jointly increased food production in Jiangsu Province, leading to higher population increases between 4,000 and 2,300 BP. After 2,300 BP, frequent wars in northern China caused large migrations southward to Jiangsu Province, facilitating the introduction of new agricultural tools and farming innovations into southern China. Rice and wheat replaced millet as the principle crops owing to their low yield in southern China. These transformations led to the enhancement of agricultural productivity and yield in southern China, ultimately shifting the national economic center southward.

CONCLUSION

Rice agriculture first appeared in Jiangsu Province around 8,500 BP, and was firmly established between 6,000 and 4,000 BP. Millet agriculture was brought to the northern Jiangsu plain around 6,000 BP, with millet and wheat introduced into southern Jiangsu after 4,000 BP. After 2,300 BP, millet agriculture disappears from Jiangsu Province, while a mixed rice and wheat agricultural system remained.

The warm and wet climate promoted the emergence of rice agriculture and settlement after 8,500 BP in Jiangsu Province. Benefiting from a continually warm and wet climate between 6,000 and 4,000 BP, rice agriculture was firmly established and spread rapidly, supporting greater human settlement in Jiangsu Province. The introduction of millet after 6,000 BP to the northern Jiangsu plain may also be a result of the southward migration of northern people caused by the warm and wet climate. Between 4,000 and 2,300 BP, a mixed agricultural system formed in Jiangsu Province due to the introduction of dry farming from northern China. Meanwhile, the introduction of bronze and iron farming tools improved human productivity and expanded the scale of human settlement. In the end, the new agricultural tools and farming techniques were brought southward after 2,300 BP, and led to the overall increase of the agricultural productive yield in the South, and finally promoted the scale of human settlement to the peak.

In addition, the difference of agricultural patterns was simple and rough in several different geographical units owing to the lack of systematic archaeobotanical research in Jiangsu Province. With further long term systematic archaeobotanical work, our understanding of these long-term transformations will be enriched.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

The study was designed by HML and XJ. The data was collected by ZL, XSL and analyzed by HML, XJ, YL, ZJH, HWS, and LQS. HML, YL, NJ, and XJ wrote the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2021.661684/full#supplementary-material

REFERENCES

An, C.-B., Tang, L., Barton, L., and Chen, F.-H. (2005). Climate Change and Cultural Response Around 4000 Cal Yr B.P. In the Western Part of Chinese Loess Plateau. *Quat. Res.* 63, 347–352. doi:10.1016/j.yqres.2005.02.004

An, C., Feng, Z., and Tang, L. (2004). Environmental Change and Cultural Response between 8000 and 4000 Cal. Yr BP in the Western Loess Plateau, Northwest China. *J. Quat. Sci.* 19, 529–535. doi:10.1002/jqs.849

Atahan, P., Itzstein-Davey, F., Itzstein-Davey, F., Taylor, D., Dodson, J., Qin, J., et al. (2008). Holocene-aged Sedimentary Records of Environmental Changes and Early Agriculture in the Lower Yangtze, China. *Quat. Sci. Rev.* 27, 556–570. doi:10.1016/j.quascirev.2007.11.003

Barker, G., and Goucher, C. (2015). *The Cambridge World History, Volume Ⅱ: A World with Agriculture, 12,000 BCE–500 CE*. London: Cambridge University Press

Bond, G., Broecker, W., Johnsen, S., McManus, J., Labeyrie, L., Jouzel, J., et al. (1993). Correlations between Climate Records from North Atlantic Sediments and Greenland Ice. *Nature*. 365, 143–147. doi:10.1038/365143a0

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M. N., Showers, W., et al. (2001). Persistent Solar Influence on north Atlantic Climate during the Holocene. *Science*. 294, 2130–2136. doi:10.1126/science.1065680

Cao, Z. H., Yang, L. Z., Lin, X. G., Hu, Z. Y., Dong, Y. H., Zhang, G. Y., et al. (2007). Morphological Characteristics of Paddy fields, Paddy Soil Profile, Phytolith and Fossil rice Grain of the Neolithic Age in Yangtze River Delta (In Chinese). *Acta Pedologica Sinica* 44, 838–847.

Chen, F. H., Dong, G. H., Zhang, D. J., Liu, X. Y., Jia, X., An, C. B., et al. (2015). Agriculture Facilitated Permanent Human Occupation of the Tibetan Plateau after 3600 B.P. *Science*. 347, 248–250. doi:10.1126/science.1259172

Chen, J. Y. (1995). Analysis of the Primitive Agricultural Factors in the Neolithic Site of Xudun, Changzhou (In Chinese). *Agric. Archaeology* 1, 101–103.

Chen, W., Wang, W.-M., and Dai, X.-R. (2009). Holocene Vegetation History with Implications of Human Impact in the Lake Chaohu Area, Anhui Province, East China. *Veget Hist. Archaeobot*. 18, 137–146. doi:10.1007/s00334-008-0173-7

Chen, Y. (2013). *On The Development of Early Agricultural in Ningzhen Region (7000-2500 BP). PhD Dissertation (In Chinese)*. Nanjing (China): Nanjing Agricultural University.

Cheng, M. S. (2004). *Economic History of Northern China (In Chinese)*. Beijing: People's Publishing House

Cheng, Z. J., Yang, Y. Z., Gan, H. Y., Lin, L. G., and Zhang, J. Z. (2020). The Macro-Plant Remains from Wanbei Site, Shuyang City, Jiangsu Province (In Chinese). *Agricul. Hist. Chin.* 39, 35–44.

Crawford, G. W., Chen, X., Luan, F., and Wang, J. (2016). People and Plant Interaction at the Houli Culture Yuezhuang Site in Shandong Province, China. *The Holocene*. 26, 1594–1604. doi:10.1177/0959683616650269

Cullen, H. M., deMenocal, P. B., Hemming, S., Hemming, G., Brown, F. H., Guilderson, T., et al. (2000). Climate Change and the Collapse of the Akkadian empire: Evidence from the Deep Sea. *Geology*. 28, 379–382. doi:10.1130/0091-7613(2000)028<0379:ccatco>2.3.co;2

Dai, J., Cai, X., Jin, J., Ge, W., Huang, Y., Wu, W., et al. (2021). Earliest Arrival of Millet in the South China Coast Dating Back to 5,500 Years Ago. *J. Archaeological Sci.* 129, 105356. doi:10.1016/j.jas.2021.105356

Dalfes, H. N., Kukla, G., and Weiss, H. (1997). Third Millennium BC Climate Change and Old World Collapse. *Springer Sci. Business Media*. 49, 1–14. doi:10.1007/978-3-642-60616-8_10

d'Alpoim Guedes, J. (2011). Millets, Rice, Social Complexity, and the Spread of Agriculture to the Chengdu Plain and Southwest China. *Rice*. 4 (3), 104–113. doi:10.1007/s12284-011-9071-1

d'Alpoim Guedes, J., and Bocinsky, R. K. (2018). Climate Change Stimulated Agricultural Innovation and Exchange across Asia. *Sci. Adv.* 4, eaar4491–12. doi:10.1126/sciadv.aar4491

DeMenocal, P. B. (2001). Cultural Responses to Climate Change during the Late Holocene. *Science*. 292, 667–673. doi:10.1126/science.105928710.1126/science.1059827

Diamond, J., and Bellwood, P. (2003). Farmers and Their Languages: The First Expansions. *Science*. 300, 597–603. doi:10.1126/science.1078208

Ding, J. L. (2004). The Origin of rice fields and rice Farming in the Neolithic Age of the Lower Reaches of the Yangtze River (In Chinese). *South. Cult.* 2, 19–31.

Ding, J. L., and Zhang, T. J. (2004). Discovery of Paddy Field in Songze Period at Chenghu Site (In Chinese). *Chin. Cult. heritage* 1, 72–73.

Dong, G., Li, R., Lu, M., Zhang, D., and James, N. (2019). Evolution of Human-Environmental Interactions in China from the Late Paleolithic to the Bronze Age. *Prog. Phys. Geogr. Earth Environ.* 44 (1), 233–250. doi:10.1177/0309133319876802

Dong, G., Li, T., Zhang, S., Ren, L., Li, R., Li, G., et al. (2021). Precipitation in Surrounding Mountains Instead of Lowlands Facilitated the prosperity of Ancient Civilizations in the Eastern Qaidam Basin of the Tibetan Plateau. *CATENA*. 203, 105318. doi:10.1016/j.catena.2021.105318

Dong, G., Yang, Y., Han, J., Wang, H., and Chen, F. (2017). Exploring the History of Cultural Exchange in Prehistoric Eurasia from the Perspectives of Crop Diffusion and Consumption. *Sci. China Earth Sci.* 60, 1110–1123. doi:10.1007/s11430-016-9037-x

Dong, G., Yang, Y., Liu, X., Li, H., Cui, Y., Wang, H., et al. (2018). Prehistoric Trans-continental Cultural Exchange in the Hexi Corridor, Northwest China. *The Holocene*. 28, 621–628. doi:10.1177/0959683617735585

Fan, Y. B. (2011). *On the Development of rice Farming in Tai lake Area during the Neolithic Age of China. Master Thesis (In Chinese)*. Nanjing (China): Nanjing Agricultural University

Fang, J. Q. (1989). The Influence of Climate Change on Population Migration in Historical Period of China (In Chinese). *Geographical Environ. Res.* 2, 41–48.

Feynman, J., and Ruzmaikin, A. (2007). Climate Stability and the Development of Agricultural Societies. *Climatic Change*. 84, 295–311. doi:10.1007/s10584-007-9248-1

Frachetti, M. D., Spengler, R. N., Fritz, G. J., and Mar'yashev, A. N. (2010). Earliest Direct Evidence for Broomcorn Millet and Wheat in the central Eurasian Steppe Region. *Antiquity*. 84, 993–1010. doi:10.1017/S0003598X0006703X

Fuller, D. Q. (2011). Pathways to Asian Civilizations: Tracing the Origins and Spread of Rice and Rice Cultures. *Rice*. 4, 78–92. doi:10.1007/s12284-011-9078-7

Fuller, D. Q., Qin, L., Zheng, Y., Zhao, Z., Chen, X., Hosoya, L. A., et al. (2009). The Domestication Process and Domestication Rate in Rice: Spikelet Bases from the Lower Yangtze. *Science*. 323, 1607–1610. doi:10.1126/science.1166605

Ge, Q. S., Fang, X. Q., and Zheng, J. Y. (2014). The Impact of Climate Change in Chinese History and its Response to Enlightenment (In Chinese). *Adv. Earth Sci.* 29, 23–29.

Gignoux, C. R., Henn, B. M., and Mountain, J. L. (2011). Rapid, Global Demographic Expansions after the Origins of Agriculture. *Proc. Natl. Acad. Sci.* 108, 6044–6049. doi:10.1073/pnas.0914274108

Gu, J. X., Zou, H. B., Li, M. C., Tang, L. H., Ding, J. L., and Yao, Q. D. (1998). Preliminary Understanding of rice Farming at Caoxieshan Site in Majiabang Period (In Chinese). *South. Cult.* 3, 15–24.

Guedes, J. d. A., Jiang, M., He, K., Wu, X., and Jiang, Z. (2013). Site of Baodun Yields Earliest Evidence for the Spread of rice and Foxtail Millet Agriculture to South-West China. *Antiquity*. 87, 758–771. doi:10.1017/S0003598X00049449

Guo, Y. B. (2000). Analysis of Neolithic Agricultural Economy in the East of Jianghuai River (In Chinese), *Agricul. Hist. Chin.* 19, 3–8.

Han, P. Z. (1997). *Nanjing Cultural Relics (In Chinese)*. Beijing: Local records Publishing House

Hori, K., Saito, Y., Zhao, Q., Cheng, X., Wang, P., Sato, Y., et al. (2001). Sedimentary Facies and Holocene Progradation Rates of the Changjiang (Yangtze) delta, China. *Geomorphology*. 41, 233–248. doi:10.1016/S0169-555X(01)00119-2

Jia, X., Dong, G., Li, H., Brunson, K., Chen, F., Ma, M., et al. (2013). The Development of Agriculture and its Impact on Cultural Expansion during the Late Neolithic in the Western Loess Plateau, China. *The Holocene*. 23 (1), 85–92. doi:10.1177/0959683612450203

Jia, X., Sun, Y., Wang, L., Sun, W., Zhao, Z., Lee, H. F., et al. (2016). The Transition of Human Subsistence Strategies in Relation to Climate Change during the Bronze Age in the West Liao River Basin, Northeast China. *The Holocene*. 26 (5), 781–789. doi:10.1177/0959683615618262

Jiang, A. J., Xiang, Y., Peng, H. Y., and Wang, B. M. (2006). The Analysis of Jiangsu Climate Variety in Forty Years. *Scien. Meteorol. Sin.* 26, 525–529.

Jin, G., Wagner, M., Tarasov, P. E., Wang, F., and Liu, Y. (2016). Archaeobotanical Records of Middle and Late Neolithic Agriculture from Shandong Province, East China, and a Major Change in Regional Subsistence during the Dawenkou Culture. *The Holocene*. 26 (10), 1605–1615. doi:10.1177/0959683616641746

Jones, M., Hunt, H., Kneale, C., Lightfoot, E., Lister, D., Liu, X., et al. (2016). Food Globalisation in Prehistory: The Agrarian Foundations of an Interconnected Continent. *Jba*. 4, 73–87. doi:10.5871/jba/004.073

Jones, M., Hunt, H., Lightfoot, E., Lister, D., Liu, X., and Motuzaite-Matuzeviciute, G. (2011). Food Globalization in Prehistory. *World Archaeology*. 43, 665–675. doi:10.1080/00438243.2011.624764

Kearns, G. (2010). Geography, Geopolitics and Empire. *Trans. Inst. Br. Geogr.* 35, 187–203. doi:10.1111/j.1475-5661.2009.00375.x

Kerr, R. A. (1998). Archaeology: Sea-Floor Dust Shows Drought Felled Akkadian Empire. *Science*. 279, 325–326. doi:10.1126/science.279.5349.325

Lev-Yadun, S., Gopher, A., and Abbo, S. (2000). ARCHAEOLOGY:Enhanced: The Cradle of Agriculture. *Science*. 288, 1602–1603. doi:10.1126/science.288.5471.1602

Li, H. M., and Dong, G. H. (2018). The Adoption of Wheat and Barley as Major Staples in Northwest China during the Early Bronze Age. *Far from the Hearth Eassays in Honour of Martin Jones Chapter*. 16, 189–198. doi:10.17863/CAM.38307

Li, L., Zhu, C., Jiang, F., Zhao, Q., and Lin, I. (2008). Research on the Disappearance Causes of the Tenghualuo Site in Lianyungang, Jiangsu Province, China. *Sci. Bull.* 53, 161–176. doi:10.1007/s11434-008-5016-5

Li, L., Zhu, C., Lin, L., Zhao, Q., Shi, G., Zheng, C., et al. (2009). Evidence for marine Transgression between 7500-5400BC at the Luotuodun Site in Yixing, Jiangsu Province. *J. Geogr. Sci.* 19, 671–680. doi:10.11821/xb20081100810.1007/s11442-009-0671-2

Li, Y., Wu, J., Hou, S., Shi, C., Mo, D., Liu, B., et al. (2010). Palaeoecological Records of Environmental Change and Cultural Development from the Liangzhu and Qujialing Archaeological Sites in the Middle and Lower Reaches of the Yangtze River. *Quat. Int.* 227, 29–37. doi:10.1016/j.quaint.2010.05.015

Liang, Y. (1986). Brief Talk on the Metal Farm Tools in the Middle and Lower Reaches of the Yangtze River during the Spring and Autumn Period and the Warring States Period (In Chinese). *J. Guangxi Normal Univ. (PHILOSOPHY SOCIAL SCIENCES)*. 2, 63–70.

Liao, Y., Lu, P., Mo, D., Wang, H., Storozum, M. J., Chen, P., et al. (2019). Landforms Influence the Development of Ancient Agriculture in the Songshan Area, central China. *Quat. Int.* 521, 85–89. doi:10.1016/j.quaint.2019.07.015

Liao, Z. H. (1982). Discussion. *Agric. Archaeology*. 18, 114. doi:10.1111/j.1475-1305.1982.tb01910.x

Lin, L. G., Gan, H. Y., and Yan, L. (2014). A Report on the Excavation of the Neolithic Site in Shunshanji, Sihong, Jiangsu Province (In Chinese). *Acta Archaeol. Sin.* 4, 519–562.

Lin, L. G., and Tian, M. L. (2009). Excavation Report of Luotuodun Site in Yixing, Jiangsu Province (In Chinese). *South. Cult.* 5, 26–44.

Lin, L. G., Tian, M. L., and Xu, J. Q. (2003). Excavation of Luotuodun Neolithic Site in Yixing City, Jiangsu Province (In Chinese). *Archaeology* 7, 5–11.

Lin, L. G., and Wang, Q. Z. (2000). Excavation of Zuohu Site in Zhenjiang City, Jiangsu Province (In Chinese). *Archaeology* 4, 14–33.

Lin, L. G., and Zhang, W. X. (2005). Study on Ancient rice at Tenghualuo and Houdatang Sites during Longshan Cultural in Huang Huai Region (In Chinese). *South. Cult.* 1, 15–19.

Liu, X., Jones, P. J., Motuzaite Matuzeviciute, G., Hunt, H. V., Lister, D. L., An, T., et al. (2019). From Ecological Opportunism to Multi-Cropping: Mapping Food Globalisation in Prehistory. *Quat. Sci. Rev.* 206, 21–28. doi:10.1016/j.quascirev.2018.12.017

Lu, H., Zhang, J., Liu, K.-b., Wu, N., Li, Y., Zhou, K., et al. (2009). Earliest Domestication of Common Millet (Panicum Miliaceum) in East Asia Extended to 10,000 Years Ago. *Proc. Natl. Acad. Sci.* 106, 7367–7372. doi:10.1073/pnas.0900158106

Luo, W., Yang, Y., Yao, L., Chen, Z., Li, J., Yin, C., et al. (2016). Phytolith Records of rice Agriculture during the Middle Neolithic in the Middle Reaches of Huai River Region, China. *Quat. Int.* 426, 133–140. doi:10.1016/j.quaint.2016.03.010

Ma, C., Zhu, C., Zheng, C., Yin, Q., and Zhao, Z. (2009). Climate Changes in East China since the Late-Glacial Inferred from High-Resolution Mountain Peat Humification Records. *Sci. China Ser. D-earth Sci.* 52, 118–131. doi:10.1007/s11430-009-0003-5

Ma Yu-qian, G. L., Li Guang-hua, J. Y., Zhang Cheng-muo, J. L., Qian Yue-min, G. L., Xiao Qian-yi, fnm., Lu Zhu-guo, fnm., et al. (1990). The Energy Spectrum of Cygnus X-1. *Chin. Astron. Astrophysics*. 14, 1–9. doi:10.1016/0275-1062(90)90002-u

Man, Z. M. (2009). *Research on Climate Change in Chinese Historical Period*. Shandong, China: Shandong Education Press

Mannion, A. M. (1999). Domestication and the Origins of Agriculture: an Appraisal. *Prog. Phys. Geogr.* 23, 37–56. doi:10.1191/030913399677315626

Min, Z. D. (1986). Rice History of Jiangsu Province (In Chinese). *Agric. Archaeology*. 1, 254–266.

Nakamura, S.-i. (2010). The Origin of rice Cultivation in the Lower Yangtze Region, China. *Archaeol Anthropol. Sci.* 2, 107–113. doi:10.1007/s12520-010-0033-0

Nanjing MuseumLianyungang Museum (2015). *Tenghualuo Site: Archaeological Excavation Report of Neolithic Sites in Lianyungang (In Chinese)*. Beijing: Science Press

National Museum of ChinaNanjing MuseumSihong Museum (2018). 2015 and 2016 Excavations Report of the Hanjing Site in Sihong, Jiangsu Province (In Chinese). *South. Cult.* 261, 28–39.

Overton, N. J., and Taylor, B. (2018). Humans in the Environment: Plants, Animals and Landscapes in Mesolithic Britain and Ireland. *J. World Prehist*. 31, 385–402. doi:10.1007/s10963-018-9116-0

Pei, Q., Lee, H. F., Zhang, D. D., and Fei, J. (2019). Climate Change, State Capacity and Nomad-Agriculturalist Conflicts in Chinese History. *Quat. Int.* 508, 36–42. doi:10.1016/j.quaint.2018.10.022

Price, T. D., and Bar-Yosef, O. (2011). The Origins of Agriculture: New Data, New Ideas. *Curr. Anthropol.* 52, S163–S174. doi:10.1086/659964

Qin, L. (2011). *Chuodun Site and Some Plant Remains Unearthed from Chenghu Site (In Chinese). Chundun Site in Kunshan*. Beijing: Suzhou Institute of ArchaeologyCultural Relics Publishing House, 334–342.

Qin, L. (2012). Research and prospect of Archaeobotany on the Origin of Agriculture in China (In Chinese), *Archaeol. Res.*, 260–315.

Qin, L. (2016). "Analysis of Plant Remains Unearthed from Dongshancun Site (In Chinese)," in *Dongshancun Site: Excavation Report of Neolithic siteNanjing Museum, Zhangjiagang Cultural Management Office* (Zhangjiagang Museum (Beijing: Cultural Relics Publishing House)), 605–624.

Qiu, Z. W., Jiang, H. E., and Ding, J. L. (2013). Study on Neolithic Plant Remains in Jiangli Site, Kunshan, Jiangsu (In Chinese). *Cult. relics*. 1, 90–96.

Qiu, Z., Jiang, H., Ding, J., Hu, Y., and Shang, X. (2014). Pollen and Phytolith Evidence for rice Cultivation and Vegetation Change during the Mid-late Holocene at the Jiangli Site, Suzhou, East China. *PLoS One*. 9, e97541. doi:10.1371/journal.pone.0097541

Qiu, Z. W., Ding, J. L., Jiang, H. E., and Hu, Y. W. (2014). Analysis on Plant Remains from Rice Paddy Fields of the Liangzhu Culture at the Zhumucun Site, Kunshan, Jangsu (In Chinese). *South. Cult.* 2, 57–67.

Qiu, Z., Jiang, H., Ding, L., and Shang, X. (2020). Late Pleistocene-Holocene Vegetation History and Anthropogenic Activities Deduced from Pollen Spectra and Archaeological Data at Guxu Lake, Eastern China. *Sci. Rep.* 10, 9306. doi:10.1038/s41598-020-65834-z

Qiu, Z., Liu, B., Li, Y., Shang, X., and Jiang, H. (2016). Analysis of Plant Remains at the Neolithic Yangjia Site, Wuxi City, Jiangsu Province (East China). *Sci. China Earth Sci.* 59, 1803–1816. doi:10.1007/s11430-016-5326-4

Qiu, Z. W., Zhuang, L. N., and Lin, L. G. (2018). Phytolith Evidence for Rice Domestication of the Hanjing Site in Sihong, Jiangsu Province and the Related Issues (In Chinese). *South. Cult.* 261, 71–80.

Qu, W., Xue, B., Dickman, M. D., Wang, S., Fan, C., Wu, R., et al. (2000). A 14 000-year Record of Paleoenvironmental Change in the Western basin of China's Third Largest lake, Lake Taihu. *Hydrobiologia*. 432, 113–120. doi:10.1023/A:1004079220926

Ren, X., Lemoine, X., Mo, D., Kidder, T. R., Guo, Y., Qin, Z., et al. (2016). Foothills and Intermountain Basins: Does China's Fertile Arc Have 'Hilly Flanks'? *Quat. Int.* 426, 86–96. doi:10.1016/j.quaint.2016.04.001

Richerson, P. J., Boyd, R., and Bettinger, R. L. (2001). Was Agriculture Impossible during the Pleistocene but Mandatory during the Holocene? A Climate Change Hypothesis. *Am. Antiq.* 66, 387–411. doi:10.2307/2694241

Sheets, P., Bawden, G., and Reycraft, R. M. (2002). Environmental Disaster and the Archaeology of Human Response. Garth Bawden and Richard Martin Reycraft, Editors. Anthropological Papers, Vol. 7. Maxwell Museum of Anthropology, University of New Mexico, Albuquerque, 2000. X + 228 pp., Figures, Tables, Bibliography, index. $34.95 (Paper). *Latin Am. Antiq.* 13 (2), 238–239. doi:10.2307/971917

Shen, Z. Z. (2009). Studies on Prehistoric Agriculture in the Eastern Jianghuai Region (In Chinese). *Agricul. Hist. Chin.* 4, 46–55.

Sheng, P., Shang, X., Sun, Z., Yang, L., Guo, X., and Jones, M. K. (2018). North-south Patterning of Millet Agriculture on the Loess Plateau: Late Neolithic Adaptations to Water Stress, NW China. *The Holocene*. 28 (10), 1554–1563. doi:10.1177/0959683618782610

Sherratt, A. G. (2006). "The Trans-eurasian Exchange: The Prehistory of Chinese Relations with the West," in *Contact and Exchange in the Ancient World*. Editor V. H. Mair (Honolulu, HI: Hawaii University Press), 32–53.

Spengler, R., Frachetti, M., Doumani, P., Rouse, L., Cerasetti, B., Bullion, E., et al. (2014). Early Agriculture and Crop Transmission Among Bronze Age mobile Pastoralists of Central Eurasia. *Proc. R. Soc. B.* 281, 20133382. doi:10.1098/rspb.2013.3382

Stanley, D. J., Chen, Z., and Song, J. (1999). Inundation, Sea-Level Rise and Transition from Neolithic to Bronze Age Cultures, Yangtze Delta, China. *Geoarchaeology*. 14, 15–26. doi:10.1002/(sici)1520-6548(199901)14:1<15::aid-gea2>3.0.co;2-n

Staubwasser, M., Sirocko, F., Grootes, P. M., and Segl, M. (2003). Climate Change at the 4.2 Ka BP Termination of the Indus valley Civilization and Holocene South Asian Monsoon Variability. *Geophys. Res. Lett.* 30, 1425. doi:10.1029/2002gl016822

Stevens, C. J., Murphy, C., Roberts, R., Lucas, L., Silva, F., and Fuller, D. Q. (2016). Between China and South Asia: A Middle Asian Corridor of Crop Dispersal and Agricultural Innovation in the Bronze Age. *The Holocene*. 26, 1541–1555. doi:10.1177/0959683616650268

Sun, L. Q., and Liu, D. S. (2011). Yongjia Rebellion and the Change of Northern Political Pattern (In Chinese). *Heibei Acad. J.* 31, 66–70. doi:10.3969/j.issn.1003-7071.2011.03.013

Sun, Q., Liu, Y., Wünnemann, B., Peng, Y., Jiang, X., Deng, L., et al. (2019). Climate as a Factor for Neolithic Cultural Collapses Approximately 4000 Years BP in China. *Earth-Science Rev.* 197, 102915. doi:10.1016/j.earscirev.2019.102915

Tang, L. H. (2016). "Analysis of Carbonized rice (In Chinese)," in *Shendun Site in LiyangNanjing Museum, Changzhou Museum, Liyang Culture, Radio, Television and Sports Bureau* (Beijing: Cultural Relics Publishing House), 483–487.

Tang, L. H. (1999). "Identification and Analysis of rice Remains in Longqiuzhuang Site (In Chinese)," in *Longqiuzhuang: A Report on the Excavation of Neolithic Sites in the East of Jianghuai RiverArchaeological Team of Longqiuzhuang Site* (Beijing: Science Press), 440–448.

Tang, L. H., Yokichiro, S., Udatsu, T., and Sun, J. X. (1999). Types of Ancient rice Seeds at Caoxieshan Site in China (In Chinese). *Jiangsu J. Agric. Sci.* 15, 193–197. doi:10.1023/a:1006701600323

Tang, L. H., and Zhang, M. (1996). The Original rice Cultivation at Longqiuzhuang Site in Gaoyou. *Acta Crop Sinica.* 22, 608–612.

Tang, L. H., Zhou, J. S., Wang, C. L., and Li, H. J. (1992). Investigation of Ancient rice Cultivation at Longnan Site in Meinian, Jiangsu Province (In Chinese). *Agric. Archaeology* 1, 78–81.

Tao, J., Chen, M.-T., and Xu, S. (2006). A Holocene Environmental Record from the Southern Yangtze River delta, Eastern China. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 230, 204–229. doi:10.1016/j.palaeo.2005.07.015

Tian, M. L., Tan, G. H., Xu, J. Q., and Zhou, R. K. (2009). Summary of Excavation of Xixi Site in Yixing, Jiangsu (In Chinese). *South. Cult.* 5, 59–62.

Udatsu, T., Tang, L. H., Wang, C. L., Zheng, Y. F., Yanagisawa, K., Sasa, T., et al. (1998). Exploration of Paddy Field Heritage in China (In Chinese). *Agric. Archaeology*. 1, 138–153.

Wang, C. L. (1999). "Analysis of rice Plant Opal from Longqiuzhuang Site (In Chinese)," in *Longqiuzhuang: A Report on the Excavation of Neolithic Sites in the East of Jianghuai RiverArchaeological Team of Longqiuzhuang Site* (Beijing: Science Press), 448–458.

Wang, C. L., and Ding, J. L. (1999). Research on Ancient rice Cultivation at Dongshansun Site in Zhangjiagang (In Chinese). *Agric. Archaeology* 3, 88–97.

Wang, C. L., and Ding, J. L. (2000). Plant Opal Analysis of Shaoqingshan Site in Kunshan City, Jiangsu Province (In Chinese). *Archaeology* 4, 89–94.

Wang, C. L., and Ding, J. L. (2001). Study on Ancient rice Cultivation at Guangfu Village Site in Wujiang (In Chinese). *Agric. Archaeology* 3, 97–103.

Wang, C., Lu, H., Gu, W., Wu, N., Zhang, J., Zuo, X., et al. (2017). The Spatial Pattern of Farming and Factors Influencing it during the Peiligang Culture Period in the Middle Yellow River valley, China. *Sci. Bull.* 62, 1565–1568. doi:10.1016/j.scib.2017.10.003

Wang, C. L., Zhou, Y. X., Wang, Z. G., and Zhang, J. X. (2013). Plant Opal Analysis of Xuecheng Site in Gaochun, Jiangsu Province. *Commemorating The 110th Anniversary of Mr* Cultivation. Zhou Shilu's birth and the International Symposium on the origin of rice, 55–61.

Wang, J. H., He, H. S., Xie, C. Z., and Zhou, J. H. (2002). The Second Excavation of Fenghuangshan Site in Danyang (In Chinese). *South. Cult.* 3, 43–49.

Wang, G. F., and Zhang, J. (2004). Sanxingcun Neolithic Site in Jintan, Jiangsu Province (In Chinese). *Cult. relics*. 2, 4–26.

Wang, J. H. (2007). New Archaeological Discoveries in Southern China in 2006 (In Chinese). *South. Cult. relics*. 4, 19–87.

Wang, S., and Gong, D. (2000). Climate in China during the Four Special Periods in the Holocene. *Prog. Nat. Sci.* 10, 379–386.

Wang, S. M., Lu, Y., Liu, X. Q., Li, X. S., He, H. Z., and Shen, Z. Z. (2019). *The History of World Agricultural Civilization Chinese)*. (Beijing: China Agriculture Press)

Wang, S., Yang, X., Yan, M. A., Pan, H., Tong, G., and Wu, X. H. (1996). Environmental Change of Gucheng Lake of Jiangsu in the Past 15 Ka and its Relation to Palaeomonsoon. *Sci. China, Ser. D: Earth Sci.* 39, 144–151. doi:10.1007/BF01079756

Wang, W. (2004). A Discussion on the Reason of Large-Scale Cultural Changes in China Around 2000 BC. *Archaeology*. 1, 67–77.

Wang, Z. G., Li, W. M., and Qian, F. (1982). Excavation of Sidun Site in Wujin, Changzhou, Jiangsu Province (In Chinese). *Archaeology* 2, 15–35+100.

Weiss, H., Courty, M.-A., Wetterstrom, W., Guichard, F., Senior, L., Meadow, R., et al. (1993). The Genesis and Collapse of Third Millennium north Mesopotamian Civilization. *Science*. 261, 995–1004. doi:10.1126/science.261.5124.995

Willcox, G., Buxo, R., and Herveux, L. (2009). Late Pleistocene and Early Holocene Climate and the Beginnings of Cultivation in Northern Syria. *The Holocene*. 19 (1), 151–158. doi:10.1177/0959683608098961

Wu, R. Z. (2011). Research on Bronze Farm Tools in the Lower Reaches of the Yangtze River during the Spring and Autumn and Warring States Periods (In Chinese). Annual Meeting of Chinese Archaeological Society: Chinese Archaeological Society. Zhejiang Provincial Bureau of cultural relics, Conference Papers

Wu, W. W., Lin, L. G., Gan, H. Y., and Jin, G. Y. (2017a). Environment and Subsistence of the Second Phase of Shunshanji Site: Evidence from Phytolith Analysis. *Agricul. Hist. Chin.* 36, 3–14.

Wu, W. W., Si, H. W., Wang, S. M., and Li, Y. J. (2017b). Preliminary Analysis of the Carbonized Plant Remains from the Dingjiacun Site in Zhenjiang, Jiangsu Province (In Chinese). *South. Cult.* 5, 78–88. doi:10.3969/j.issn.1001-179X.2017.05.009

Wu, W. W., Lin, L. G., Gan, H. Y., and Yan, L. (2019). The Conscious Production of Liangzhu Culture at Jiangzhuang Site from the Macro-Remains Perspective (In Chinese), *Agricul. Hist. Chin.* 6, 3–16.

Wu, W. W., Yuan, F., and Tian, E. W. (2021). Archaeobotanical Analysis of the Settlement Subsistence of the Miaotaizi Site in Xuzhou (In Chinese). *Agricul. Hist. Chin.* in press

Wu, W. X., and Liu, D. S. (2004). 4000A B.P. Changes of East Asian Monsoon and Decline of Neolithic Culture Around central China (In Chinese). *Quat. Sci.* 24, 278–284.

Wu, W. X., and Liu, D. S. (2001). Cooling Events Around 4000A B.P. And the Birth of Chinese Civilization (In Chinese). *Quat. Sci.* 21, 443–451.

Xhauflair, H., Revel, N., Vitales, T. J., Callado, J. R., Tandang, D., Gaillard, C., et al. (2017). What Plants Might Potentially Have Been Used in the Forests of Prehistoric Southeast Asia? an Insight from the Resources Used Nowadays by Local Communities in the Forested highlands of Palawan Island. *Quat. Int.* 448, 169–189. doi:10.1016/j.quaint.2017.02.011

Xi, C. P. (2003). *Excavation Results of Shaoqingshan Site (In Chinese). Chuodun Mountain: A Collection of Papers on Chuodun Site*. Nanjing, China: Nanjing MuseumSoutheast culture press

Xia, L., Zhang, Q., Sun, N., Zhai, Y. J., and Wang, S. H. (2015). Climate Change Characteristics in Jiangsu Province, 1960-2012. *J. Glaciology Geocryology* 37, 1480–1489.

Xinying, Z., Xiaoqiang, L., Dodson, J., and Keliang, Z. (2016). Rapid Agricultural Transformation in the Prehistoric Hexi Corridor, China. *Quat. Int.* 426, 33–41. doi:10.1016/j.quaint.2016.04.021

Xu, D. D. (2016). *Statistic Analysis of Spatial and Temporal Characteristics of Precipitation in Jiangsu Province. PhD Dissertation (In Chinese)*. Nanjing (China): Nanjing University of Information Science & Technology

Yang, Y., Li, W., Yao, L., Cheng, Z., Luo, W., Zhang, J., et al. (2016). Plant Food Sources and Stone Tools' Function at the Site of Shunshanji Based on Starch Grain Analysis. *Sci. China Earth Sci.* 59, 1574–1582. doi:10.1007/s11430-016-5321-9

Yi, D. (1988). *Discovery of Ancient Sites in Xiaodanyang Town, Jiangning (In Chinese)*. South: Cult. Z1, 194

Yin, H. Z., Zhang, Z. X., and Ji, Z. Q. (1964). Report on Excavation of Dadunzi Site in Pixian County, Jiangsu Province (In Chinese). *Acta Archaeol. Sin.* 2, 12–59+208.

You, B. (2018). *The Change of Jingkang: The Decline of the Northern Song Dynasty (In Chinese)*. Changsha: Hunan People's Publishing House

You, X. L. (2001). Identification of Carbonized rice from Weidun Site (In Chinese). *Acta Archaeol. Sin.* 1, 109–110.

Zeder, M. A. (2008). Domestication and Early Agriculture in the Mediterranean Basin: Origins, Diffusion, and Impact. *Proc. Natl. Acad. Sci.* 105, 11597–11604. doi:10.1073/pnas.0801317105

Zeng, X. S. (2005). An Analysis of the Theory of "Double Cropping of rice and Wheat" in Song Dynasty (In Chinese). *Hist. Stud.* 1, 86–106.

Zhang, D. D., Pei, Q., Lee, H. F., Zhang, J., Chang, C. Q., Li, B., et al. (2015). The Pulse of imperial C Hina: a Quantitative Analysis of Long-term Geopolitical and Climatic Cycles. *Glob. Ecol. Biogeogr.* 24 (1), 87–96. doi:10.1111/geb.12247

Zhang, J. G. (2008). *Research on the Influence of Anlushan Rebellion on the Economic Development of Tang Dynasty (In Chinese)*. Beijing: Chinese financial & Economic Publishing House

Zhang, J., Zhang, X., and Xia, Z. (2014). Research on Charred Plant Remains from the Neolithic to the Bronze Age in Luoyang Basin. *Chin. Sci. Bull.* 59, 3388–3397. doi:10.1360/N972013-00022

Zhang, Q., Zhu, C., Liu, C. L., and Jiang, T. (2004). Environmental Changes in the Yangtze Delta since 7000 a BP (In Chinese). *Acta Geogr. Sin.* 59, 534–542.

Zhang, R. H. (2005). Sporopollen Record in Chuodun Site in Suzhou, Jiangsu and Palaeoenvironment in Taihu Region (In Chinese). *Acta Palaeontol. Sin.* 44, 314–321.

Zhang, Y., and Zhu, C. (2008). "Environmental Archaeology of the Dachang Region in the Daning Valley, the Three Gorges Reservoir Region of the Yangtze River, China, *Sci. Bull.*" in *Anthology of Prehistoric Rice Research*. Editors A. P. Pei and W. X. Zhang(Beijing: Science Press), 53, 140–152. doi:10.1007/s11434-008-5012-9

Zhao, Y. (2011). *Jiangsu Geography (In Chinese)*. Beijing: Beijing Normal University Press

Zhao, Z. (2011). New Archaeobotanic Data for the Study of the Origins of Agriculture in China. *Curr. Anthropol.* 52, S295–S306. doi:10.1086/659308

Zhao, Z. J. (2014). The Process of Origin of Agriculture in China: Archaeological Evidence from Flotation Results (In Chinese). *Quat. Sci.* 34, 7–84. doi:10.3969/j.issn.1001-7410.2014.10

Zhao, Z. J. (2020). Origin of Agriculture and Archaeobotanical Works in China (In Chinese). *Agricul. Hist. Chin.* 39, 3–9.

Zheng, X. M. (2003). *The Southward Shift of Economic center in Ancient China and Economic Study of Jiangnan in Tang-Song Dynasties*. Changsha: Yuelu Press

Zheng, Y. F., and Chen, X. G. (2006). An Archaeological Study on the Origin of Muskmelon-On The Seeds of Muskmelon from the Lower Reaches of the Yangtze River (In Chinese). *Journal of Zhejiang Institute of Cultural Relics and Archaeology*, Vol. 8. Beijing: Zhejiang Institute of cultural relics and ArchaeologyScience Press, 78–585.

Zheng, Y. F., You, X. L., Xu, J. M., and Bian, Q. J. (1994). Plant Opal Analysis of Longnan Neolithic Site (In Chinese). *Rice Sci. China* 8, 55–56.

Zhenjiang Museum (1979). Mound Tomb of Fushanguoyuan in Jurong, Jiangsu Province (In Chinese). *Archaeology*. 2, 13–24+103.

Zhong, M. (1987). Dianjiangtai Site in Tangshan, Jiangning (In Chinese). *South. Cult.* 3, 38–50.

Zhou, Q., and Han, Y. H. (2008). *New Theory on Jiangsu Geography (In Chinese)*. Nanjing: Nanjing University Press

Zhu, C., Zhang, Y., Zhang, Q., and Lu, J. F. (2003). Archaeological Stratigraphy of the Neolithic Site in Qitoushan, Jiangyin, Jiangsu Province (In Chinese). *J. Stratigr.* 27, 314–317.

Zohary, D., and Hopf, M. (2000). *Domestication of Plants in the Old World: The Origin and Spread of Cultivated Plants in West Asia*. New York: Oxford University Press

Zohary, D., Hopf, M., and Weiss, E. (2012). *Domestication of Plants in the Old World: The Origin and Spread of Domesticated Plants in Southwest Asia, Europe, and the Mediterranean Basin*. New York: Oxford University Press

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Ancient Starch Remains Reveal the Vegetal Diet of the Neolithic Late Dawenkou Culture in Jiangsu, East China

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The Liangwangcheng site, located in Pizhou County, Xuzhou City, northern Jiangsu Province, is one of the most important Neolithic Dawenkou Culture archeological sites in the Haidai area of China's eastern seaboard. In recent years, archaeobotanical studies in the Haidai area, mainly focusing on Shandong Province, have yielded fruitful results, while relatively few such studies have been undertaken in northern Jiangsu Province. Here, we report the results of dental residue analysis conducted on 31 individual human skulls unearthed from the Late Dawenkou Culture Liangwangcheng site. The starch granules extracted from these residue samples indicate that foxtail and broomcorn millet, rice, roots and tubers, and legumes comprised the vegetal diet of Liangwangcheng's occupants. Evidence suggests that mixed rice–millet agriculture played a definite role, with the coexistence of gathering as an economic element. According to archaeobotanical evidence from surrounding cotemporaneous sites, the Late Neolithic human groups that lived in the lower Huang-Huai River drainage shared similar subsistence patterns. Our results provide new evidence for a more comprehensive understanding of plant resource utilization and agricultural development in northern Jiangsu during the Dawenkou period.

Keywords: Liangwangcheng site, Neolithic, ancient starch, prehistoric subsistence, Dawenkou Culture

INTRODUCTION

The Haidai Cultural Region (abbreviated Haidai) refers to prehistoric cultural groups that include a continuous and rich sequence of Neolithic and Bronze Age archeological cultures, covering Shandong, northern Jiangsu and Anhui, eastern Henan, and the southern Liaodong Peninsula in eastern China (Gao and Shao, 1984; Luan, 1997; **Figure 1**). This region plays a significant role in the Neolithic archeology of China by providing a long, continuous cultural sequence, exhibiting regional characteristics that distinguish it from other parts of China, and by preserving extensive deposits of ancient human occupations. This area's prehistoric human activity peaked during the Dawenkou (ca. 4100–2600 BCE) and Longshan (ca. 2600–1900 BCE) Neolithic periods, then

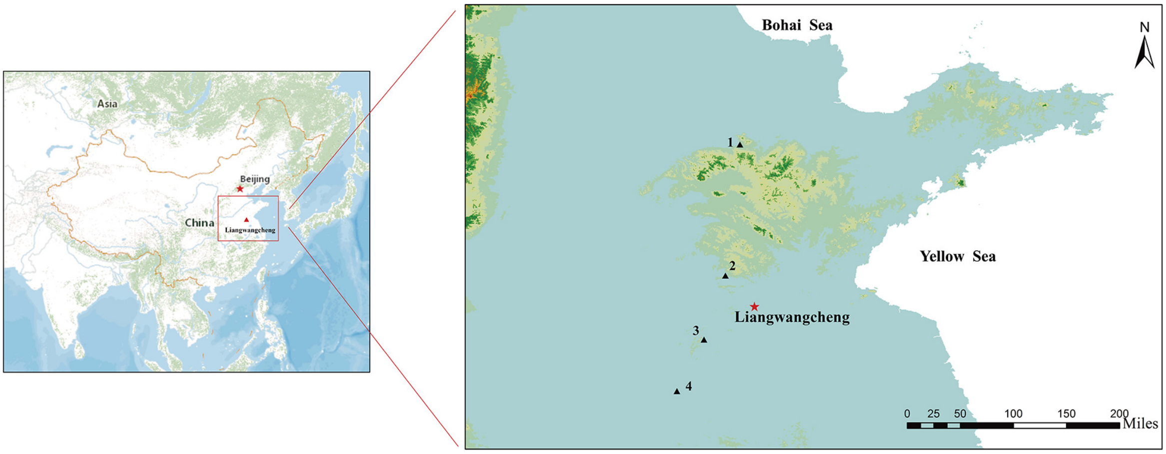

FIGURE 1 | Geographic location of Liangwangcheng and other Dawenkou Culture sites mentioned in this paper. (**1**, Jiaojia site; **2**, Jianxin site; **3**, Yangpu site; and **4**, Yuchisi site).

declined, gradually vanishing during the Yueshi period (ca. 1900–1500 BCE). Thus, Dawenkou and Longshan cultural remains in the Haidai area provide key evidence for understanding the evolution of social behavior and subsistence transformations during the Middle and Late Neolithic. Based on Neolithic archeological discoveries made in China thus far, the Haidai Culture is considered a distinct local cultural entity, differing from cotemporaneous prehistoric complexes on the Chinese Central Plain in Shanxi, Henan, and Shaanxi provinces. Therefore, it is necessary to pursue a comprehensive study of Haidai Culture, especially during the Dawenkou stage, when prehistoric populations expanded over a much more extensive geographical range in comparison with the preceding Houli (ca. 6500–5500 BCE) and Beixin (ca. 5300–4100 BCE) periods.

Ancient human subsistence patterns have been considered one of the most important issues in the scientific study of Neolithic adaptations, including the analysis of ancient diets, productivity, human social structures, and human–environment interaction, which are collectively extremely useful in the reconstruction of prehistoric societies. Among these subjects, the utilization of plant resources and the origin of agriculture in the Haidai region have been widely addressed, especially with respect to the appearance of rice–millet mixed agriculture (Jin et al., 2014; Wu et al., 2014; Guedes et al., 2015; Wu, 2019). It is thought that the development of Neolithic cultures in this region was related to diachronic climatic and paleoenvironmental changes (Jin and Wang, 2010a,b). The region's warm and humid climate present ca. 8000–6000 years ago (i.e., the postglacial hypsithermal) provided suitable natural conditions for the development and florescence of the Houli and Beixin cultures and the development of early agriculture. From 5500 to 5000 years ago, continuous fluctuations between relatively warm and relatively cool climatic conditions forced the Dawenkou people to respond to consequent environmental changes, triggering significant alterations in their subsistence systems and social structures (Dong et al., 2021). In addition, during this stage, ancient populations in the Haidai region were distributed across multiple varied landforms (e.g., coastal, in proximity to mountains, and near rivers), which offered different natural and ecological conditions, resulting in a plethora of economic adaptations. For example, during the late Neolithic Longshan period (ca. 2600–1900 BCE), populations inhabiting coastal areas of southeast Shandong took advantage of local hydrothermal conditions to intensively cultivate rice.

Contemporaneously, people occupying inland areas of northwest Shandong principally developed dry farming agricultural techniques (Jin et al., 2010; Guedes et al., 2015). Marine transgressions occurred several times during the early Dawenkou period (ca. 4100–2600 BCE) on the northern Jiangsu Plain and in Jiaozhou Bay (Huang, 1998), frequently altering the coastline, which had a dramatic impact on human settlement and subsistence activities. The overall number of archeological sites in this area decreased during the early Dawenkou period, and more shell mounds are found in coastal areas dating to this stage. Artifacts associated with fishing and hunting and remains of marine animals have been unearthed in such shell middens, and aggregate evidence from such contexts suggests a poorly developed agricultural economy which was quite different from the subsistence systems apparent at contemporaneous inland sites (Shandong, 1973; Yan and Zhang, 1987; Wang and Wu, 1992). It is clear that marine transgressions had a considerable impact on ancient people's subsistence practices in this area.

Recent research indicates that in the Haidai area, mainly in Shandong Province, incipient agricultural practices were initiated by the Houli Culture about 8000 cal BP, based on the discovery of morphologically cultivated millet plants from that context (Jin, 2012). Carbonized rice remains were discovered at the late Houli period Yuezhuang site and ^{14}C dated to 7050 ± 80 BP (Gary et al., 2006, 2013). However, during the Houli period, foxtail millet-based farming was not dominant, and a hunting–gathering–foraging economy still prevailed (Wu, 2019). Rice, foxtail millet, and broomcorn millet have been discovered at several sites dating to the following Beixin Culture period (5300–4100 BCE) (Chen, 2007; Wang H. et al., 2011; Wang and Jin, 2013; Jin et al., 2016, 2020), indicating the initiation of a rice–millet mixed agricultural economy. In addition, during this period, the proportion of agriculture as a component of the overall economy increased in comparison with the Houli. During the Dawenkou period (4100–2600 BCE), which followed the Beixin, agricultural economies continued to develop and accounted for a greater proportion of the subsistence system than previously. Based on the analysis of carbonized plant remains, however, broomcorn millet replaced foxtail millet in the agricultural repertoire at the beginning of the Dawenkou period (Jin et al., 2016).

Located on the margin of the Haidai Cultural region, northern Jiangsu Province shares a similar climate with southern Shandong but seems to have been less intensively occupied during the Neolithic than other parts of the Haidai. There, archeological sites are thinly distributed and have been the subject of very few chronological studies, leading to a lack of systematic understanding of Neolithic cultural development and subsistence patterns of the later Stone Age occupants of Jiangsu. Zooarchaeological and archaeobotanical studies were not systematically conducted at most early-excavated sites, thus the reconstruction of prehistoric economic forms has been limited by a lack of substantive evidence. The Liangwangcheng site is one of the most potentially valuable prehistoric sites uncovered thus far in northern Jiangsu Province and is widely considered an important archeological discovery (Nanjing et al., 2013), thus providing the opportunity and materials to explore prehistoric social constructs in this area. However, since flotation has not been conducted at the site, there are no macrobotanical remains available to support the discussion of scientific issues relating to plants or incipient agriculture. Plant micro-remains open the window for us to reconstruct plant utilization at Liangwangcheng and assist the interpretation of subsistence patterns in the Haidai area.

SITE AND ENVIRONMENT

The Liangwangcheng site (34°30′713″N, 117°47′629″E, 23–28 m above mean sea level) is located in Pizhou County, Xuzhou City, northern Jiangsu Province, on the east bank of the Beijing–Hangzhou Canal (Nanjing et al., 2013). From 2004 to 2009, the Nanjing Museum carried out fieldwork at this site. The cultural components of the Liangwangcheng site are multiple and diverse, including prehistoric remains from the Dawenkou Neolithic period to the historic era. Numerous Dawenkou period settlement remains were unearthed. Houses, pits, and 139 human interments representing more than 140 individuals were discovered, including adults and juveniles. According to Dong Yu's study (Dong et al., 2019), Carbon-14 dating suggests that these humans were interred between 4055 ± 20 BP (4425–4780 cal BP, 95.4% probability) and 4175 ± 25 BP (4586–4833 cal BP, 95.4% probability) [modeled in OxCal v.4.4, using IntCal20 calibration curve (Bronk Ramsey, 2009; Heaton et al., 2020; Reimer et al., 2020)]. In addition, based upon the burials and mortuary evidence and the results of stable isotope analysis of human bones, Dong and her colleagues suggested that social complexity was great and competition and differentiation between human groups and social classes were becoming more and more intense during the Dawenkou period. People began to choose various expressive forms to define and signal their identities, such as the number of funerary objects included in burials and the like. Therefore, during the Dawenkou period, the occupants of Liangwangcheng were likely undergoing fundamental transformations of their social complexity.

Northern Jiangsu, located in eastern China on the lower reaches of the Yellow River and the northern Huai River region, currently has a warm, temperate climate characterized by moderate rainfall and abundant sunshine. At present, a humid and semi-humid monsoon climate prevails (Köppen climate classification Cfa). Natural climatic conditions in this area are similar to those in southern Shandong. Northern Jiangsu is part of the transition zone between the Huanghuai Plain and Jianghuai Plain, bordering the mountainous area in southern Shandong Province to the north, with high terrain in the northwest and low topography in the southeast. The region is part of the Yi River, Shu River, and Sishui River basins, and the inland riverine network is densely distributed. The local vegetation is luxuriant, mainly composed of deciduous broad-leaved forests (Zhao, 2015). Paleoenvironmental studies suggest that the Holocene vegetation type in this area was mainly deciduous broad-leaved forest (Tang et al., 1993). Members of the Poaceae and Compositae dominated the community of herbaceous plants. The pollen record and trace element studies indicate that the climate in this region fluctuated several times 5000–4000 years ago, generally trending toward warm and dry (Jin, 1990; Zhao et al., 2014) with warmer average temperatures than at present. The environment of the late Neolithic in the Haidai area provided suitable conditions for human communities to survive and develop and significantly encouraged the Dawenkou Culture's prosperity.

MATERIALS AND METHODS

Human Dental Residue Analysis

Plant microfossil residue analysis has gained increasing popularity in archeology (McGovern et al., 2017; Prebble et al., 2019; Wang et al., 2019; Barber, 2020). Among such studies, dental residue analysis provides direct evidence of human diet and thus becomes an effective avenue for exploring ancient human subsistence, rather than indirect evidence obtained from artifacts or archeological sedimentary deposits. This method was begun in the 1970s, when scholars observed microbotanical remains in both dental calculus and invisible tooth residues, initiating pioneer achievements for research plant residues preserved on fossil teeth. Researchers also extracted plant residues for species identification by processing the residuum collected from tooth surfaces. In the 1970s, Lustmann employed a scanning electron microscope to study the morphological structure of anorganic dental calculus and found that calculus was composed of two components with different patterns of calcification (Lustmann et al., 1976). Dobney and colleagues also used a scanning electron microscope to analyze ancient dental calculus and were the first to discover plant microfossils such as phytoliths and starch granules embedded in dental calculus (Dobney and Brothwell, 1988; Olsen, 1988). Since then, this method has increasingly attracted the attention of scholars, globally. At the beginning of the 21st century, Piperno and Dillehay (2008) applied this method to the question of agricultural origins in Central America and achieved positive results. Based on this work, researchers identified plant species reflected by residues preserved in dental calculus and were able to distinguish wild versus cultivated attributes of plant remains, which played a crucial role in determining the timing of the rise of cultivation in Central America.

Nava et al. (2021) studied microfossils in mineralized dental plaque, and comprehensively analyzed buccal microwear and oral pathology, revealing dietary differences between the last foragers and first farmers at Grotta Continenza in central Italy. This method has subsequently been widely applied in China with great potential. Li et al. (2010) extracted and identified starch grains from dental calculus of Qijia Culture (ca. 4000 BP) people in Gansu Province and discovered that diversified dry farming was the primary subsistence strategy at that time (Li et al., 2010). Tao (2018) used this method to explore human diet at the Peiligang site in Xinzheng County, Henan Province, discovering starch granules from *Quercus*, members of the Fabaceae, tubers, and millets. Tao et al. (2020) also combined stable isotope analysis of human bones and the study of starch granules in human dental calculus from the Laodaojing Cemetery to further investigate the dietary role of wheat and the Eastern Zhou (770–256 BCE) agricultural economy on the Chinese Central Plains (Tao et al., 2020). This method has great potential for elucidating how prehistoric humans utilized plant resources and consequently broaden our insight into the structure of ancient societies and enhance our understanding of our ancestors' subsistence strategies and the process of agricultural development and intensification.

For the Liangwangcheng project, teeth were selected from 31 humans unearthed from 31 Dawenkou Culture graves (Layer 9 in the Liangwangcheng excavation report) for dental residue analysis (**Table 1**). We collected residue samples according to protocols established by Pearsall et al. (2004) and Guan et al. (2014). The residue samples comprise three levels: Level I, sediment attached to the surface of teeth; Level II, a liquid sample obtained by washing the tooth surface with distilled water; Level III, liquid samples derived by ultrasonic cleansing of teeth. A total of 72 residue samples were obtained and processed in the Key Laboratory of Vertebrate Evolution and Human Origins of the Chinese Academy of Sciences in Beijing. The experimental process followed that of Guan et al. (2010), integrating several laboratory operations (Chandler-Ezell and Pearsall, 2003; Pearsall et al., 2004). Processing included the following steps: concentration, deflocculation, and heavy liquid flotation. Starch granule and phytolith extraction slides were scanned with a Nikon Ni-E biological polarizing microscope. One hundred percent of glycerol was used as a mounting medium for starch and phytolith extractions. NIS-Elements D3.2 software was applied to perform two-dimensional (2D) measurements and other examinations. Both phytolith and starch slides were scanned at 200× magnification and photographed at 400× magnification.

Methodology of Geometric Morphometric Analysis of Starch Granules

Starch granule identification is challenging due to the biological attributes of those bodies. For starch granule analysis, researchers have employed an image comparison method, rendering taxonomic identification according to shape, location of the hilum, granule diameter, etc. As part of the development of this method, many modern starch images have been published providing significant comparative reference points for future study. At present, however, researchers have become dissatisfied with such identification techniques and are trying various quantitative methods to reliably identify unknown starch granules (Torrence et al., 2004; Liu et al., 2014; Coster and Field, 2015; Arráiz et al., 2016). The traditional measurement method cannot convey information concerning geometric structure, and radial measurement cannot adequately explain changes in organism shapes.

Geometric morphology, however, avoids the shortcomings of varying data sources, non-repeatability, and size and shape can be calculated altogether (Chen, 2017), which is beneficial to the further study of morphological differences in starch granules. Geometric morphometry analysis has been widely used recently in entomology, aquatic biology, medical science, and archeology (Slice, 2007; Mitteroecker and Gunz, 2009; Addis et al., 2010; Webster and Sheets, 2010; Adams and Otárola-Castillo, 2013; Park et al., 2013; McNulty and Vinyard, 2015; Savriama, 2018). However, it has not thus far been applied in starch granule analysis. For these reasons, we chose to apply geometric morphometry in our study. Thirty-five landmarks were identified for a single starch granule (**Figure 2**). TpsDig2 software was used to obtain landmark 2D coordinate data on starch granules and generating a thin plate spline (TPS) file for each species or unknown group. The plant species name is used as the classifier, and the landmark x and y value are used as variables in the matrix, constituting a grid with 71 columns. Data for one individual starch granule is recorded as one observation, i.e., one row in the data matrix. The TPS file then is imported into MorphoJ statistical software (Klingenberg, 2011) for general procrustes analysis (GPA) and canonical variate analysis (CVA).

General procrustes analysis is a straightforward approach to determining shape correspondence. Additionally, GPA is a multivariate exploratory technique that involves transformations of individual data matrices to provide optimal comparability. This technique scales and rotates each configuration of landmarks so that shape information can be extracted and compared among samples. CVA is used to identify shape features that best distinguish among multiple groups of specimens (Klingenberg, 2011) and is one of the most widespread analytical approaches in morphometrics. In our work, a CVA of the covariance matrix was conducted on the GPA transformed coordinates to reduce dimensionality for further analyses. We imported the TPS files into MorphoJ software for new

TABLE 1 | Liangwangcheng residue sample information.

No.	Specimen no.	Lab no.	Cultural period	Sex	Sample type
1	M154	S500	Late Dawenkou	Male	Level I
2	M154	S501	Late Dawenkou	Male	Level II
3	M154	S502	Late Dawenkou	Male	Level III
4	M129	S503	Late Dawenkou	Male	Level I
5	M129	S504	Late Dawenkou	Male	Level III
6	M120	S505	Late Dawenkou	Female	Level I
7	M120	S506	Late Dawenkou	Female	Level III
8	M81	S507	Late Dawenkou	Male	Level I
9	M81	S508	Late Dawenkou	Male	Level III
10	M254	S509	Late Dawenkou	Male	Level I
11	M254	S510	Late Dawenkou	Male	Level III
12	M151	S511	Late Dawenkou	Female	Level I
13	M151	S512	Late Dawenkou	Female	Level II
14	M151	S513	Late Dawenkou	Female	Level III
15	M113	S514	Late Dawenkou	Male	Level I
16	M113	S515	Late Dawenkou	Male	Level III
17	M225	S516	Late Dawenkou	Male	Level I
18	M225	S517	Late Dawenkou	Male	Level III
19	M143	S518	Late Dawenkou	Female	Level III
20	M135	S519	Late Dawenkou	Male	Level I
21	M135	S520	Late Dawenkou	Male	Level II
22	M135	S521	Late Dawenkou	Male	Level III
23	M114	S522	Late Dawenkou	Female	Level I
24	M114	S523	Late Dawenkou	Female	Level III
25	M144	S524	Late Dawenkou	Unknown	Level I
26	M144	S525	Late Dawenkou	Unknown	Level III
27	M92	S526	Late Dawenkou	Female	Level I
28	M92	S527	Late Dawenkou	Female	Level III
29	M118	S528	Late Dawenkou	Female	Level I
30	M118	S529	Late Dawenkou	Female	Level III
31	M216	S530	Late Dawenkou	Male	Level I
32	M216	S531	Late Dawenkou	Male	Level III
33	M145	S532	Late Dawenkou	Female	Level I
34	M145	S533	Late Dawenkou	Female	Level III
35	M108	S536	Late Dawenkou	Unknown	Level I
36	M108	S537	Late Dawenkou	Unknown	Level III
37	M147	S538	Late Dawenkou	Unknown	Level I
38	M147	S539	Late Dawenkou	Unknown	Level II
39	M147	S540	Late Dawenkou	Unknown	Level III
40	M226	S541	Late Dawenkou	Male	Level II
41	M226	S542	Late Dawenkou	Male	Level III
42	M125	S545	Late Dawenkou	Female	Level I
43	M125	S546	Late Dawenkou	Female	Level II
44	M125	S547	Late Dawenkou	Female	Level III
45	M111	S548	Late Dawenkou	Male	Level II
46	M111	S549	Late Dawenkou	Male	Level III
47	M127	S553	Late Dawenkou	Female	Level II
48	M127	S554	Late Dawenkou	Female	Level III
49	M256	S555	Late Dawenkou	Male	Level I
50	M256	S556	Late Dawenkou	Male	Level II
51	M256	S557	Late Dawenkou	Male	Level III
52	M252	S558	Late Dawenkou	Female	Level I
53	M252	S559	Late Dawenkou	Female	Level III
54	M251	S560	Late Dawenkou	Female	Level I
55	M251	S561	Late Dawenkou	Female	Level II
56	M251	S562	Late Dawenkou	Female	Level III
57	M130	S563	Late Dawenkou	Unknown	Level I
58	M130	S564	Late Dawenkou	Unknown	Level II
59	M130	S565	Late Dawenkou	Unknown	Level III
60	M116	S566	Late Dawenkou	Male	Calculus
61	M116	S567	Late Dawenkou	Male	Level III
62	M121	S568	Late Dawenkou	Male	Level I
63	M121	S569	Late Dawenkou	Male	Level II
64	M121	S570	Late Dawenkou	Male	Level III
65	M109	S571	Late Dawenkou	Unknown	Level II
66	M109	S572	Late Dawenkou	Unknown	Level III
67	M218	S573	Late Dawenkou	Unknown	Level I
68	M218	S574	Late Dawenkou	Unknown	Level II
69	M218	S575	Late Dawenkou	Unknown	Level III
70	M271	S576	Late Dawenkou	Female	Level I
71	M271	S577	Late Dawenkou	Female	Level II
72	M271	S578	Late Dawenkou	Female	Level III

Procrustes fit and to generate a covariance matrix. CVA assumes that the covariance structure within all groups is the same, therefore, a pooled within-group covariance matrix is used throughout for CVA and for computing Mahalanobis distances between pairs of groups. The Mahalanobis distance matrix and Procrustes distance matrix may help explain group similarities and differences.

Our study also applied a supervised machine learning method for model training to modern starch geometric morphometric data. The supporting vector machine (SVM) algorithm was used for model training. SVM is a supervised learning model and related learning algorithm for analyzing data in classification and regression analysis. This algorithm maximizes the margin between class boundaries and is often used in data mining projects (Boser et al., 1992; Steinwart and Christmann, 2008). At present, this method is widely used in the deep learning field, such as in image classification. The geometrical morphometric data on modern starch is thus trained by SVM to yield more precise identifications of unknown starch granules. The species name is used as the classifier, 35 coordinates of x and y, i.e., 70 values constitute the variables. R programming language (version 3.6.2) (R Core Team, 2020) is used for the SVM computing.

Species identification, and classification of unknown archeologically derived starch granules were based mainly on comparison with a modern starch database established by our laboratory team and with reference to the recent published record. We have thus far compiled a modern reference database of more than 67 Chinese starch-producing species/varietals (see **Figure 3**) including both domesticated and wild taxa. Some plants such as certain species of *Colocasia*, produce extremely small (<5 μm) starch granules, thus inappropriate for the

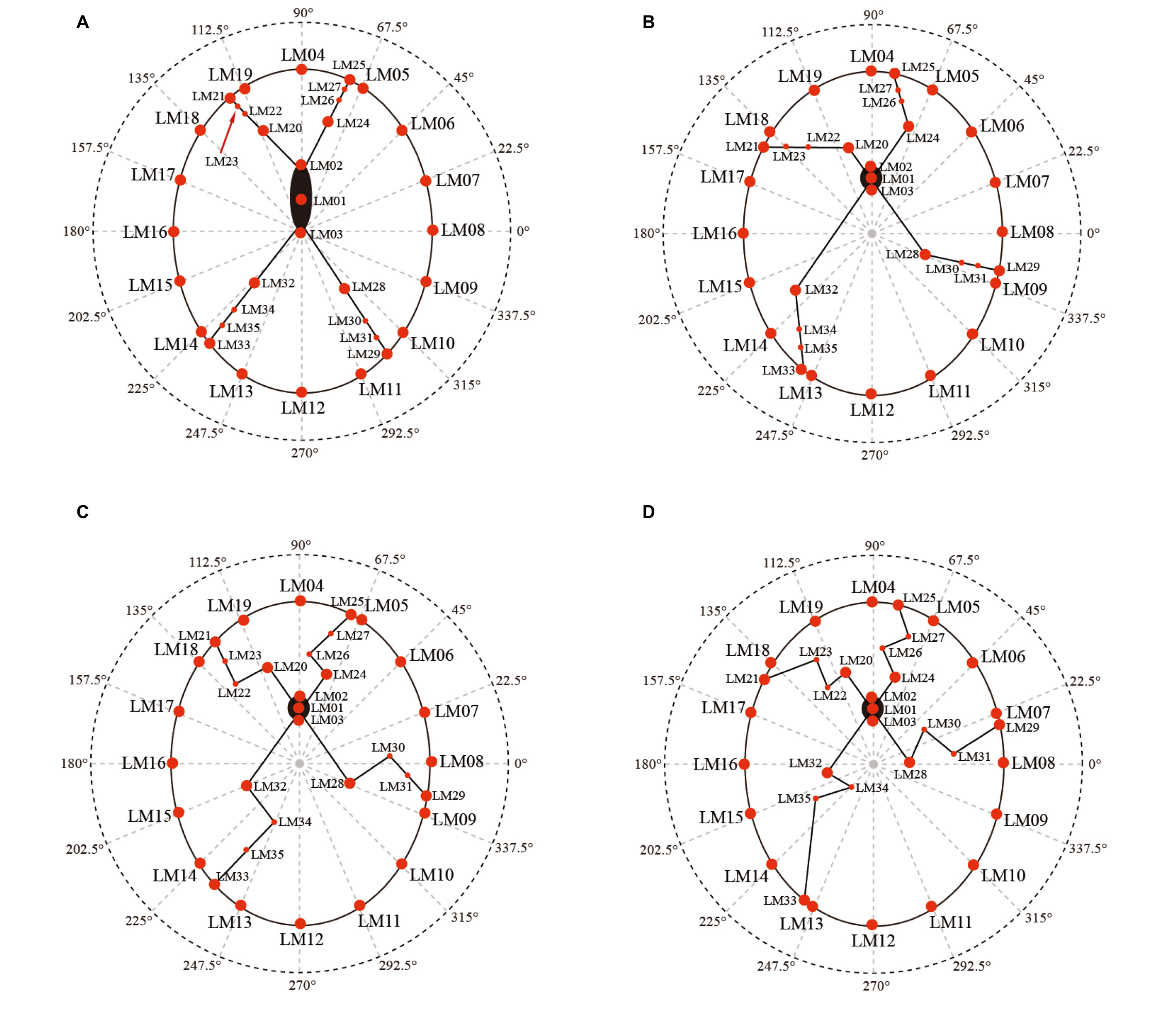

FIGURE 2 | Definition of the 35 landmarks on starch granule. **(A)** Extinction cross with no bend; **(B)** each arm with one bend; **(C)** each arm with two bends; and **(D)**, each arm with three bends.

acquisition of geometric morphometric data. In this case, TPS files were acquired from 41 species/varietals. Phytolith comparisons were based completely on published resources (Yang et al., 2009, 2013; Liu et al., 2011, 2014, 2019; Wan et al., 2011a,b, 2016; Wang S. et al., 2011; Wang et al., 2013; Yang and Perry, 2013; Ma et al., 2019; Li et al., 2020). Plant anatomy references were used to identify other plant organ fragments (Zheng and Wang, 1983).

RESULTS

A total of 1241 starch granules were recovered from all the three levels of residue samples. All teeth yielded starch granules except those from M143. Among these starch granules, 533 were recovered from Level I samples, 335 from Level II samples, and 373 from Level III samples (see **Supplementary Table**). Among these starch remains, 1031 granules (83.07% of the total) are identifiable by comparison with our reference database. The residue samples were taken by levels for several reasons. Level I samples are thought to reflect micro-residue originating in soil, while Level II samples, which are obtained by wet brushing, are thought to contain micro-residues from both soil and the surface of the sampled specimens. The main aim of the wet brushing is to isolate Levels I and III samples, to avoid cross-contamination from Levels I to III samples to the greatest extent possible. In this case, Level I samples are equally as important as Level III samples since both could provide valid indications, while Level II samples are difficult to analyze because they are, by definition, mixtures with multiple points of

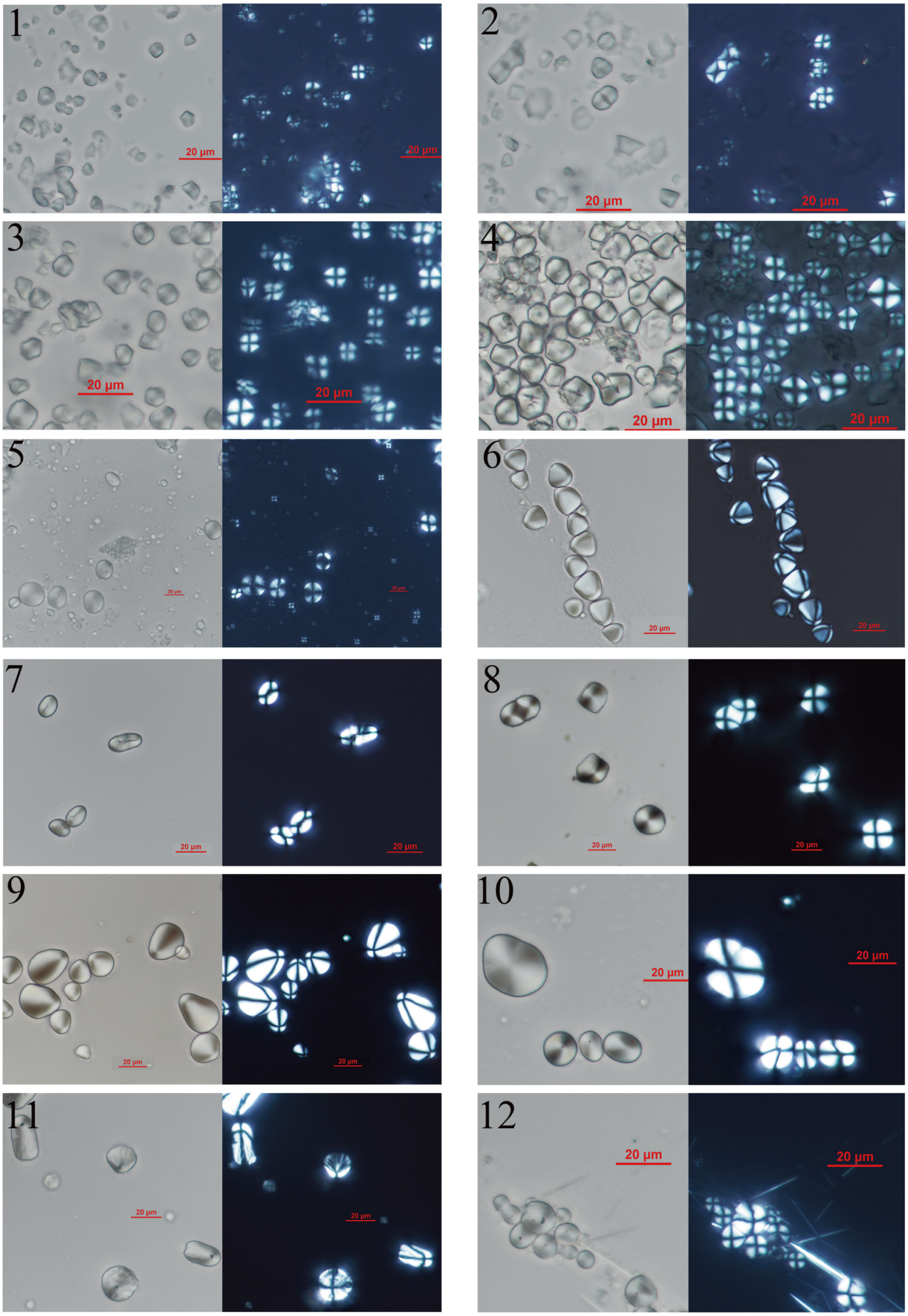

FIGURE 3 | Modern plant starch references included in this paper. [**1**–**2**, *Oryza sativa*; **3**, *Panicum miliaceum*; **4**, *Setaria italica*; **5**, *Triticum aestivum*; **6**, *Dioscorea opposita*; **7**, *Vigna vexillata*; **8**, *Smilax china*; **9**, *Bolbostemma paniculatum*; **10**, *Trapa bispinosa*; **11**, *Nelumbo nucifera* (root); and **12**, *Pinellia ternate*].

origination. Therefore, micro-residues from Level II samples are not discussed in our work.

We compared starch granules yielded by Level I samples with those recovered from Level III samples by direct image comparison and geometric morphology. In the images, different morpho-types could be observed between starch granules from Levels I and III. CVA results revealed substantial differences between Levels I and III samples, reflected by the peak values of canonical variates appearing in different positions (**Figure 4**). The Mahalanobis distance also showed apparent differences between the groups ($P < 0.001$). As a result, we conclude that the starch granules contained in Level III samples are not contaminated by layer deposits and can be regarded as direct evidence of the Liangwangcheng ancient human's plant utilization.

In addition to starch granules, phytolith remains were also discovered, although in a much smaller proportion, and were mostly not diagnostic to the species level. A small number of unidentifiable plant fibers, pollen grains, and fungi were observed.

Typology of Starch Granules

Archeological starch granules were classified into five types according to the system established by Guan et al. (2020) based on morphology and size (**Figure 5**):

Type 1, polyhedral body, possibly produced by foxtail millet (*Setaria italica*) (**Figure 3: 4**), broomcorn millet (*Panicum miliaceum*) (**Figure 3: 3**), or rice (*Oryza sativa*). The 2D shapes are mostly polygonal or spherical, with invisible lamellae and centric to slightly eccentric hila. Furthermore, many granules classified in this type exhibit pronounced fissures. Among these polyhedron bodies, ones with smaller diameters and sharper edges are likely to derive from rice according to our reference database (**Figure 3: 1–2**) and the published literature (Liu et al., 2011; Wang S. et al., 2011).

Type 2, lenticular body, probably produced by members of the tribe Triticeae. The 2D shapes of these starch granules are nearly round, elliptical, or lenticular, with closed and centrally located hila and fuzzy lamellae. Fissures are absent in most individual grains and the extinction crosses are primarily straight. It should be noted that the Triticeae tribe includes more than 10 genera in China, and both domesticated and wild species. These starch granules resemble the morphology of modern specimens from *Aegilops*, *Roegneria*, *Secale*, and *Triticum* according to our reference database (**Figure 3: 5**) and published literature (Wei et al., 2007; Hart, 2014; Wan et al., 2016, 2020).

Type 3, ellipsoidal, semi-ellipsoidal and elongated ellipsoidal body, maybe produced by plant underground storage organs, and probably including members of the Nymphaeaceae (water lilies), Trapaceae (water chestnuts), and Araceae families such as lotus root (*Nelumbo nucifera*), water caltrop (*Trapa bispinosa*), and *banxia* or crow-dipper (*Pinellia ternata*), the latter used in Traditional Chinese Medicine and identified by comparison with our reference database (**Figure 3: 6**, **8–12**). This type exhibits primarily fuzzy lamellae and eccentric hila, and the extinction crosses are mostly bent, making it easier to distinguish.

Type 4, kidney bean shaped body, which includes starch from legumes (Family Fabaceae) according to our reference database (**Figure 3: 7**) and published literature (Wang et al., 2013). Most exhibit visible fissures and lamellae, but the hila are mostly invisible. The center of the extinction crosses appears as a dark linear area.

Type 5, includes compound and damaged starch granules. Compound granules are not separated, and damaged starch granules are broken or incomplete; therefore, we were unable to specify their morphological characteristics and identify them to the species level.

Phytolith Remains

A total of 79 phytoliths were extracted from the Level III residue samples (**Figure 6**). These phytoliths could be classified into six types based upon criteria provided by Lu et al. (2006) including Elongate, Saddle, Bilobate short cells, Bulliform cells, Dendriform phytoliths from hulls and short cells. Bilobate short cells appeared most frequently. The small number of foxtail and broomcorn millet husk phytoliths nonetheless suggest that these millet varieties were used by the Neolithic occupants of Liangwangcheng.

Other Plant Organ Fragments and Remains of Fungi

Bordered pits, fibers, cells of unknown biological origin, and other fragments were discovered in all the residue samples, including Level I, Level II, and Level III. However, these organ fragments lack biological attributes and are, thus, not identifiable. In addition, these remains are extremely fragmentary, and were recovered in only minor quantities, therefore, such fragments were not included in this paper.

One discovery is particularly noteworthy. In addition to starch granules, phytoliths, and other tissue fragments, we also observed some biological granules. These smaller granules are spheroidal, oval, and radial in shape and display extinction crosses under polarized light. Initially, these granules were identified as damaged starch. However, after comparison with relevant published data (Haslam, 2006; Torrence, 2006; Krull et al., 2013; Atsatt and Whiteside, 2014; Walsh et al., 2018; Shen et al., 2019), we consider these granules to be molds; even hyphae were observed in some individual specimens. These mold granules have smaller average diameters than regular starch granules; generally <10 μm. Their extinction crosses caused initial misidentification, further emphasizing the importance of ensuring the precision of plant starch identification.

In Level III samples, 19 such mold bodies were observed. These fungi remains can be classified into three types based on their morphological features (**Figure 7**). Because of the integrity of their spore structure, we believe these fungi are generated later in the samples. However, it is a difficult issue to adequately evaluate. We hope that a more comprehensive examination can be made in the future to facilitate discussion of the origin of these fungi.

Results of Geometric Morphometric Analysis of Starch Granules

The Liangwangcheng CVA procedure identified eight significant canonical variates. Eigenvalues indicate that canonical variable

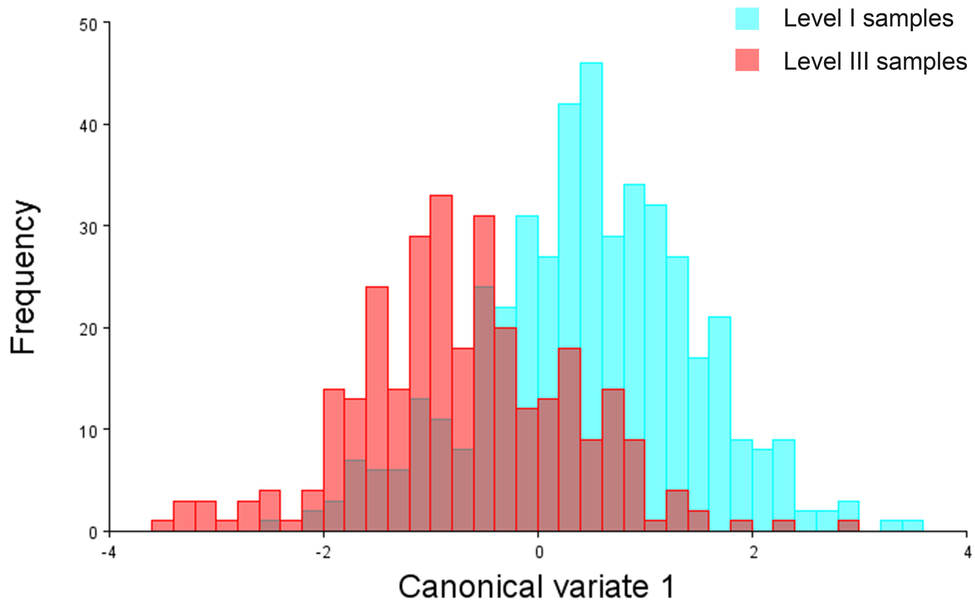

FIGURE 4 | Canonical variable frequency bar chart of Levels I and III samples.

(CV) 1 accounted for 45.83%, 34.04% for CV2, and 10.91% for CV3, representing 90.78% of the total variations. According to the CVA scatter plot, Liangwangcheng starch overlaps with about eight control groups. Among these control groups, *O. sativa*, *S. italica*, and *P. miliaceum* are closer to the Liangwangcheng group and the other four groups are more distant (**Figure 8**). In other words, the CVA shows that starch granules from Liangwangcheng derive mainly from rice, foxtail millet and broomcorn millet, and a small portion derives from legumes, members of the Triticeae tribe, roots and tubers, and some aquatic plant fruits. **Figure 9** displays the confidence ellipses (probability = 0.9) for each group. Moreover, the Mahalanobis distances (**Table 2**) and Procrustes distances (**Table 3**) further describe the canonical variate scores and support our conclusion.

SVM Prediction of Geometric Morphometric Data

The SVM model suggests that the Liangwangcheng starch granules (n = 301) possibly derive from several plant species. **Table 4** displays predicted data groups with percentages >2%. This prediction suggests that cereal crops (millets and rice) (37.21%), roots and tubers (33.56%), aquatic plant fruit (7.64%), and legumes (4.32%) are present in the Liangwangcheng starch remains.

DISCUSSION

Plant Resources Revealed by Residue Analysis

In this study, starch granules and other plant microfossils extracted from human dental remains inform vital issues concerning human diets and the development of agriculture-based subsistence. Plant starch and phytolith residues indicate that the Neolithic inhabitants of the Liangwangcheng site cultivated millet and rice as the primary source of their vegetal food and simultaneously exploited a variety of edible wild plants including legumes, the fruit of aquatic plants, and underground storage organs. In the Haidai region, rice, foxtail millet, and broomcorn millet coexisted since the Houli period (ca. 6500–5500 BCE), indicated by carbonized plant remains recovered at the Yuezhuang site (Gary et al., 2013), and a relatively stable rice–millet mixed agricultural pattern was established during the Middle and Late Dawenkou periods (ca. 3500–2600 BCE) (Zhao, 2020). The rice and millet starch and millet phytoliths extracted from Liangwangcheng dental residues further supports this perspective, and has helped fill in the blanks of late Stone Age subsistence studies in northern Jiangsu. The total proportion of cereal starch within the whole assemblage is much greater than those of other plant types, indicating that the Liangwangcheng people probably carried out large-scale farming activities. In other words, agricultural production may have become an increasingly stable means for them to acquire edible plant resources. Cultivated crops played a vital role in the Liangwangcheng subsistence base, and occupied a dominant position in the diet of the site's Neolithic inhabitants.

Although comprising a secondary and auxiliary role, wild plant resources were also crucial to the prehistoric occupants of Liangwangcheng, who gathered and utilized wild plant resources such as roots and tubers, legumes and aquatic plants, indicating the extensive use of diverse plant resources. Roots and tubers are generally easy to gather and process, and contain rich energy, thus they are considered one of the most common food resources in both prehistory and the present. Legumes include various

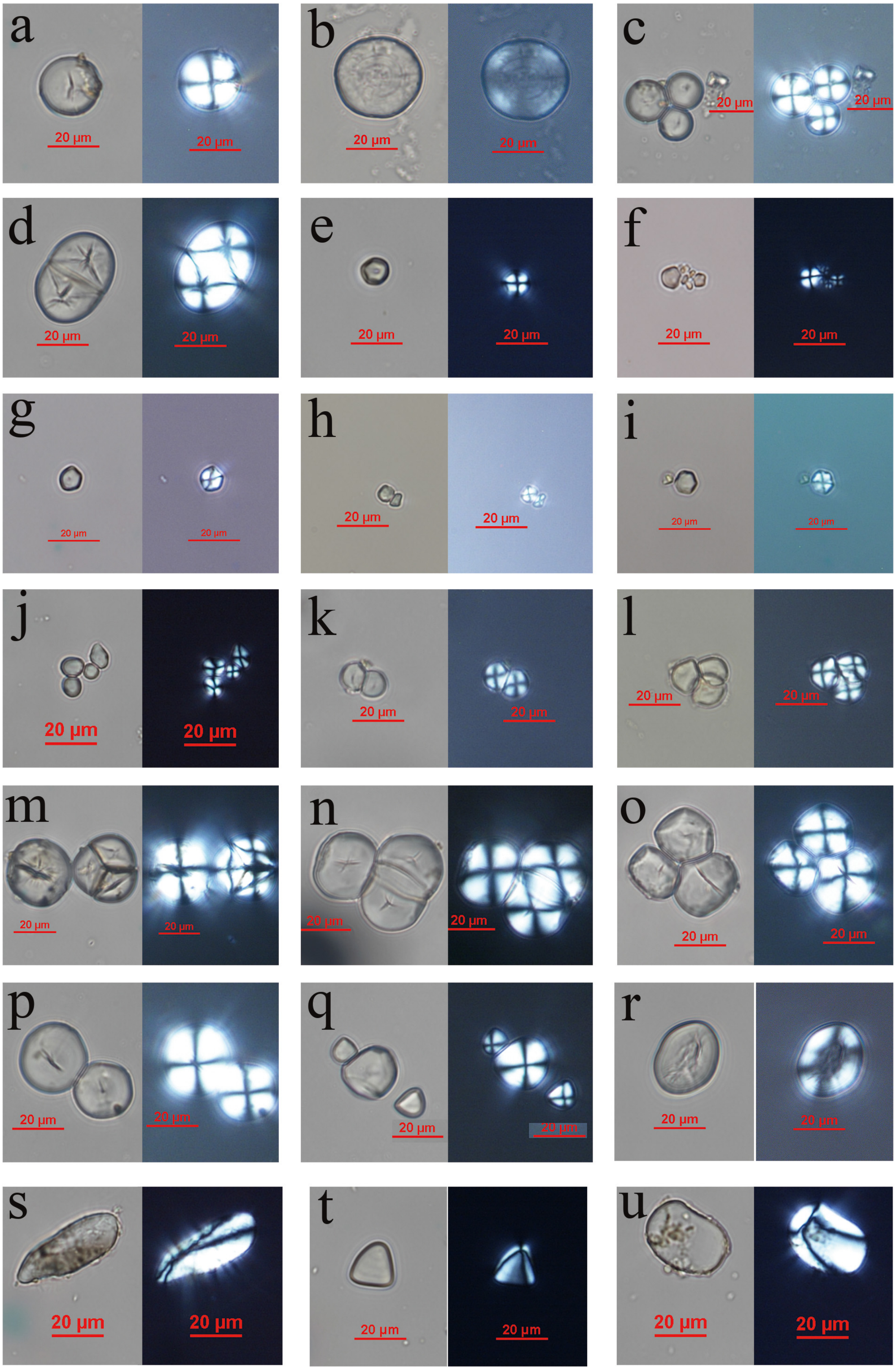

FIGURE 5 | Starch granules from Level III Liangwangcheng dental residue samples. (**a,j,m,s,u**: starch granule from M125; **b,r**: starch granule from M121; **c**: starch granule from M127; **d,h,k,l,n,p,q**: starch granule from M147; **e**: starch granule from M226; **f**: starch granule from M129; **g,i**: starch granule from M144; **o**: starch granule from M251; **t**: starch granule from M111).

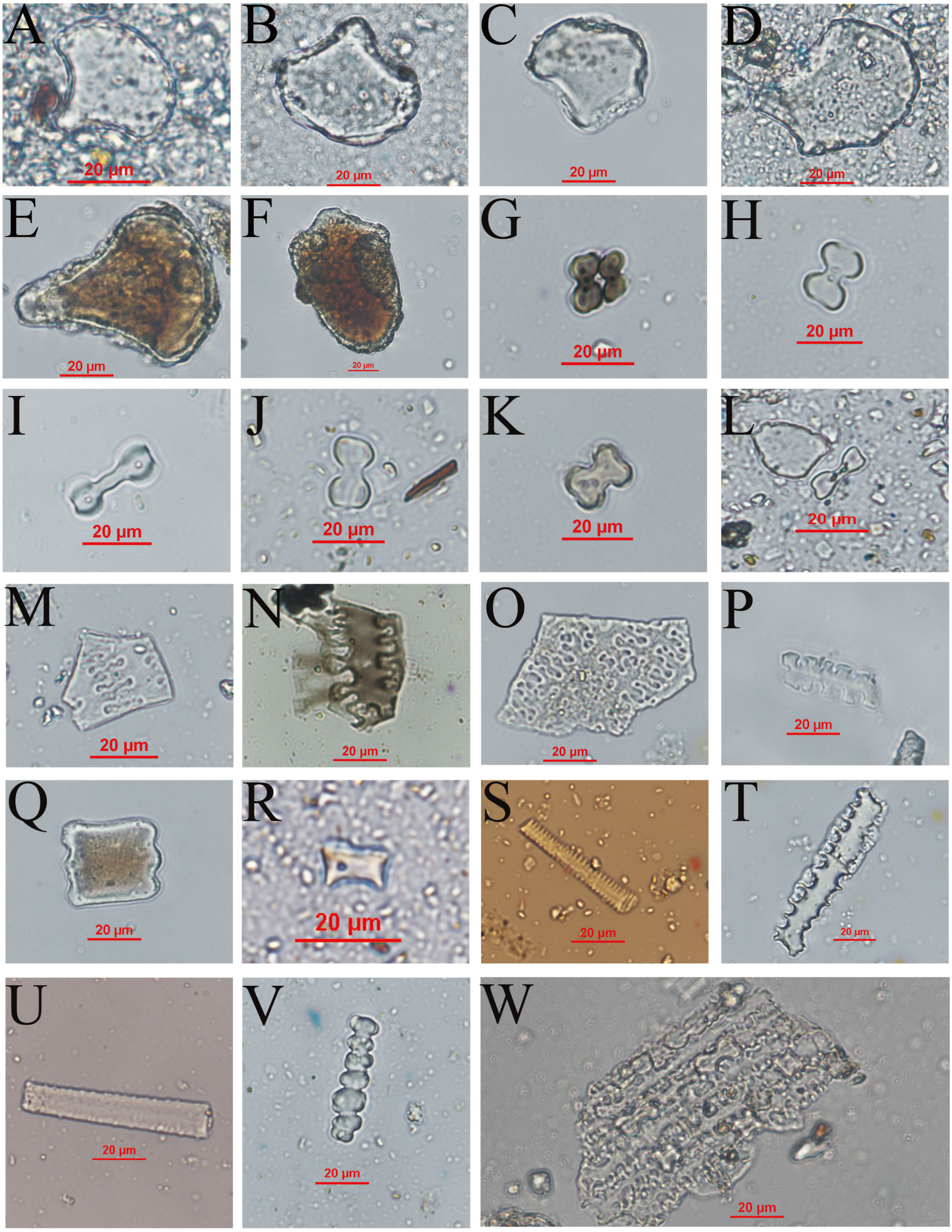

FIGURE 6 | Phytoliths recovered from Liangwangcheng dental residues. (**A–F**, Bulliform cells; **G–L**, Bilobate short cells; **M**, broomcorn millet husk; **N–P**, foxtail millet husk; **Q**, Wavy-trapezoid; **R**, short cell; **S**, Rondel; **T–V**, Elongate; **W**, Bilobate short cells).

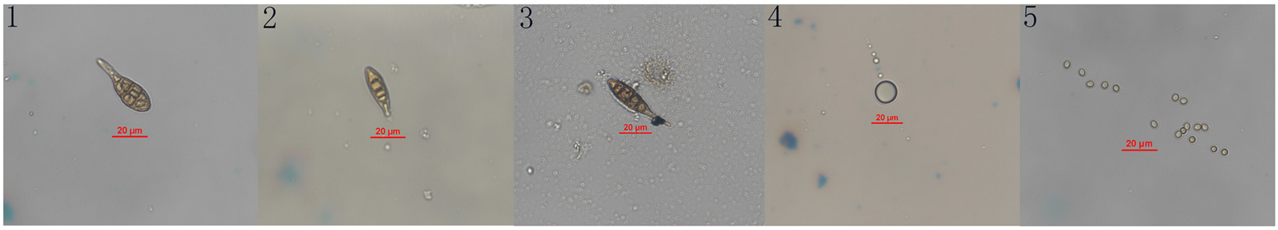

FIGURE 7 | Fungi remains recovered from Liangwangcheng dental residues.

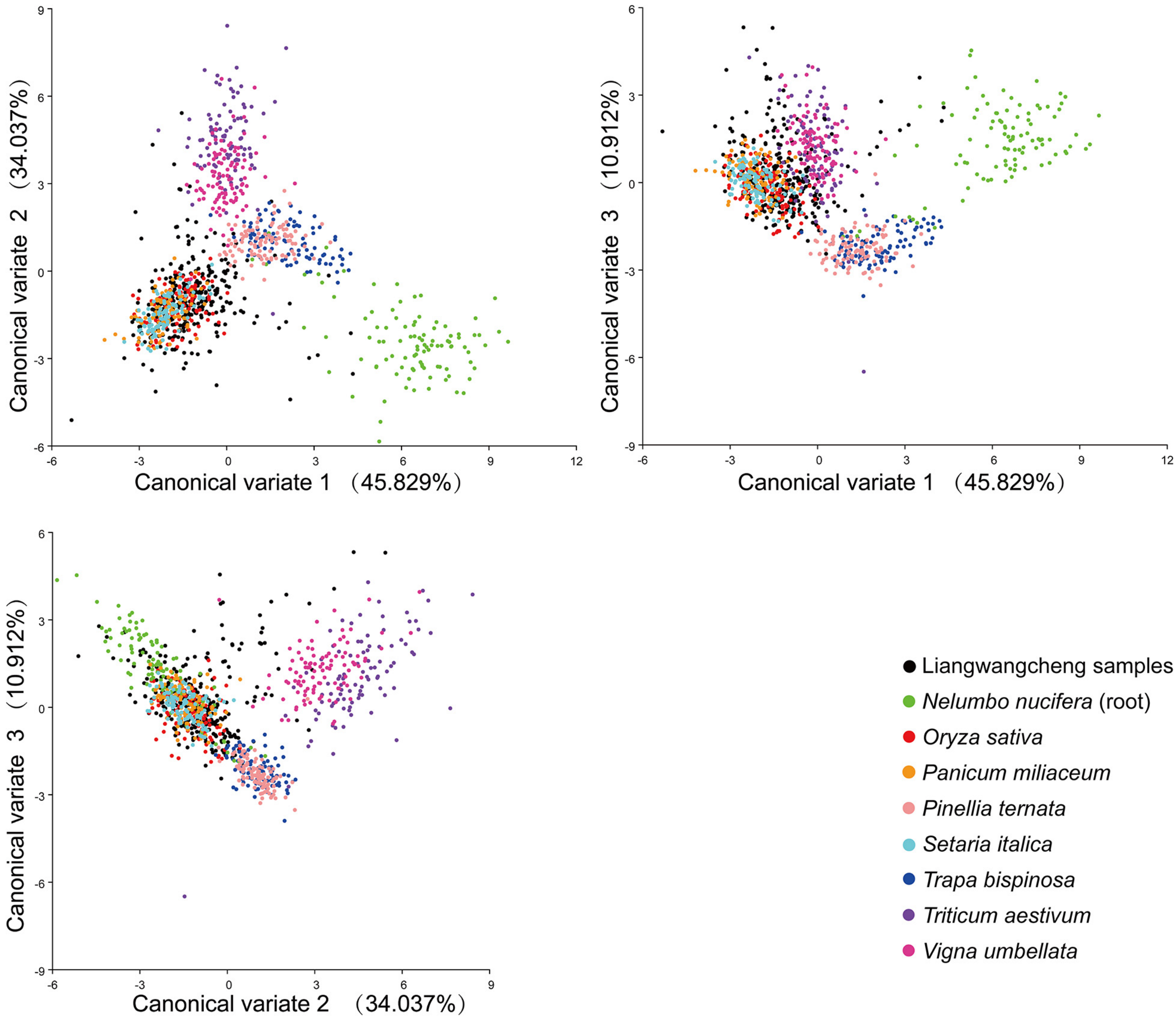

FIGURE 8 | Canonical variate scatter plot of CV1, CV2, and CV3 accounting for approximately 90% of variation.

species and are widely distributed. Due to their high protein content, they have comprised a part of the human diet for eons (Wang et al., 2009). Beans are still an indispensable component of the daily diet in northern Jiangsu today. Aquatic plants such as water chestnut and lotus root, widely distributed in the North Temperate and Subtropical Zones, are nutritiously rich. Our analyses suggest that the hydrothermal conditions and natural environment of the Liangwangcheng area fostered a level of

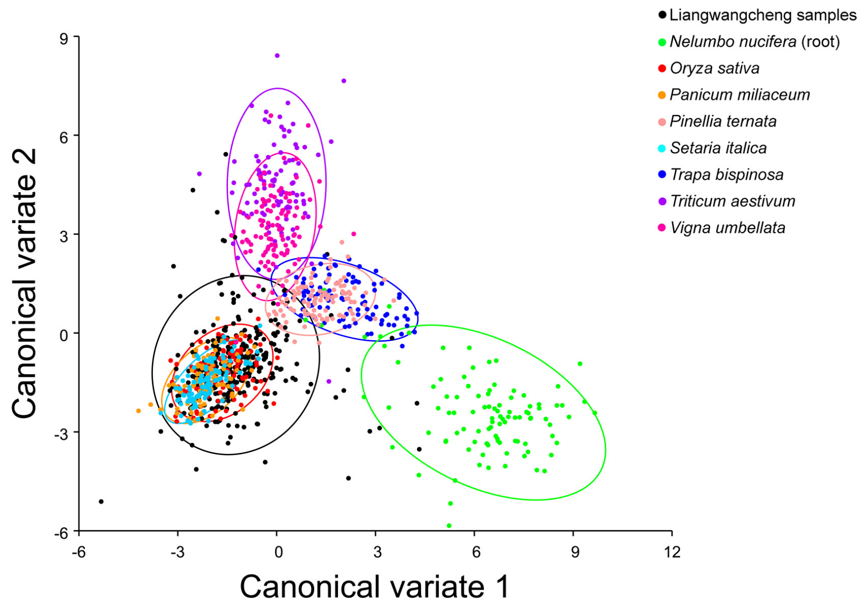

FIGURE 9 | Confidence ellipses (probability = 0.9) based on canonical variate scatter plot of CV1 and CV2.

biodiversity that gave the region's ancient inhabitants ready access to diverse food sources.

Human–Environment Interaction in the Liangwangcheng Area

Flotation work has not been conducted thus far at the Liangwangcheng site, considerably limiting our understanding of the subsistence pattern preserved at this site. Therefore, our study provides crucial evidence facilitating discussion of which plant species were utilized and consumed by the site's inhabitants. Specifically, dental residues provide direct and conclusive evidence essential for reconstructing the diet of Liangwangcheng's prehistoric inhabitants. Routine and sustainable cultivation of cereal plants may provide a stable dietary source. The selection of long-term edible plant resources was closely related to the natural environment and the subsistence productivity developed by ancient humans. According to published paleoenvironment data for the site, in the Late Dawenkou period, the climate in this area was warm and humid, and herbaceous and woody plants flourished. Prehistoric humans seized upon those climatic advantages and actively engaged in agricultural production (Zhao et al., 2014). Many residential houses, a pottery production complex, and a road paved with clay were exposed during excavations at Liangwangcheng (Nanjing et al., 2013) and well-established pottery typologies and evidence of the production of tools made of bone and stone illuminated. These artifacts suggest large-scale settlement during the Dawenkou period, which encouraged residents to engage in reliable agricultural production to support their burgeoning population. Anthropological analyses also indicate that skeletal lesions apparent on human bones were likely caused by heavy agricultural labor activities (Zhu et al., 2013). It seems that Liangwangcheng had favorable social and natural conditions for developing an agricultural economy in the Late Dawenkou period. Environmental conditions at the time were sufficient to support a rich and diverse array of foodstuffs, establishing a subsistence system based on agriculture while retaining a gathering and foraging economy as supplemental.

The rice–millet mixed agriculture pattern was a unique configuration in the Haidai area (Zhao, 2020), in which the cultivation of both rice and two varieties of millet were established and developed by ancient humans due to salubrious local environmental conditions. In the late Neolithic, agricultural patterns were generally consistent over the whole Haidai area; however, due to differences in geographical locations and environmental fluctuations, specific agricultural adaptations were also adjusted according to the local circumstances, thus temporal and regional differences emerged. No rice remains were found in the Jianxin (He and Liu, 1996) or Jiaojia sites (Wu, 2018) which apparently practiced typical dry farming, being located in inland areas and at higher latitudes north of Liangwangcheng. On the other hand, the Yuchisi (Institute of Archaeology, 2007) and Yangpu sites (Wu, 2018), located in Anhui at a lower latitude, practiced mixed rice–millet farming. The Liangwangcheng site is located on the lower reaches of the Huai River, as are Yuchisi and Yangpu in terms of hydrothermal and environmental conditions, with low-relief terrain and a dense fluvial network. Compared with Jianxin and Jiaojia, this region provides more abundant sources for irrigation and, thus, more suitable environmental conditions for propagating and cultivating rice.

The plant macrofossil and microfossil remains could present what specific plant foods were available to a community, while stable isotopic analytical data directly reflect a long-term configuration of which species had been consumed over many decades, which creates an efficient method for scholars to

TABLE 2 | Mahalanobis distance matrix of Liangwangcheng and control groups.

	Liangwangcheng	***Nelumbo nucifera***	***Oryza sativa***	***Panicum miliaceum***	***Pinellia ternata***	***Setaria italica***	***Trapa bispinosa***	***Triticum aestivum***	***Vigna umbellata***
Nelumbo nucifera	7.7988	0							
Oryza sativa	2.2237	8.2928	0						
Panicum miliaceum	2.1603	8.6368	1.9248	0					
Pinellia ternata	4.3466	7.1142	4.6282	5.1825	0				
Setaria italica	1.9577	8.6145	2.1293	1.7366	5.0945	0			
Trapa bispinosa	4.7390	6.5699	5.1041	5.5989	2.1658	5.5206	0		
Triticum aestivum	5.8538	9.4249	6.4180	6.5914	5.3110	6.6476	5.3937	0	
Vigna umbellata	4.8272	8.5861	5.2456	5.5567	4.6709	5.5536	4.9076	2.8238	0

The P-values from permutation tests (10,000 permutation rounds) for Mahalanobis distances among groups are all <0.0001; P-values < 0.0001 indicate that all groups are significantly different.

TABLE 3 | Procrustes distance matrix of Liangwangcheng and control groups.

	Liangwangcheng	***Nelumbo nucifera***	***Oryza sativa***	***Panicum miliaceum***	***Pinellia ternata***	***Setaria italica***	***Trapa bispinosa***	***Triticum aestivum***	***Vigna umbellata***
Nelumbo nucifera	0.3279								
Oryza sativa	0.0404	0.3439							
Panicum miliaceum	0.0593	0.3704	0.0688						
Pinellia ternata	0.0334	0.3276	0.0430	0.0743					
Setariaitalica	0.1026	0.3952	0.1157	0.0513	0.1175				
Trapa bispinosa	0.1608	0.2435	0.1602	0.2064	0.1507	0.2493			
Triticum aestivum	0.2207	0.3103	0.2088	0.2644	0.2097	0.3115	0.1022		
Vigna umbellata	0.1145	0.3028	0.1020	0.1584	0.1023	0.2056	0.0802	0.1129	0

TABLE 4 | Prediction result in Liangwangcheng starch granule dataset.

Plant taxon	Number of granules	Percentage (%)
Setaria italica	77	25.58
Smilax china (root)	31	10.30
Panicum miliaceum	28	9.30
Trapa bispinosa	23	7.64
Pueraria lobata	21	6.98
Nelumbo nucifera (root)	18	5.98
Eleocharis dulcis	18	5.98
Pinellia ternata	17	5.65
Amorphophallus virosus	14	4.65
Vigna umbellata	13	4.32
Oryza sativa	7	2.33
Total	267	88.71

establish a fuller picture of dietary practices in ancient China (Liu et al., 2020). According to Dong's radiocarbon dating and stable isotopic studies (Dong, 2013), the Liangwangcheng, Fujia, and Huating sites are contemporaneous, and the contemporaneity of these sites make synchronic comparisons of diet composition possible. The stable isotopic evidence also suggests that the diet of different contemporary sites in the Haidai area were not precisely the same. At Fujia, human diets were dominated by millets and millet-fed pigs, while at Huating and Liangwangcheng, people had more diverse diets, including many C3 plants such as rice and aquatic resources. Liangwangcheng and Huating are located in northern Jiangsu, further south than the Fujia site in Shandong province. In brief, millet is a plant resource that existed widely in the subsistence pattern of the Haidai area and has been relied upon for millennia. On the other hand, the rice and other C3 plants consumed by ancient humans were dramatically impacted by the natural environment, especially prevailing hydrothermal conditions.

CONCLUSION

In this study, we detected several species of starch granules in residue samples from 31 Late Dawenkou Culture burials, providing evidence of plant foods consumed by the Neolithic inhabitants of Liangwangcheng, Jiangsu. Geometric morphometric analysis indicates that a portion of these starch grains may be derived from domesticated cereal crops such as foxtail millet, broomcorn millet and rice; and part of them may derive from roots and tubers, legumes and aquatic plant fruits. Based upon CVA results, millets and rice are present in dental samples at the highest percentages. Millet and rice likely became the major consumed crop food sources beginning in middle Neolithic times in the Haidai area. Underground storage organs, aquatic plant fruits, and beans are also present at Liangwangcheng, but are represented at quantitatively lower levels.

Our study indicates that agricultural production was the primary means by which the Neolithic inhabitants of Liangwangcheng obtained plant-sourced foods, supplemented by gathering wild plant resources, and that the composition of the plant food spectrum was broad and diverse. The prehistoric inhabitants of Liangwangcheng would have employed locally appropriate subsistence strategies. Based on archaeobotanical research conducted at surrounding sites in the Haidai area, we conclude that in the late Neolithic period, the subsistence economy in northern Jiangsu was dominated by mixed rice–millet agriculture, and that a foraging and gathering economy persisted in a supplemental role. The plant microfossils discovered at this site provide essential information about the utilization of plant species and the development and florescence of agriculture in the late Neolithic of northern Jiangsu. This is of great significance in reconstructing prehistoric subsistence patterns in the middle and lower reaches of the Huai River, and for exploring interactions between prehistoric human activities and the paleoenvironmental context in which they were situated. These results also contribute to our understanding of crop diversity and the level of agricultural development attained in the late Neolithic period in the Haidai region of China's Pacific seaboard.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

XZ: conducting a research and investigation process, specifically performing the experiments, or data/evidence collection, and writing the initial draft. XtZ, YH, and ZZ: provision of study materials. JO: critical review, commentary, and revision. YG: development and design of methodology, creation of models, and oversight and leadership responsibility for the research activity planning. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2021.722103/full#supplementary-material

REFERENCES

Adams, D. C., and Otárola-Castillo, E. (2013). Geomorph: an r package for the collection and analysis of geometric morphometric shape data. *Ecol. Evol.* 4, 393–399. doi: 10.1111/2041-210X.12035

Addis, P., Melis, P., Cannas, R., Secci, M., Tinti, F., Piccinetti, C., et al. (2010). A morphometric approach for the analysis of body shap in Bluefin Tuna: preliminary results. *Collect. Vol. Sci. Papers* 65, 982–987.

Arráiz, H., Barbarin, N., Pasturel, M., Beaufort, L., Domínguez-Rodrigo, M., and Barboni, D. (2016). Starch granules identification and automatic classification based on an extended set of morphometric and optical measurements. *J. Arc. Sci. Rep.* 7, 169–179. doi: 10.1016/j.jasrep.2016.03.039

Atsatt, P. R., and Whiteside, M. D. (2014). Novel Symbiotic Protoplasts Formed by Endophytic Fungi Explain Their Hidden Existence, Lifestyle Switching, and Diversity within the Plant Kingdom. *PLoS One* 9:e95266. doi: 10.1371/journal.pone.0095266

Barber, I. G. (2020). Further wet-taro evidence from Polynesia's southernmost Neolithic production margins. *Proc. Natl. Acad. Sci.* 117, 1257–1258. doi: 10.1073/pnas.1918374117

Boser, B. E., Guyon, I. M., and Vapnik, V. N. (1992). *A training algorithm for optimal margin classifiers, Proceedings of the fifth annual workshop on Computational learning theory*. Pittsburgh: Association for Computing Machinery, 144–152.

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. *Radiocarbon* 51, 337–360.

Chandler-Ezell, K., and Pearsall, D. M. (2003). Piggyback Microfossil Processing: Joint Starch and Phytolith Sampling from Stone Tools. *Phytolitharien* 15, 2–8.

Chen, X. (2007). Shandong Rizhao Liangchu Xinshiqishidai yizhi fuxuan tuyang jieguo fenxi (in Chinese). *Nanfang Wenwu* 2007, 92–94. doi: 10.3969/j.issn.1004-6275.2007.01.014

Chen, X. (2017). *Application of Geometric Morphometry to Aquatic Organisms*. Beijing: Science Press.

Coster, A. C. F., and Field, J. H. (2015). What starch grain is that? – A geometric morphometric approach to determining plant species origin. *J. Archaeolog. Sci.* 58, 9–25. doi: 10.1016/j.jas.2015.03.014

Dobney, K., and Brothwell, D. (1988). "A scanning electron microscope study of archaeological dental calculus," in *Scanning Electron Microscopy in Archaeology. British Archaeological Reports International Series*, ed. S. L. Olsen (Oxford: Archaeopress), 372–385.

Dong, Y. (2013). *Eating identity: food, gender, and social organization in Late Neolithic northern China*. Unpublished Ph.D. dissertation, Illinois: University of Illinois at Urbana-Champaign.

Dong, Y., Chen, S., Ambrose, S. H., Underhill, A., Ling, X., Gao, M., et al. (2021). Social and environmental factors influencing dietary choices among Dawenkou culture sites, Late Neolithic China. *Holocene* 31, 271–284. doi: 10.1177/0959683620970273

Dong, Y., Lin, L., Zhu, X., Luan, F., and Underhill, A. P. (2019). Mortuary ritual and social identities during the late Dawenkou period in China. *Antiquity* 93, 378–392. doi: 10.15184/aqy.2019.34

Gao, G., and Shao, W. (1984). Zhonghua wenming faxiangdi zhiyi—haidai lishi wenhuaqu (in Chinese). *Shiqian Yanjiu* 7-25:6.

Gary, C., Chen, X., Luan, F., and Wang, J. (2013). A Preliminary Analysis on Plant Remains of the Yuezhuang Site in Changqing District, Jinan City, Shandong Province. *Jianghan Kaogu* 2013, 107–116.

Gary, C., Chen, X., and Wang, J. (2006). Discovery of fossilized crops from the Houli site of Yuezhuang in the Jinan Region of Shandong (in Chinese). *Dongfang Kaogu* 3, 247–251.

Guan, Y., Pearsall, D. M., Gao, X., Chen, F., Pei, S., and Zhou, Z. (2014). Plant use activities during the Upper Paleolithic in East Eurasia: Evidence from the Shuidonggou Site, Northwest China. *Q. Internat.* 347, 74–83. doi: 10.1016/j.quaint.2014.04.007

Guan, Y., Pearsall, D. M., Gao, X., and Zhou, Z. (2010). Shizhipin zhiwu canliuwu fenxi de shiyanshi fangfa—yi Shuidonggou shizhipin weili (in Chinese). *Acta Anthropolog. Sinica* 29, 395–404.

Guan, Y., Tian, C., Peng, F., Guo, J., Wang, H., Zhou, Z., et al. (2020). Plant diet during the Pleistocene-Holocene transition in northwest China: Evidence from starch remains from Pigeon Mountain site in Ningxia Province. *Q. Internat.* 559, 110–118. doi: 10.1016/j.quaint.2020.03.016

Guedes, J. D. A., Jin, G., and Bocinsky, R. K. (2015). The impact of climate on the spread of rice to north-eastern China: A new look at the data from Shandong Province. *PLoS One* 10:130430. doi: 10.1371/journal.pone.0130430

Hart, T. (2014). Analysis of starch grains produced in select taxa encountered in Southwest Asia. *Ethnobiol. Lett.* 5:135. doi: 10.14237/ebl.5.2014.251

Haslam, M. (2006). Potential misidentification of in situ archaeological tool-residues: starch and conidia. *J. Arch. Sci.* 33, 114–121. doi: 10.1016/j.jas.2005.07.004

He, D., and Liu, Z. (1996). *Zaozhuang Jianxin: Xinshiqi shidai yizhi fajue baogao (in Chinese)*. Beijing: Science Press.

Heaton, T., Blaauw, M., Blackwell, P., Bronk Ramsey, C., Reimer, P., and Scott, M. (2020). The IntCal20 approach to radiocarbon calibration curve construction: a new methodology using Bayesian splines and errors-in-variables. *Radiocarbon* 2020:62.

Huang, C. (1998). *Huanjing Bianqian (in Chinese)*. Beijing: Science Press.

Institute of Archaeology (2007). *Mengcheng Yuchisi*. Beijing: Science Press.

Jin, G. (2012). Preliminary study on the subsistence of the Houli Culture (in Chinese). *Dongfang Kaogu* 9, 579–594.

Jin, G., Chen, S., Li, H., Fan, X., Yang, A., and Mithen, S. (2020). The Beixin Culture: archaeobotanical evidence for a population dispersal of Neolithic hunter-gatherer-cultivators in northern China. *Antiquity* 94, 1426–1443. doi: 10.15184/aqy.2020.63

Jin, G., Wagner, M., Tarasov, P. E., Wang, F., and Liu, Y. (2016). Archaeobotanical records of Middle and Late Neolithic agriculture from Shandong Province, East China, and a major change in regional subsistence during the Dawenkou Culture. *Holocene* 26, 1605–1615. doi: 10.1177/0959683616641746

Jin, G., and Wang, C. (2010a). Study on the agriculture and environment from 3000BC to 1500BC in the Haidai Region: Phytolith evidence from archaeological sites (in Chinese). *Dongfang Kaogu* 2010, 322–332.

Jin, G., and Wang, C. (2010b). Climate and environment of the Neolithic Age in Haidai Region. *J. Palaeogeogr.* 2010, 355–363. doi: 10.7605/gdlxb.2010.03.011

Jin, G., Wu, W., Zhang, K., Wang, Z., and Wu, X. (2014). 8000-Year old rice remains from the north edge of the Shandong Highlands, East China. *J. Archaeolog. Sci.* 51, 34–42. doi: 10.1016/j.jas.2013.01.007

Jin, G., Zhao, M., Wang, C., and Dang, H. (2010). A report on the foxtail millet systems of the Longshan: Report on the Yuhuanding site in Jining, Shandong (in Chinese). *Haidai Kaogu* 3, 100–113.

Jin, Q. (1990). *Anhui Huaibei pingyuan Disixi*. Beijing: Geological Press.

Klingenberg, C. P. (2011). MorphoJ: an integrated software package for geometric morphometrics. *Mole. Ecol. Resour.* 11, 353–357. doi: 10.1111/j.1755-0998.2010.02924.x

Krull, R., Wucherpfennig, T., Esfandabadi, M. E., Walisko, R., Melzer, G., Hempel, D. C., et al. (2013). Characterization and control of fungal morphology for improved production performance in biotechnology. *J. Biotechnol.* 163, 112–123. doi: 10.1016/j.jbiotec.2012.06.024

Li, M., Yang, X., Wang, H., Wang, Q., Jia, X., and Ge, Q. (2010). Starch grains from dental calculus reveal ancient plant foodstuffs at Chenqimogou site, Gansu Province. *Sci. China Earth Sci.* 53, 694–699. doi: 10.1007/s11430-010-0052-9

Li, W., Pagán-Jiménez, J. R., Tsoraki, C., Yao, L., and Van Gijn, A. (2020). Influence of grinding on the preservation of starch grains from rice. *Archaeometry* 62, 157–171. doi: 10.1111/arcm.12510

Liu, L., Duncan, N. A., Chen, X., and Cui, J. (2019). Exploitation of Job's Tears in Paleolithic and Neolithic China: Methodological problems and solutions. *Q. Internat.* 529, 25–37. doi: 10.1016/j.quaint.2018.11.019

Liu, L., Ma, S., and Cui, J. (2014). Identification of starch granules using a two-step identification method. *J. Archaeolog. Sci.* 52, 421–427. doi: 10.1016/j.jas.2014.09.008

Liu, R., Pollard, M., Schulting, R., Rawson, J., and Cheng, L. (2020). Synthesis of stable isotopic data for human bone collagen: a study of the broad dietary patterns across ancient china. *Holocene* 31, 302–312. doi: 10.1177/0959683620941168

Liu, Z., Wang, L. L., Zhou, W. D., Chen, Y. F., and Wang, Z. (2011). The surface of the geometric characteristics analysis for rice endosperm starch granules by using Image J (in Chinese). *J. Chin. Electr. Microsc. Soc.* 30, 466–471. doi: 10.3969/j.issn.1000-6281.2011.04.035

Lu, H., Wu, N., Yang, X., Jiang, H., Liu, K., and Liu, T. (2006). Phytoliths as quantitative indicators for the reconstruction of past environmental conditions in China I: phytolith-based transfer functions. *Q. Sci. Rev.* 25, 945–959. doi: 10.1016/j.quascirev.2005.07.014

Luan, F. (1997). *Archaeological Research in the Haidai Region (in Chinese)*. Jinan: Shandong University Press.

Lustmann, J., Lewin-Epstein, J., and Shteyer, A. (1976). Scanning electron microscopy of dental calculus. *Calcif. Tissue Res.* 21, 47–55. doi: 10.1007/BF02547382

Ma, Z., Perry, L., Li, Q., and Yang, X. (2019). Morphological changes in starch grains after dehusking and grinding with stone tools. *Sci. Rep.* 9:2355. doi: 10.1038/s41598-019-38758-6

McGovern, P., Jalabadze, M., Batiuk, S., Callahan, M. P., Smith, K. E., Hall, G. R., et al. (2017). Early Neolithic wine of Georgia in the South Caucasus. *Proc. Natl. Acad. Sci.* 114, E10309–E10318. doi: 10.1073/pnas.1714728114

McNulty, K. P., and Vinyard, C. J. (2015). Morphometry, geometry, function, and the future. *Anatom. Rec.* 298, 328–333. doi: 10.1002/ar.23064

Mitteroecker, P., and Gunz, P. (2009). Advances in Geometric Morphometrics. *Evol. Biol.* 36, 235–247. doi: 10.1007/s11692-009-9055-x

Nanjing, M., Xuzhou, M., and Pizhou, M. (2013). *Liangwangcheng Yizhi Fajue Baogao: Shiqian Juan (in Chinese)*. Beijing: Cultural Relics.

Nava, A., Fiorin, E., Zupancich, A., Carra, M., Ottoni, C., Di Carlo, G., et al. (2021). Multipronged dental analyses reveal dietary differences in last foragers and first farmers at Grotta Continenza, central Italy (15,500-7000 B.P.). *Sci. Rep.* 11:2. doi: 10.1038/s41598-021-82401-2

Olsen, S. L. (1988). "Applications of Scanning Electron Microscopy in archaeology," in *Advances in Electronics and Electron Physics*, ed. P. W. Hawkes (Cambridge, MA: Academic Press), 357–380.

Park, P. J., Aguirre, W. E., Spikes, D. A., and Miyazaki, J. M. (2013). Landmark-based Geometric Morphometrics: What fish shapes can tell us about fish evolution. *Test. Stud. Lab. Teach. Proc. Assoc. Biol. Lab. Educ.* 34, 361–371.

Pearsall, D. M., Chandler-Ezell, K., and Zeidler, J. A. (2004). Maize in ancient Ecuador: results of residue analysis of stone tools from the Real Alto site. *J. Arch. Sci.* 31, 423–442. doi: 10.1016/j.jas.2003.09.010

Piperno, D. R., and Dillehay, T. D. (2008). Starch grains on human teeth reveal early broad crop diet in northern Peru. *Proc. Natl. Acad. Sci.* 105, 19622–19627. doi: 10.1073/pnas.0808752105

Prebble, M., Anderson, A. J., Augustinus, P., Emmitt, J., Fallon, S. J., Furey, L. L., et al. (2019). Early tropical crop production in marginal subtropical and temperate Polynesia. *Proc. Natl. Acad. Sci.* 116, 8824–8833. doi: 10.1073/pnas.1821732116

R Core Team (2020). *R: A Language and Environment for Statistical Computing*. Vienna: R Foundation for Statistical Computing.

Reimer, P., Austin, W., Bard, E., Bayliss, A., Blackwell, P., Bronk Ramsey, C., et al. (2020). The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon* 2020:62.

Savriama, Y. (2018). A step-by-step guide for geometric morphometrics of floral symmetry. *Front. Plant Sci.* 9:1433. doi: 10.3389/fpls.2018.01433

Shandong, M. (1973). Shandong penlai Zijingshan yizhi shijue jianbao (in Chinese). *Archaeology* 1973, 13–17.

Shen, Z., Liu, H., Wang, X., and Wang, C. (2019). Surface degradation of micro-mold in micro-scale laser dynamic forming and its effects on workpiece. *Opt. Laser Technol.* 117, 114–125. doi: 10.1016/j.optlastec.2019.03.047

Slice, D. E. (2007). Geometric Morphometrics. *Ann. Rev. Anthropol.* 6, 261–281.

Steinwart, I., and Christmann, A. (2008). *Support Vector Machines*. New York, NY: Springer.

Tang, L., Shen, C., Zhao, X., Xiao, J., Yu, G., and Han, H. (1993). Jiangsu Jianhu Qingfeng poumian 10000 nianlai de zhibei yu qihou (in Chinese). *Sci. Chin.* 1993, 637–643.

Tao, D. (2018). Investigation of plant food sources at Peiligang Site based on starch grain analysis of human dental calculus (in Chinese). *Sci. Conserv. Archaeol.* 30, 1–9.

Tao, D., Zhang, G., Zhou, Y., and Zhao, H. (2020). Investigating wheat consumption based on multiple evidences: Stable isotope analysis on human bone and starch grain analysis on dental calculus of humans from the Laodaojing Cemetery, Central Plains, China. *Internat. J. Osteoarchaeol.* 2020, 594–606. doi: 10.1002/oa.2884

Torrence, R. (2006). "Description, classification and identification," in *Ancient Starch Research*, eds R. Torrence and H. Barton (California: Left Coast Press), 115–144.

Torrence, R., Wright, R., and Conway, R. (2004). Identification of starch granules using image analysis and multivariate techniques. *J. Archaeolog. Sci.* 31, 519–532. doi: 10.1016/j.jas.2003.09.014

Walsh, T. H., Hayden, R. T., and Larone, D. H. (2018). *Larone's Medically Important Fungi: A Guide to Identification, Sixth Edition*. Washington, DC: ASM Press.

Wan, Z., Li, M., and Li, H. (2016). Study on morphological characteristics of starch granules in the Triticeae (in Chinese with English abstract). *J. Tritic. Crops* 36, 1020–1027. doi: 10.7606/j.issn.1009-1041.2016.08.07

Wan, Z., Lin, S., Ju, M., Ling, C., Jia, Y., Jiang, M., et al. (2020). Morphotypological analysis of starch granules through discriminant method and application in plant archaeological samples. *Appl. Ecol. Environ. Res.* 18, 4595–4608. doi: 10.15666/aeer/1803_45954608

Wan, Z., Yang, X., Ge, Q., and Jiang, M. (2011a). Morphological characteristics of starch grains of root and tuber plants in South China (in Chinese with English abstract). *Q. Sci.* 31, 736–745. doi: 10.3969/j.issn.1001-7410.2011.04.18

Wan, Z., Yang, X., Ma, Z., and Liu, G. (2011b). Morphological change of starch grain based on simulated experiment and its significance of agricultural archaeology - taking wheat as an example. *Agricult. Sci. Technol.* 12, 1621–1624. doi: 10.3969/j.issn.1009-4229-B.2011.11.017

Wang, H., and Jin, G. (2013). Shandong jimo beiqian yizhi (2009) tanhua zhongzi guoshi yicun yanjiu (in Chinese). *Dongfang Kaogu* 10, 265–289.

Wang, H., Liu, Y., and Jin, G. (2011). Report on the carbonized seeds from the Dongpan site in Linshu County, Shandong (in Chinese). *Dongfang Kaogu* 357-372, 455–459.

Wang, J., Zhao, X., Wang, H., and Liu, L. (2019). Plant exploitation of the first farmers in northwest China: Microbotanical evidence from Dadiwan. *Q. Internat.* 529, 3–9. doi: 10.1016/j.quaint.2018.10.019

Wang, P., Ren, S., and Wang, G. (2009). Common food legumes nutritional characterstics and functional features (in Chinese with English abstract). *Shipin Yanjiu yu Kaifa* 30, 171–174. doi: 10.3969/j.issn.1005-6521.2009.12.050

Wang, Q., Jia, X., Li, M., and Yang, X. (2013). Zhongguo changjian doulei dianfenli xingtai fenxi jiqi zai nongyekaogu zhong de yingyong (The morphological analysis of common edible beans starch grains and the application in agricultural Archaeology) (in Chinese). *Wenwu Chunqiu* 2013, 3–11. doi: 10.3969/j.issn.1003-6555.2013.03.001

Wang, S., Wang, L., Fan, W., Cao, H., and Cao, B. (2011). Morphplogical analysis of common edible starch granules by scanning electron microscopy (in Chinese with English abstract). *Food Sci.* 32, 74–79. doi: 10.1097/RLU.0b013e3181f49ac7

Wang, X., and Wu, H. (1992). Shandong Yantai Baishicun Xinshiqi shidai yizhi fajue jianbao. *Archaeology* 1992, 577–588.

Webster, M., and Sheets, H. D. (2010). A Practical Introduction to Landmark-Based Geometric Morphometrics. *Paleontolog. Soc. Papers* 16, 163–188. doi: 10.1017/S1089332600001868

Wei, C., Zhang, X., Zhang, J., Xu, B., Zhou, W., and Xu, R. (2007). Isolation and properties of large and small starch grains of different types of wheat cultivars (in Chinese with English abstract). *J. Tritic. Crops* 27, 255–260. doi: 10.3969/j.issn.1009-1041.2007.02.016

Wu, R. (2018). *Research on the Subsistence of Dawenkou Culture—Evidence from Archaeobotany (in Chinese)*. Master's thesis, Jinan: Shandong University.

Wu, W. (2019). Haidai diqu houli wenhua shengye jingji de yanjiu yu sikao. *Archaeology* 2019, 103–115.

Wu, W., Wang, X., Wu, X., Jin, G., and Tarasov, P. E. (2014). The early Holocene archaeobotanical record from the Zhangmatun site situated at the northern edge of the Shandong Highlands, China. *Q. Internat.* 348, 183–193. doi: 10.1016/j.quaint.2014.02.008

Yan, W., and Zhang, J. (1987). Shandong changdao beizhuang yizhi fajue jianbao. *Archaeology* 1987, 385–394.

Yang, X., Kong, Z., Liu, C., Zhang, Y., and Ge, Q. (2009). Characteristics of starch grains from main nuts in North China (in Chinese with English abstract). *Q. Sci.* 29, 153–158.

Yang, X., Ma, Z., Li, Q., Perry, L., Huan, X., Wan, Z., et al. (2013). Experiments with lithic tools: understanding starch residues from crop harvesting. *Archaeometry* 56, 12034. doi: 10.1111/arcm.12034

Yang, X., and Perry, L. (2013). Identification of ancient starch grains from the tribe Triticeae in the North China Plain. *J. Archaeolog. Sci.* 40, 3170–3177. doi: 10.1016/j.jas.2013.04.004

Zhao, J. (2015). *Xinbian Zhongguo Ziran Dili*. Beijing: Higher Education Press.

Zhao, L., Ma, C., Lin, L., Zhu, C., Tian, X., and Huang, K. (2014). Environmental evolution and human activities recorded in the Liangwangcheng Site, northern Jiangsu Province (in Chinese with English abstract). *J. Stratigr.* 38, 33–41.

Zhao, Z. (2020). Origin of agriculture and archaeobotanical works in China (in Chinese with English abstract). *Agricult. Chin.* 2020, 3–13.

Zheng, X., and Wang, X. (1983). *Zhiwu jiepou jiegou xianwei tupu*. Beijing: China Agriculture Press.

Zhu, X., Lin, L., and Zhu, H. (2013). A study on bones unearthed from a Dawenkou Culture tomb at the Liangwangcheng Site in Pizhou, Jiangsu Province (in Chinese with English abstract). *Dongnan Wenhua* 2013, 55–66.

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Social and Ecological Factors Affect Long-Term Resilience of Voyaging Canoes in Pre-contact Eastern Polynesia: A Multiproxy Approach From the ArchaeoEcology Project

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While Eastern Polynesian archaeologists rarely recover archaeological remains of canoes (*va'a*), ethnohistoric texts document how such vessels played a central role in the daily lives of commoners and chiefs alike. Here, we refocus discussions of *va'a* in Polynesian societies through synthesizing proxy information (archaeological data, evidence from ethnographic and ethnohistoric sources, ecological modeling, human-centered interaction networks) on canoe use in the Society Islands of French Polynesia. While all communities who initially settled Eastern Polynesia archipelagoes must have done so with large double-hulled canoes, their use was absent in some societies by the time of European contact. We question why some Eastern Polynesian societies retained the use of large ocean-going canoes, while others did not. For high island archipelagoes like the Society Islands, sources document how large double-hulled canoes facilitated and supported elite intra-archipelago voyaging, warfare, and exchange with near and remote hinterlands up until European contact in the mid-eighteenth century. While smaller canoes were used by commoners on a daily basis for subsistence fishing and island-wide transport, larger ocean-going canoes were strictly the purview of high-ranking elites. Our human-centered interaction network models help us to identify how social processes put constraints on the manufacture and continued use of large ocean-going *va'a* in Eastern Polynesian contexts. We deploy such data to outline steps in the production, use, and re-use of canoes. We employ network science to better understand the relationships between animal and plant species used by the Mā'ohi in canoe manufacture, quantifying the number of resources used, the number of social personae involved, and the amount of labor/energy involved in their manufacture. Finally, we use Mo'orea settlement pattern data, as well as landscape and elevation data, to visually model the extent to which local ecologies or habitats constrained access to long-lived hard wood trees, key raw materials in the construction of ocean-going vessels. We consider the additional variables of soil pH and tree regrowth rates in our modeling of the ecological limits of preferred *va'a* species. We then query differential patterns of continued use of ocean-going vessels in two Eastern Polynesian archipelagoes: the

Gambier archipelago and the Society Islands. Utilizing these multiple sources of data, we return to the age-old question of what roles social and natural processes played in the resiliency of the socio-political systems of Polynesian chiefdoms. We view ocean-going canoes as critical social tools in terms of resilience, as use of these water craft reduced island isolation and allowed for contact with near, and sometimes far, neighbors who served as critical buffering agents, particularly in times of ecological crises, such as drought, famine, or tsunamis.

Keywords: Eastern Polynesia, canoe societies, resilience, ecology and habitat modeling, ethnohistory, prestige goods, human-centered interaction network, archaeoecology

> "This people are very ingenious in building their Proes, or Canoes, and seek to take as much care of them having large shades of houses to put them in built for the purpose and in these houses they likewise build and repair them and in this they shew a great deal of ingenuity, far more than one an expect: they are built full bellied. In these Pahee's… these people sail in those seas from Island to Island for several hundred Leagues ……" (Cook in Beaglehole, 1955/1961/1967, pp. 153–154).

INTRODUCTION

As the quote above from Captain Cook's first voyage to the Society Islands between 1768 and 1771 attests, large ocean-worthy canoes played a key role in Māʻohi society at the time of European contact. Yet Eastern Polynesian archaeologists rarely recover archaeological remains of canoes, despite ethnohistoric texts documenting how large ocean-going watercraft and smaller everyday vessels played a central role in the lives of commoners and chiefs. Arguably, only one archaeological example of a truly ocean-going canoe has been recovered in Eastern Polynesia (from New Zealand). Here, we refocus discussions of *vaʻa* (canoes) in Eastern Polynesian societies through synthesizing varied forms of proxy information (archaeological data, ethnographic and ethnohistoric data). We then harness these data to simulate models (human-centered interaction networks and spatial patterns of ecological limits) on canoe use in the Society Islands of French Polynesia. While all communities who initially settled Eastern Polynesia must have done so with large double-hulled canoes, their use was absent in some societies by the time of European contact. We question why did some Eastern Polynesian societies retain the use of large ocean-going canoes, while others did not?

Such questions are intertwined with human-environmental relations, as anthropogenic deforestation has been seen as a causal factor in the loss of timber for canoe manufacture and subsequently, the loss of the ability for ocean-going voyaging (Van Tilburg, 1994; Weisler, 1994, pp. 98–99; Rolett, 2002). The size of Eastern Polynesian canoes was largely based on the availability of large trees, with ocean-going canoes requiring the largest of trees to craft immense hulls (Ranney, 2018, p. 30). Thus, we privilege the ability of certain islands to grow large hardwood trees as a necessary condition for continued ocean-going voyaging capabilities in pre-contact Eastern Polynesia or at a minimum, access to canoes manufactured within such island's long-distance trade networks. Historically, Tongan political influence over the Lau island group in Fiji for extraction of *Intsia bijuga* provides a good example for the latter in Western Polynesia (Banack and Cox, 1987), while in our Eastern Polynesian case study, the Society Island-Mehetia-Tuamotu interaction sphere provides a good example of such a practice in Eastern Polynesia.

We launch our canoe-centric study by synthesizing ethnographic and ethnohistoric data on canoe use in the Society Islands and more broadly in Eastern Polynesia at the time of European contact. For high island archipelagoes like the Society Islands, sources document how large double-hulled canoes facilitated and supported elite intra-archipelago voyaging, the waging of war, and exchange with near and remote hinterlands up until European contact in the mid-eighteenth century. While smaller canoes were used by (mainly male) commoners on a daily basis for subsistence fishing and island-wide transport, larger ocean-going canoes were strictly the purview of high-ranking elites (again, mainly male). In the most complex of Polynesian chiefdoms, like the Society Islands, ocean-going canoes were highly valued functional items, but also symbolic items, as the size of a canoe materially expressed chiefly status. Only high-ranking chiefs had the wealth required to support the manufacture of such *vaʻa* by craft specialists. As such, we can identify large double-hulled royal canoes and war canoes as highly prized and restricted elite prestige items.

Our human-centered interaction network research helps us to identify how social processes put constraints on the manufacture and continued use of large ocean-going *vaʻa* in Eastern Polynesian contexts. We deploy such data to outline steps in the production, use, and re-use of canoes. We quantify the number of resources used, the number of social personae involved, and the amount of labor/energy involved in their manufacture. Finally, we use Moʻorea settlement pattern data, landscape data on elevation, and modern botanical survey data to visually model the extent to which local ecologies or habitats constrained access to long-lived hardwood trees, key raw materials in the construction of ocean-going vessels. We then query differential patterns of continued use of ocean-going vessels in two Eastern Polynesian archipelagoes: the Gambier archipelago and the Society Islands. Utilizing these multiple sources of data, we return to the age-old question of what role both social and natural processes, working in tandem, played in the resilience of the socio-political systems of Polynesian chiefdoms. Here we follow a perspective viewing ocean-going canoes as critical tools in terms of resilience.

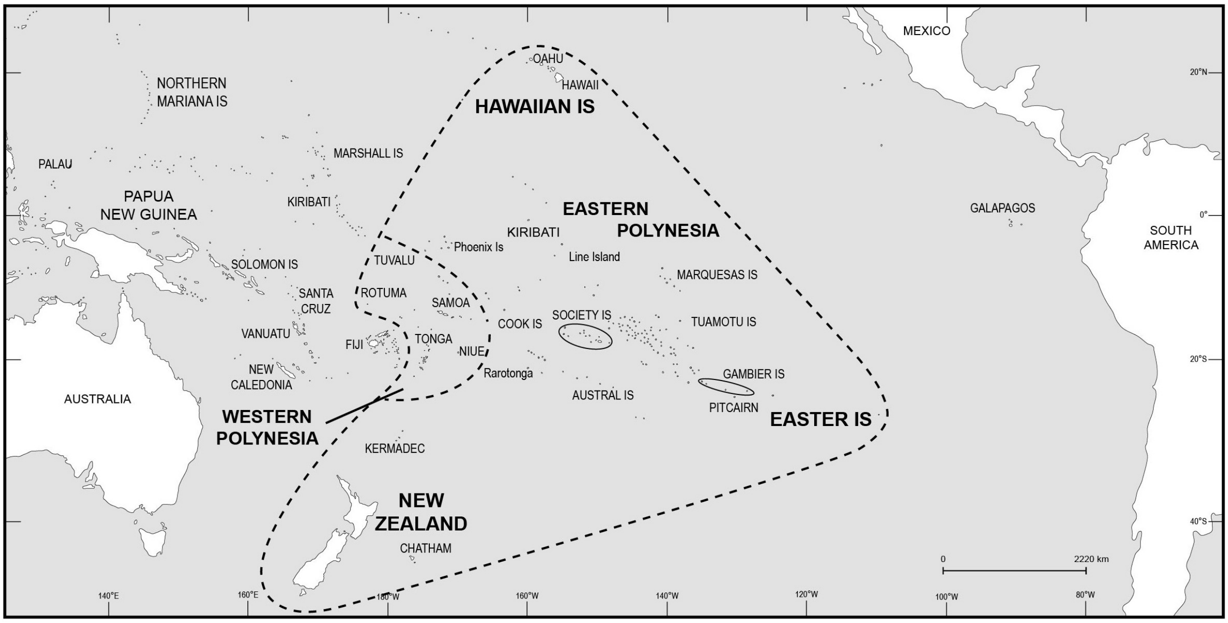

FIGURE 1 | Map of Eastern Polynesia and location of the Society Islands and Gambier Islands (Mangareva).

Use of these watercraft reduced island isolation and allowed for contact with near, and sometimes far, neighbors who served as critical buffering agents, particularly in times of ecological crises, like drought, famine, or tsunamis, otherwise known as the "rescue effect." As such, our work has broad relevance for studies of other pre-contact "canoe cultures," like those found in the Caribbean (Shearn, 2020) and the Northwest Coast (Mathews and Turner, 2017).

Eastern Polynesia as a Study Area and the Society and Gambier Case Studies

Eastern Polynesia is comprised of five main Central Eastern Polynesian archipelagoes (Cook, Society, Marquesas, Gambier, Tuamotu), in addition to the Pitcairn Group, Equatorial Islands, Kermadecs, Chatham Island, and the remote Eastern Polynesia islands (Hawaiian Islands, New Zealand, and Easter Island) (**Figure 1**). This area stretches over a vast ocean, spanning tropical to sub-tropical climates. All Eastern Polynesian islands are characterized by isolation and limited size (Kirch, 1984, p. 20), yet these are relative, as are differential physical resources given island type, age, and height. Geologically young high island archipelagoes, like the Hawaiian Islands and the Societies, offered the largest land masses, well-watered valleys with permanent streams, and moderate to well-developed lagoons (Kirch, 2010; Hommon, 2013; Kahn, in press), thus affording new settlers with the richest landscapes in terms of natural resources. While not the largest, youngest, or tallest island in the Society chain (this would be Tahiti at 1,045 km^2 in size, 0.3–1.3 myr in age, 2,241 m in elevation), Moʻorea is a geologically young island of moderate size and elevation (134 km^2 in size, 1.3–1.8 myr in age, 1,207 m in elevation). In contrast, the geologically older islands in the Gambier chain are both much smaller in size and much lower in elevation than Moʻorea (see **Table 1**). Geologically older archipelagoes, like the Gambiers, were more impoverished in terms of available natural resources. Their old age and small island size limited their terrestrial biodiversity, however, this was offset by enormous lagoons and rich marine resources (Conte and Kirch, 2004), in addition to the plants and animals introduced as canoe species ("Polynesian Introductions"). The Gambier Islands' reduced elevations resulted in a local context where only the largest valleys had permanent watercourses (Conte and Kirch, 2004, pp. 18–19).

TABLE 1 | Environmental and cultural characteristics of the Society Islands and the Gambier Islands (after Conte and Kirch, 2004; Kahn, 2018, in press).

Archipelago	Size (km^2)	Type	Max elevation (m)	Climate	Mean annual precipitation (mm)	Degree of isolation	Complexity	Comments
Society Islands	1590	Volcanic	2,241	Tropical	1,820–4,500	Low	Complex	Dynamic shorelines; highest level of social complexity; integrated complex chiefdoms
Gambier Islands	31	Volcanic	441	Tropical (cooler than Societies)	1,400–1,900	High	Open	Older islands, massive lagoon; moderate level of social complexity

As seen in **Table 1**, the geologically young high island archipelago of the Society Islands benefits from higher elevations that generate orographically induced rainfall. Their low degree of isolation provided colonizing communities with relatively high biodiversity of terrestrial and marine flora and fauna. It likewise situated Māʻohi communities to exploit nearby islands, islets, and atolls in sometimes an extractive fashion (as with the uninhabited Fenuaʻura Islands) and sometimes as mutually beneficial exchange (as with Mehetia and the western Tuamotus) (see **Figure 2**; Hermann et al., 2019; Molle et al., 2019; Kahn, 2020). In contrast, the more isolated Gambiers, situated in a cooler tropical climate, suffered from lower biodiversity in terms of plants and animals as well as from having lower annual rainfall. When coupled with their higher degree of isolation, such physical characteristics likely constrained social efforts of Gambier's pre-contact communities to buffer environmental shifts, whether natural or the result of anthropogenic causes.

Culturally, all Eastern Polynesian societies can be considered one phylogenetic unit, as each derives from the same set of ancestral cultures found in the Western Polynesian homeland (Kirch and Green, 2001). However, once each island or archipelago was colonized, new settlers adapted to local environments and resource bases, effectively leading to changes in material culture, subsistence intensification, hierarchy, and social relations (Kirch, 1984; Kahn, 2018). At first contact in the late eighteenth century, Eastern Polynesia exhibited a diversity of social-environmental systems. These ranged from hierarchically structured polities in the Society Islands with high population densities and intensive agricultural landscapes, to islands such as the Gambiers, which lacked centralized political authority and whose terrestrial landscapes were markedly degraded (Sahlins, 1958; Goldman, 1970; Kirch, 1984; Conte and Kirch, 2004, p. 21–22; Kahn, in press). In terms of cultural evolution, Sahlins (1958) was the first to suggest a correlation between resource availability, degree of social complexity, and instability of climate/natural resources in Eastern Polynesia (see also Kirch, 1984). We explore these variables with relation to the Society Islands and the Gambier Islands to examine the degree to which differing island size, slope, precipitation, and soil pH affected islander's abilities to manufacture large ocean-going canoes. Finally, we explore to what extent isolation derived from the lack of ocean-going canoes, and hence intra-archipelago interaction, constrained some Polynesian communities' choices vis-à-vis long-term sociopolitical resilience.

MATERIALS AND METHODS

Textual Sources

As we argue, the dearth of direct archaeological evidence for canoe technologies has contributed to an under-representation of the processes surrounding the manufacture and voyaging of canoes and their impact on the structure of Eastern Polynesian settlement patterns, social hierarchies, and economic interactions

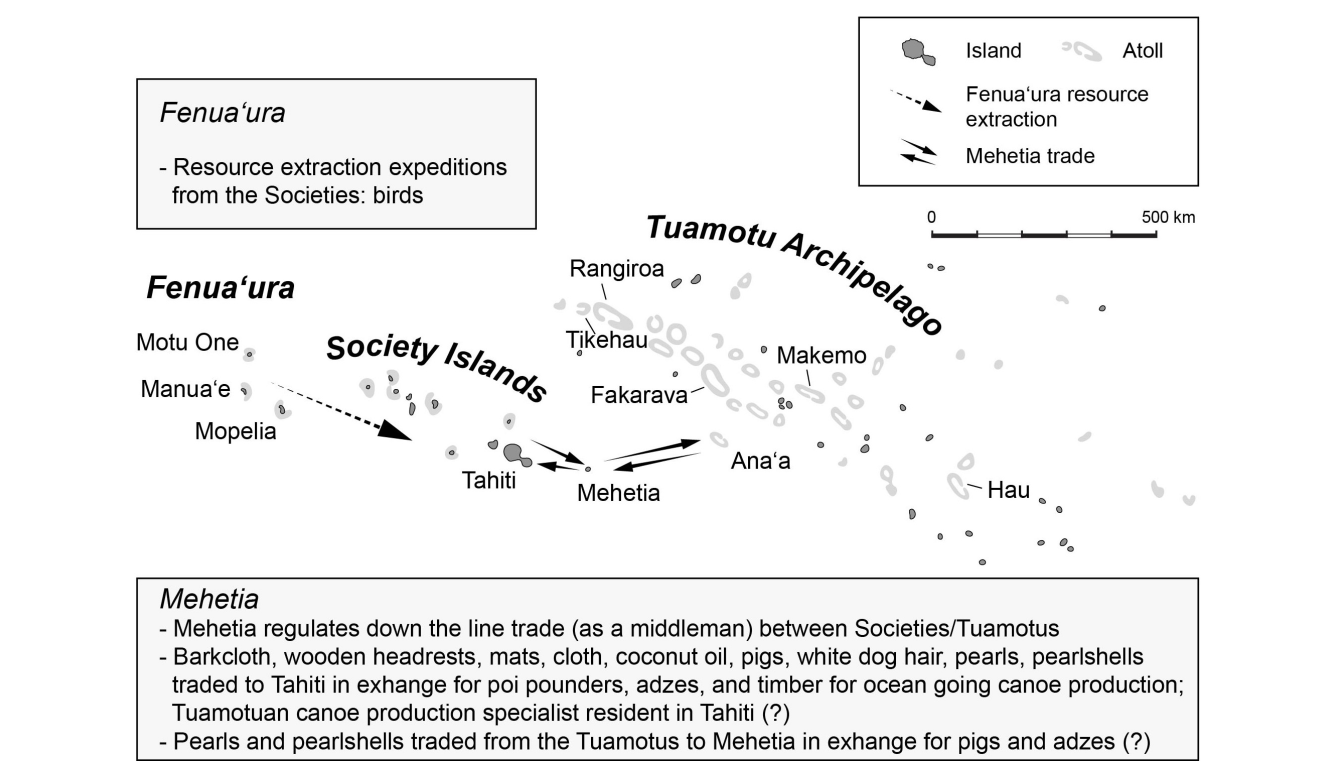

FIGURE 2 | Visual map of the Society Islands as the principal agent in Fenua-Ura resource extraction and as a key node in the Society Island-Mehetia-Tuamotu. Phrases followed by (?) denote possible interpretations that we have less solid foundation for regional interaction sphere.

as well as intra-archipelago interactions involving the exchange of material goods and ideas. Thus, understanding canoe cultures in Eastern Polynesia, as well as which societies lacked large ocean-going canoes at contact, requires the use of proxy data. Following this, we gathered data concerning pre-contact Eastern Polynesian canoe manufacture, use, and re-use from 43 published textual sources ranging from botanical articles/books; archaeological, anthropological, and linguistic works; traditional myths and oral traditions; and European explorer, missionary, and later historic accounts.

Presence and Absence of Ocean-Going Canoes at Contact

Several scholars have identified historical references to Eastern Polynesian societies at European contact who lacked ocean-going canoes (Mulloy, 1975; Weisler, 1994; Rolett, 2002); generally, this is seen as the de-evolution of more formally complex canoe technologies, although alternative views do exist (Anderson, 2008, 2017). We gathered data about the presence and absence of Ocean-going canoes in Eastern Polynesian societies at the time of European contact from both primary (European explorers and missionaries, early Tahitian dictionary) and secondary sources (later published syntheses). Generally, ocean-going canoes are defined as large double-hulled canoes used outside the lagoon, in contrast to smaller single-hulled canoes with or without outriggers used inside the lagoon (Finney, 2006, p. 113).

Human-Centered Interaction Network and Human-Centered Canoe Web

As part of the ArchaeoEcology Project[1], we developed a use web coding uses of all plants and animals recovered in Society Island archaeological sites. For each taxon present in archaeological sites, we recorded use data as reported in textual sources (European explorer texts, later historic accounts, ethnographies, botanical and ethnobotanical sources and surveys; the Tahitian dictionary, oral traditions, and genealogies). Our objective was to understand "human-centered interaction networks" (HCIN), including how relationships between pre-contact Māʻohi communities and island flora and fauna were organized, what these relationships can tell us about diachronic shifts in human-environmental interactions, and how such network approaches can identify changes in socio-economic systems (see Verhagen et al., 2021, p. 2). From our larger HCIN database, we developed a human-centered canoe-web database, intending to define the number of steps in the life cycles of canoes; which animals, plants, and tools were used in such steps; and which social personae were involved in each step.

Social Personae

We define social personae as social roles that are present in specific interactions in a society and which are recognized by other members of the social group as responsibilities of that individual. Broadly within Eastern Polynesia, social personae might include chiefs, commoners, and occupational specialists; the latter can be broken down into craft specialists (e.g., canoe manufacturer, adze manufacturer), other experts with specific knowledge (sea expert, navigator, expert fishermen), and ritual specialists (priests) (Kirch and Green, 2001, pp. 221–2279, Tables 8.7, 8.9; see Kahn, 2005 for the Society Islands, Taomia, 2000 for the Cook Islands). Social personae mentioned specifically in terms of Society Island canoe manufacture and use included chiefs, *ahi-tu* (the assistants of a canoe builder, canoe builders for chiefs on temple grounds), and *tahuʻa tari vaʻa* and *tahuʻa tari pāhi* (specialized canoemakers). These Tahitian glosses are derived from the first Tahitian dictionary published in 1851 (Davies, 1991).

Life Cycles

We classified canoe life cycles according to four generalized categories: construction, launching, sailing, re-use. Construction was broken down into two sub-categories, extraction of raw materials used and processing of the raw materials used. Within each of these, we likewise coded for tools used (e.g., adze, auger, chisel, fire) and activity (hollowing out the hull, boring holes). The launching category was broken down into the physical act of launching and ceremonies surrounding this event. Sailing was coded along three sub-categories: navigation (otherwise known as wayfinding), sailing, and voyaging (the latter refers to open ocean voyaging). The re-use category recorded data related to secondary repurposing events. Importantly, ritual activities were coded as sub-categories of each of the four life-cycles whenever ceremonial activities were deemed present, such as rubbing rigging cords on the stones of temples to determine the fate of the canoe before launching.

For each life-cycle category, we recorded which tools or items were used for which specific activity within each life-cycle, such as a wind compass used to determine the direction of the prevailing winds or an amulet offered to the sea gods upon safe arrival back to shore. Wherever possible we recorded the specific nature and names of social personae involved in life cycle events and ritual activities, as with *ahi-tu*, the builders of sacred canoes who lived consecrated lives and who would not cut their hair until a canoe was complete. We likewise recorded the specific places where events in the life-cycle took place (e.g., special huts near temples where the canoe was constructed).

Species Used

Based on work developing our HCIN database (Kahn et al., forthcoming), we reduced the ocean-going canoe body element category (associated with the hull elements) to two species: *Calophyllum inophyllum* (glossed in Tahitian as *Tamanu*) and *Neonauclea forsteri* (*Mara*); these species have known historic preference for use in double-hulled canoe manufacture in the Society Islands, Mangareva, or both. We recorded use across 12 categories: food, structural, ritual, health, clothing, fuel, housing, ornamental, artifact, companions, cosmology, and trade (for category definitions see **Supplementary Table 1**).

[1] http://www.archsynth.org/the-archaeoecology-project.html (accessed 7/15/2021)

For our canoe database (available online, see Kahn and Escue, 2021), we captured which particular plant and animal taxa were used across five categories: structure, purpose, vessel, maintenance, and use. Here, the structure category is defined as species used to create the original canoe structure excluding removable parts like paddles, sails, and masts. It has five sub-fields, including ornamentation, processing, body elements, extraction, and general, with sub-categories including tools and ritual. Ornamentation refers generally to aesthetic, social, or spiritual elements of the canoe, like carved figureheads or shell inlays or other sorts of decoration of the hull, rather than functional elements of the canoe, such as the shape of the mast or the hull (see Rogers and Ehrlich, 2008). The purpose category relates to particular use-events recorded around canoes, with the five-sub-fields of trade (use of canoes to transport trade items or to transport people with items to trade), hunting/fishing, ritual, cosmology, and navigation. Hunting of marine mammals like dolphins and whales is differentiated from fishing which includes capture of fish or shellfish. Ritual relates to generalized ceremonial activities, while cosmology relates specifically to beliefs or activities related to origin myths and world-views. Navigation relates to any practice linked with wayfinding. Sub-categories of the purpose category include vessel (items related to the physical canoe), equipment (auxiliary items not part of the actual canoe like masts, paddles), sacrificial (transportation of items like human bodies, pigs), and general (unspecified use).

The vessel category relates to specific mention of canoe type, whether single-hulled, double-hulled, or general (type unspecified). The double-hulled category has three sub-fields, canoes for use in war, those for use in voyaging, and those for use in ritual. The maintenance category relates to post-manufacture refabrication practices, with sub-categories of repair (practices to prolong use), recycling (practices to refabricate materials for other use), ritual (a species used for ritual to repair a canoe, but these were lacking in our study), and general (maintenance activity unspecified). The use elements category relates to the raw materials used for specific canoe elements, with the sub-categories of sail, mast, paddles, and general (unspecified). Wherever possible, use data was reported at the species level, yet some entries only provided data to the genus level.

Social Network Modeling

We generated a useweb model of the canoe production system by subsetting the larger HCIN dataset described in the previous section. Our first subset limited the species for construction to those categorized as used in constructing double-hulled canoes, namely *Tamanu* and *Mara*. We then converted this dataset into nodes (species, objects, personae, and events, $n = 105$) and links (processes, $n = 1{,}493$) to generate a human-centered interaction network model; as part of our supplementary data we include the R code file and the Excel data file so users can examine the canoe networks reported herein (see **Supplementary Tables 2**, **3**). The nodes were further classified as ornamentation, construction, general, body elements, launching, sailing, and ritual, and the links were classified as extraction, processing, construction, and ritual. We used these data to generate an igraph in R Studio 3.6.3. We then quantified this network model by summarizing the number of links per node using the degree function, which results in a list of centralization scores.

Archaeological Data

We coded data from textual sources whenever physical materials recovered in archaeological sites or housed in museums mentioned particular plant and animal taxa used in constructing canoe types (vessel, single-hulled, double-hulled), canoe elements (sail, mast, paddles, and general), or mentioned particular plant and animal taxa used to fabricate tools used in canoe manufacture, use, maintenance, and recycling events. The transportation of stone architectural elements and tools, particularly adzes, away from islands serving as their source of origin likewise provides indirect proxy data for intra-island, inter-island, and intra-archipelago voyaging; the latter two in many, if not most cases, required large ocean-going canoes.

Ecology and Landscape Data and Habitat Modeling

To test how island settlement densities, agricultural development, and demographic processes would impact access to species used in canoe hull manufacture, we generated habitat suitability maps in ArcMap 10.4 for the island of Moʻorea. Moʻorea was chosen as a test case, as it has a relatively rich biota (300 native and endemic taxa) and has high-resolution settlement data, particularly from the ʻOpunohu Valley.

Our first habitat model focuses on settlement densities by elevation. Knowledge of site densities across the island were gathered from published and unpublished sources[2], with modern data on 53 archaeological sites, a high concentration of which derive from the ʻOpunohu valley ($n = 41$). These data derive from 10 archaeological survey and excavation projects directed by Kahn over the last two decades. Such data were used to generate three zones of site density: high, moderate, and low. We must note that the low site density category often occurs in high altitude contexts, many of which, but not all, have very rare instances of known archaeological sites.

Our second and third habitat models illustrate erosional data and elevational limits of species known to have been used in constructing the hulls of double-hulled canoes, *Tamanu* and *Mara*. The depth of erosional deposits were derived from all known excavated archaeological contexts with available data (Green et al., 1967; Lepofsky, 1994; Kahn, 2005, 2010, 2012; Kahn and Kirch, 2011, 2014; Kahn et al., 2015). We theorized that soil erosion from the interior onto the coastal plain, which appears to have generally ceased around 1250–1400 CE (Lepofsky and Kahn, 2011; Kahn et al., 2015), impacted the regrowth potential of large, slow-growing, hardwood trees preferred for ocean-going *vaʻa* hulls. *Tamanu* and *Mara* have specific elevational limits (425 and 1,000 m, respectively) and require specific growing conditions like pH and soil type (4.0–7.4 pH respectively, in sandy well-draining soils for *Tamanu* and hydrophilic forests with well-draining soils for *Mara*). At the outer limits of these boundaries, trees may be viable, but growth potential may be impacted, resulting in smaller stature trees. To map these constraints, we

[2]Kahn, J. G. (unpublished data). *Mo'orea Field Notebooks, 1999–2017*.

used the Raster Calculation tool to produce overlays for *Tamanu* and *Mara* limits by elevation. We traced the erosion values based on the data derived from the excavation units.

RESULTS

The methods that we use can be replicated easily and extrapolated to other regions. In **Supplementary Table 1** we include our code and network analysis datasets, while in Kahn and Escue (2021) we publish the canoe dataset used in this publication. While our methods could be used with our data to replicate our findings, more importantly, our methods are open access and can be used to understand other regions where habitat growth could have negative impacts on critical species.

Our model results suggest that there were varying abilities to regrow large trees required for double-hulled ocean-going canoes. Erosion would have been a primary concern for Polynesians, potentially creating a snowball effect that would be difficult to ameliorate. Removing large trees for ocean-going canoes would decrease the resilience of the soil, and only through reforestation—a long and lengthy process—could Polynesians regrow the essential resources. As our models show, pH changes in areas of deforestation suggest that some islands would have a difficult time rebounding to early conditions.

Our use web models suggest the critical nature of many organic materials for the function of Polynesian societies. As availability of these resources became strained, Eastern Polynesians would have needed to rely on their larger networks, if they could.

Use Webs and Human-Centered Interaction Networks: How Do Social Processes Constrain Canoe Manufacture and Use?

General Use Categories

In considering the greater impacts of tree availability, it is key to understand the range of uses for large tree taxa like *Tamanu* and *Mara*, as canoe manufacture is likely not their only realm of human use. Our HCIN databases documented the number of concurrent uses reported for these taxa in the Society Islands and Mangareva. Both trees and their elements are highly used in the Societies. Seven to eight uses are reported, with *Tamanu* used for artifact, cosmology, food, fuel, health, structural, and transportation and *Mara* used quite similarly for artifact, cosmology, health, ornamental, structural, trade, and transportation. In Mangareva, *Tamanu* is also highly used[3], having four use categories (fuel, housing, artifact, transportation), while *Mara* is absent from the archipelagoes' native flora. Mangareva shares 75% of *Tamanu* use categories with the Societies, yet lacks *Mara*.

In terms of the ability to resource switch, Mangareva's more depauperate flora reduced access to the species for large canoe building. In the Societies, the use of parts of the living tree of *Tamanu* for food and medicine may have put additional constraints on the availability of parts of this tree, but likely would not have affected the actual size of the trunk. The Māʻohi also had the benefit of being able to resource switch to use *Mara* in canoe construction if *Tamanu* became scarce or smaller in size due to over-harvesting or erosion. Because of this, *Tamanu's* concurrent uses in Mangareva likely created heavier constraints on long-term harvesting potential there than in the Societies. This is especially true given that *Tamanu's* 7–8 year growth cycle, which may have led to harvesting trunks before their full size and thus impeding the construction of large ocean-going hulls.

Canoe Use Categories and Complex Life Cycles

In our canoe use network, we had a total of 1,385 links relating to activities occurring during canoe life cycles. In terms of life cycles, the construction category had the most links (n = 722, 53%), while sailing had the least (n = 59, 4%). The presence of a four-part use-life to large double-hulled canoes signals complex stages of construction, from felling the tree, hollowing out the hull, smoothing the side planks, ritualized movement of the canoe to the water and ceremonies involved in first launching and sailing of the canoe, in addition to ritualized re-use episodes. For example, the fact that old canoe parts were placed on altars before launching new canoes and were used to create sacred fires at temple sites illustrates how in all their four life stages, canoes and their constituent material parts were considered sacred.

In terms of the structure category, or species used to create the original canoe structure excluding removable parts like paddles, sails, and masts, the node with the highest number of links is *Mara* (n = 84). *Tamanu* has the second highest number of links along with clothing worn by canoe building specialists (n = 72). That *Tamanu* and *Mara* are among the nodes with the most links in the entire network shows their integral use in constructing diverse aspects of the main hull and canoe structure. That canoes were multi-component technologies is clearly illustrated in the presence of 16 named body elements, ranging from the projecting bow, the hull, the side board, the outrigger, and the pegs on the outrigger, etc.

In the processing sub-category of construction, coral (n = 55) and stingray (n = 48) were the nodes with the highest number of use links, illustrating the importance of tools made from these raw materials in the processing of canoe parts. Such tools were likely used to polish and burnish canoe surfaces in preparation for other ornamental treatments. Tool use across all four use-life categories (construction, launching, sailing, re-use) involved 25 items, ranging from simple tools like coral rasps and whetstones (the latter were used to sharpen stone adzes), to complex multi-component tools, like paint comprised of numerous elements, or sennit cord (twined and braided organic cordage used as rigging), which itself had several stages in its time-consuming manufacture. Because some of the materials used in canoe construction and use themselves

[3]Mangarevan flora, in general, have lower use rates than in the Societies. The highest use rate for Mangarevan plants is across six categories, whereas in the Societies it is across 11 categories. Thus, while seven to eight use categories in the Societies is substantial, four use categories in Mangareva is comparatively substantial.

had time-consuming production rates, we can view the staged construction of large-ocean growing canoes as substantial, both in terms of the raw materials needed and the time need to process them.

In the ornamentation sub-category of canoe structure, the nodes with the highest number of use links include candlenut (*Aleurites moluccana*) and *Chamaecyse celastroides* (a flowering shrub) (n = 20). Candlenut ornamental use included extraction of liquid from its inner bark to color cloth and mats and for use as an element in canoe paint (Butaud, 297; Medeiros et al., n.d.). *Chamaecyse celastroides* was also used as an ingredient in canoe paint (Medeiros et al., n.d.). Forms of ornamentation were found across the first three of the four use-life categories (construction, launching, sailing), ranging from painting the canoe hull black, hanging white tapa cloth on canoes carrying sacrifices, placing small wooden figures representing the gods in canoe sterns, and placing ornate sculptures on canoes prows as figureheads. These data highlight how canoes were more than just functional tools to transport people and things, as they were used in vibrant social displays in varied social contexts (warfare, canoe/visiting elites' arrival ceremonies, presentation of tribute, etc.).

Ritual activities are well-represented (n = 17) across the four stages of the canoe life cycle, demonstrating the ceremonial importance of all steps in canoe production. It is then no surprise that in the ritual sub-grouping of each life-cycle, feasting (n = 65) and sleeping rituals for stone adzes used in canoe construction (*ha'amoe ra'a to'i*) (n = 53) have the highest number of use links. Such high linkage in the network for different types of rituals supports how canoe production was performed under highly circumscribed ritual practices. Importantly, ritualized production occurred from the outset of construction. Stone adzes used to fell the tree trunk cut for the hull and later used in hull carving were "put to sleep" at night (*ha'amoe ra'a to'i*) in temple walls by canoe specialists. Priests decided which tree to fell in the forest and recited prayers during tree felling. The launching life-cycle category, referring to ceremonies surrounding use and first use of the canoe, is particularly replete with rituals, like rubbing sennit cord on the stones of temples to determine the fate of the canoe before launching, using feathers to invoke spirits and as presentation to the gods at launching feasts, and *fa'ainuraa i te va'a*, making the canoe drink to consecrate the boat. Furthermore, in the sailing group, amulets (n = 13), and drums (n = 14), items used in ceremonies performed to ensure successful voyages or successful acts of war, are the nodes with the highest number of links.

That in the launching category, pig (*Sus scrofa*) (n = 19), feathers (n = 19), and offerings (n = 19) are the nodes having the highest number of links is telling. These data not only illustrate the importance of canoes in transporting high prestige items as tribute to Māʻohi socio-ritual elites, but the significant use of highly valued prestige items as offerings made to the gods during the ritual life-cycles of canoes. Pigs and red feathers were among the most highly prized goods in elite Māʻohi society. Of Māʻohi staple goods, pigs were the most highly valued prestige items, figuring prominently in sociopolitical and ritual life. They served as frequent items of gift exchange and intra-island exchange (Kahn, in press). Feathers were raw materials integral to items of wealth finance, like the *to'o*, or feathered god figures. In the pre-contact Society Islands, feathers (black, yellow, and especially red) and feathered objects were not just highly valued objects, but were symbols of power, fecundity, and the divine (Kahn, in press). Pigs and red feathers were also ritual symbols associated with the 'Oro state religion and the *'arioi* cult, members of which were frequent passengers in double-hulled canoes voyaging between islands in the archipelago. Here again we see how ritual, ideology, and sacred power were bundled together with the symbolic and economic uses of ocean-going canoes. This is underscored by results from the social personae category, where the *ahitu* node, canoe builders for chiefs on temple grounds, has 75 links, and the *tahu'a tarai va'a* node, specialist canoe builders, likewise has a high number of links (n = 72). Highly ritually prescribed stages of craft production are more likely to be carried out by highly skilled and highly specialized craft specialists than more mundane tasks.

Our network visualization (**Figure 3**) shows the links between the three dominant life stages (construction, launching, sailing), and sub-categories therein (structure-body elements, ornamentation, processing), as well as all links related to ritual. We split out activities related to chiefs vs. activities related to other social personae (specialist canoe builders). There are several pertinent points to highlight. First, processing shares many taxa with construction, suggesting that this life-stage may be better conceived of as a sub-set of a more generalized construction life cycle. Second, ritual forms important nodes in all three life stages. As an example, the amulet links the ritual and launching group to the sailing group. Third, specialized canoe builders (depicted in white as personae) play a significant role in the first three life stages of the canoe, as they form nodes linking construction, launching, sailing, and ritual events. Finally, chiefs (represented by red) serve as an important node with 37 links, connecting launching and ritual to construction, as well as the sets of tools used in the construction of the hulls. Other patterns that can be observed include two clusters of construction suggestive of potential sub-categories to this life cycle and some partitioning of ornamentation events

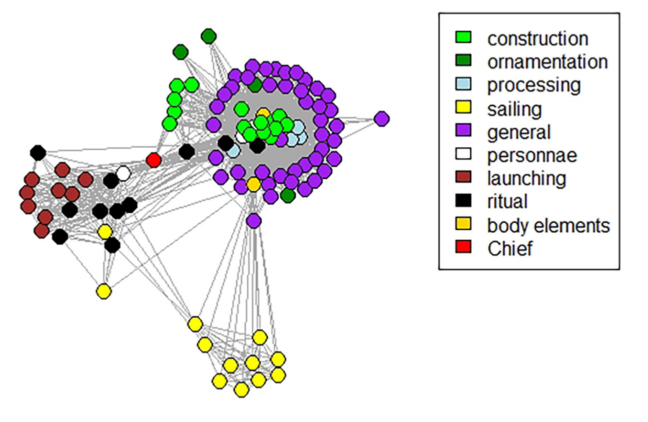

FIGURE 3 | Network visualization for the canoe use web.

that might suggest that canoe ornamentation perhaps was carried out by different craft specialists than hull construction, although these secondary patterns are more speculative and need further testing.

DISCUSSION

Ethnohistoric and Linguistic Data and Eastern Polynesian Canoes

Polynesian historical linguistics studies have clearly reconstructed a Proto-Polynesian term for double-hulled canoe, in addition to terms for large ocean-going sailing canoes, smaller single outrigger canoes, and dugout canoes (see Kirch and Green, 2001, pp. 197–198, Table 7.8). By the time of European contact, several European Explorers noted how some Eastern Polynesian islands and archipelagoes, such as Easter Island, the Gambier Islands, and some of the Tuamotu Islands, lacked large ocean-going canoes, relying instead on single-hulled canoes or other types of water craft for near shore travel and fishing (**Supplementary Table 4**). The Gambiers represent an extreme example, as at the time of contact, rafts fashioned from tree bark twines lashed together were the only style of watercraft seen. Similarly, Easter Island lacked true ocean-going canoes, as Europeans described only small single-hulled canoes that heavily leaked (Roggeveen, 1908, p. 19; Haddon and Hornell, 1936, pp. 96–97).

Some shifts in Eastern Polynesian canoe design likely represented adaptions to long-term isolation post-colonization. In New Zealand, watercraft shifted from double-hulled colonization canoes to single-hulled canoes and war canoes (*waka taua)* better adapted to intra-island voyaging and marine combat (Irwin et al., 2017, p. 32). As Irwin et al. (2017, p. 32) argue, Māori canoe technology adapted to "the changing cultural and geographical context of communications." Others have argued that a reduction in Māori voyaging in the pre-contact era derived from local conditions (unpredictable winds) and a large landmass that dampened demographic pressures to out-migrate (Biggs, 2006). There likely were varied reasons why Eastern Polynesian canoe societies modified the form and size of their watercraft after initial island colonization.

While there are suggestions that some shifts to smaller single-hull or plank canoes in Eastern Polynesian cultures may have been linked to social factors, other data indicate changing ecological conditions were a forcing factor. Indeed, Irwin and Flay (2015, p. 437–438) have argued that the adoption of "complex plank canoes with internal frames" served as an ecological adaptation on Polynesian islands lacking large trees. As **Supplementary Table 4** illustrates, there is a tendency for smaller islands and archipelagoes with low elevation and high isolation to have lacked double-hulled voyaging canoe manufacture and use at European contact. Several studies have linked this trend to higher levels of deforestation on smaller, low, and isolated islands (Weisler, 1994; Rolett, 2002; Diamond, 2014), while others have noted that some islands, like Easter Island, likely never had high numbers of large trees needed to build ocean-going canoes (Finney, 1993). As Rolett (2002) rightly highlights, deforestation as a limiting factor would have intensified through time, yet so too would have socio-political factors, like human population pressure supporting out-migration, expansionist chiefs requiring double-hulled war canoes for military campaigns, or atoll communities needing to maintain links to neighboring high islands. So what, we might ask, were the primary reasons for the loss of double-hulled canoes in some Eastern Polynesian societies? Namely, did social hierarchies (i.e., powerful chiefs) promulgate their continued production or use? Or did certain ecological contexts permit their continued production or use? Or is the answer somewhere in between?

Archaeological Data and Eastern Polynesian Canoes

The wet, tropical environments of Eastern Polynesia create challenging conditions for the preservation of the organic materials used in canoe production. Yet Sinoto's excavations at the waterlogged Vaitoʻotia and Faʻahia sites on Huahine (Society Islands) yielded exceptionally well-preserved wooden artifacts he interpreted as canoes parts and canoe accessories like paddles and bailers (Sinoto and McCoy, 1975; Sinoto and Han, 1985; Sinoto, 1988)[4]. At Faʻahia, Sinoto argued that two long wooden objects of similar length (c. 7 m) and shape were platform planks from a double-hulled canoe measuring c. 26 m in length (Sinoto, 1979, p. 13, Figure 1). Anderson et al.'s (2019, pp. 6–7) re-excavation of Faʻahia cast some doubt on this interpretation, noting that the two planks lack many features commonly found in hull pieces of large canoes, notably curvature, ribs, or lashing holes associated with fitted ribs. While Anderson et al. (2019) concur that some canoe construction likely took place at the site, they reason that whether the recovered canoe pieces belonged to a single, large, ocean-going canoe cannot be established given the lack of published stratigraphic details for the finds and the lack of direct chronometric dating.

At Anaweka Bay on the South Island of New Zealand, a large section of a complex composite canoe was discovered and radiocarbon dated to c. A.D. 1400 (Johns et al., 2014). The recovered section represents part of a hull measuring 6.08 m long and carved from a single timber. Given the vessels' hull form, size (thought to be at a minimum 12 m long), and sophistication, Johns et al. (2014, p. 14729) interpreted the Anaweka vessel as most likely part of a double-hulled ocean-going sailing canoe. The presence of a carved sea turtle motif on the outer portion of the canoe's hull supports our earlier assessment that Eastern Polynesian canoes often had

[4]Anderson et al. (2019) have recently argued that Sinoto's purported remains of a large ocean-going canoe were, in fact, pieces that could date to different time periods or could represent parts of different canoes. Based on form, they argue Sinoto's probable canoe planks likely had other functions and perhaps derived from domestic or ritual structures. They likewise argue that Sinoto's purported canoe mast may represent a piece of unmodified driftwood, examples of which were common across the site. Based on their reading, Anderson et al. (2019) argue that the construction of canoe parts may have taken place on the site but that there is no definitive evidence for the recovery of a large ocean-going canoe.

symbolic association. Despite several finds of other canoe pieces in New Zealand, the Anaweka find represented the only example of a "truly-ocean going canoe" (Irwin et al., 2017, p. 42). While few archaeological traces of Eastern Polynesian voyaging canoes have been recovered, current finds suggests the presence of moderate-sized voyaging canoes similar to Māʻohi *tipaerua*.

Society Islands Case Study: High Island Archipelago With Complex Chiefdoms

Since the Society Islands have some of the richest ethnohistoric references to double-hulled canoes at the time of European contact, it provides an excellent in-depth case study of a highly complex chiefdom retaining such vessels. The Māʻohi voyaged in specialized sea-going vessels termed *pāhi*. These vessels were differentiated in size and form from single-hulled canoes (*vaʻa, pu hoʻe*) used for everyday fishing and local travel by commoners (Corney, 1913/1914/1918 (I), p. 334; Guiot, 2001, p. 4). *Pāhi* were immense double-hulled canoes (up to 30+ m) with double masts and composite plank keels who carried small shelters on their platforms (Forster, 1778, pp. 459–460; Cook, 1893, p. 98; Banks, 1896, pp. 115–116, 159; Oliver, 1974, pp. 195–196, 173; Corney, 1913/1914/1918 (I), p. 358; (II), p. 82). Other moderately sized craft (20–26 m) termed *tipaerua* were also used by the Māʻohi in open sea voyaging.

Māʻohi war canoes were large (up to 32 m+) double-hulled vessels with up curved sterns (see **Figure 4**; Oliver, 1974, pp. 400–401). On their fore part, a fighting stage was installed. On Cook's second voyage, George Forster and Sparrman viewed a large double-hulled war canoe under construction. This vessel was 27 m long, with room for 144 paddlers to sit on the beams and 8–10 steersmen (Salmond, 2009; Thomas et al., 2016). Its fighting stage was 7 m × 3 m; the edges of this stage as well as the prow and stern were intricately carved with anthropomorphic figures. Europeans commented on how the manufacture of canoes cost communities "infinite labor," no doubt why their access and storage were highly controlled. Communities must have invested great time and effort to produce chiefs' war fleets. While ethnohistoric sources at times conflate *pāhi* with large war canoes, it seems as if all moderately large (6–9 m) to large (>9–30 m) double-hulled canoes were valuable chiefly prestige items chiefs (Ellis, 1829(I), p. 170).

Varied historic sources document how Māʻohi high chiefs (*ariʻi nui, ariʻi rahi*) controlled the production of long-distance canoes and war canoes. *Pāhi* manufacture was considered a "public work" carried out by specialized canoe makers under the control of high chiefs and financed through corvée labor, tribute, and other means (Ellis, 1829(I), p. 175; Henry, 1928, pp. 180–182; Morrison, 1935, pp. 165, 205–206; see Guiot, 2006). High chiefs likewise underwrote the construction of war canoes. Priests would inform the chiefs of the god's request for canoes; chiefs subsequently extracted tribute from the greater community to hold a series of feasts, to gather foodstuffs to support the ritual and craft specialists during the period of canoe manufacture, and to procure a human sacrifice for the launching event (Morrison, 1935, pp. 205–206).

Multiple lines of evidence speak to the highly ritualized nature of Māʻohi ocean-going canoes, both in terms of their manufacture and use. *Pāhi* and war canoes were manufactured on temple grounds or near the coast in specialized structures under formalized rules of ritualized production (Wilson, 1799, pp. 190, 377; Henry, 1928, pp. 146–147, 180–182; Orliac, 1982, p. 99); when finished they were launched with elaborate rituals and feasting. Traditional Māʻohi chants and ethnohistoric texts frequently reference expert canoe makers. Henry (1928) proposes that there were two classes of canoe builders, those for the general public (*tahuʻa papai vaʻa*, *tahuʻa tarai vaʻa*) and those who worked for the chiefs building sacred canoes on temple grounds (*ahi-tu*). Specialist canoe-builders had their own temples or shrines in which they made offerings and prayers to their patron deities (Henry, 1928, pp. 146–148). High chiefs' royal compounds, associated with national *marae* (temples) and formal meeting places and assembly grounds (*tahua*), also housed *fare vaʻa*, storage structures for the immense double-hulled royal canoes used to travel between the islands (Corney, 1913/1914/1918(I), pp. 334, 336, 1915(II), p. 56; Orliac, 2000). Like royal insignia such as feathered girdles, that *pāhi* and war canoes were manufactured under prescribed rules indicates their role as highly valued wealth items, similar to war canoes (Henry, 1928, p. 189). That high-ranking chiefs could demand canoes as a form of tribute, particularly as a preparation for war (Oliver, 1974, pp. 998–999), reflects some direct control over the political economy.

Why were large ocean-going canoes and war canoes so highly valued in Māʻohi society? Such canoes were instrumental in facilitating island-to-island exchange within the archipelago. They were likewise critical for ocean-going voyages of inter-archipelago exchange between the Society Islands and their far hinterland neighbors, the Tuamotu atolls, similar to practices seen in the Western Pacific (the *sawei* system in Micronesia, see Hunter-Anderson and Zan, 1996). They also made possible resource extraction trips to the Society Island's near hinterlands, Fenua-Ura (**Figure 2**). So from a purely economic and mobility perspective, ocean-going canoes were key transport vessels.

Yet, if we broaden our perspective to include social processes, canoes served as key elements in this realm of life as well. In fact, access to large ocean-going canoes was instrumental in the expansion of the late pre-contact ʻOro war cult out of Raʻiātea and its spread to the rest of the islands in the archipelago, primarily through members of the *ʻarioi*, a high-status fertility cult linked to ʻOro worship. Grand groups of traveling *ʻarioi*, high priests, and chiefs, with canoes laden with material goods, play prominent mention in European Explorers' accounts (G. Forster in Salmond, 2009). When the ʻOro god figures traveled for ceremonies, these royal sacra were transported in their own canoe (*te vaʻa a roa i te mataʻi*, the long canoe in the wind), with a special chamber for the god house and bunches of red feathers and decorative wooden sculptures on the prow (Henry, 1928, pp. 136, 190). In Māʻohi oral traditions, famed canoes carrying male chiefs and high priests between islands were named and regaled, such as Manuatere, Tainui, and Te-apori. Such data support the functional import of long-distance voyaging canoes in pre-contact Māʻohi culture and their association with the movement of elites (largely male elites), and the adoption of the

FIGURE 4 | Engraving of large double-hulled canoes amassed on the coast of Tahiti waiting to launch and wage war on Moʻorea. "The Fleet of Otaheite assembled at Oparee," 1776. Artist William Hodges, courtesy of National Maritime Museum, Greenwich, London (BHC2395).

ʻOro war cult (Ellis, 1829 (I), pp. 168–170; Salmon, 1910; Henry, 1928, p. 459). Indeed, the advent of the ʻOro war cult likely spurred specialized production of *pāhi,* given that *ʻarioi* had to frequently travel from island to island during the ritual calendar. European explorers describe *ʻarioi* in flotillas of 60–70 canoes carrying some 700 persons; others suggest even higher numbers, with 150 boats carrying a group of 4,500–6,000 persons (Oliver, 1974, p. 918, f 25).

Large ocean-going canoes likewise played a key role in Māʻohi high chiefs' abilities to control the political economy. Large canoes commonly transported immense amounts of staple goods and prestige goods, moving such tribute from the populace to the chiefs during *rites de passage*, during the construction of specialized and monumental architecture, and during the ritual cycle. A case from Huahine describing a public work serves as an example:

> The people from different parts are assembling in our neighborhood in order to thatch the big house called Nanu which is built at great public expense. The people of both Huahines. . .brought their several divisions of thatch and also a great quantity of food for the Chiefs consisting of baked hogs, mahe, Yams, Taro, Cocoanuts, pia, plantains, Xc. There are in all about 120 Canoes come, each of which had with his division of food either a hog or baked fish, about 100 hogs of different sizes all baked were heaped up on the beach today with the baskets of Yams, Taro, Mahe & delivered up to the Chiefs with great ceremony (Davies, cited in Oliver, 1974, pp. 997–998).

The term *tavau* glosses a fleet of canoes bringing items to the principal chief in the form of tribute; such events moved substantial foodstuffs and wealth items such as red feathers, feathered breastplates, feathered headdresses, canoes, and large bundles of mats and barkcloth from commoner communities to ruling chiefs (Oliver, 1974, pp. 1003–1005). Annual *Pararaʻa Matahiti* ceremonies likewise involved the movement of people and things. Such ceremonies began with the arrival of *ʻarioi* cult members in district canoes with public offerings of staple goods (pigs, dogs, fish, breadfruit, bananas, mountain banana, fermented coconut sauce) and wealth finance objects (mats, canoes, *tapa*) to high ranking chiefs at national *marae* (Moerenhout, 1837(I), pp. 518–521; Oliver, 1974, pp. 260–261; Babadzan, 1993, p. 244). In this way, large ocean-going canoes facilitated the movement of elites and vast amounts of goods following the annual and ritual calendars, thereby forming key elements of elite power-building strategies (Kahn, in press). They likewise permitted exploitation of near hinterlands like Fenua-Ura for the extraction of bird feathers, some of which were used in elite regalia and costumes, in addition to facilitating the continuation of regional exchange networks between the Society Islands, Mehetia, and the Tuamotu Islands. Such regional exchange networks were key to Tuamotuan Islander efforts to buffer the negative impacts of living on resource poor atolls. Yet, this regional exchange network likewise filtered important resources into the Societies, such as Tuamotuan expert boatbuilder knowledge (Klem, 2017)[5] and white dog's hair used in fabricating *taumi*, the elite breastplates worn as a sign of upper-class male status.

It also seems clear that Māʻohi chiefly access to war canoe production and use consolidated their control over military campaigns. Oral traditions and historic accounts illustrate that at the time of European contact, the Society Islands were characterized by endemic and institutionalized warfare between independent chiefdoms or confederations thereof. In the Society Islands, naval battles were the dominant form of warfare prior to European contact (Moerenhout, 1837(II), p. 40). Such skirmishes involved large double-hulled war canoes manned by large numbers of paddlers and fighters in addition to battle shapers and exhorters (Morrison, 1935, p. 175; Moerenhout, 1837(II), p. 40,

[5]Klem (2017, pp. 4–5, 7–8) provides a discussion of ethnohistoric sources recounting how Tuamotuans were revered for their expertise in canoe building and may have had residence in the Society Islands as expert boat builders. Historic sources from which such descriptions derive all date to the post-contact period. Given historic sources document the presence of the Society-Mehetia-Tuamotua interaction sphere in the pre-contact era, there is some likelihood that expert Tuamotuan boat-builders resided in the Societies in pre-contact times.

see Oliver, 1974, pp. 401–405). Thus, we can view war canoes as key avenues by which Paramount chiefs amassed military might.

Warfare undoubtedly served numerous roles, here we want to emphasize its economic, political, and ideological impacts. Victors in war had access to the spoils of war and the ability to wreak havoc on their enemies' varied sources of power. Victors not only could seize land and other highly valued wealth items such as pigs, they could also take one's royal sacra (god idols, feathered loin cloths) by force. Long-lasting reduction of an opponent's economic power and ideological power could be had by burning agricultural fields and the pole and thatch structures on their ritual sites (Salmond, 2009). Thus, control over warfare *via* control over the manufacture and use of war canoes gave Māʻohi high chiefs access to widespread sources of power. Given that the ʻOro war cult of the mid-eighteenth century ushered in a period whereby the highest ranking socio-ritual elites actively and often effectively used coercive force as a means to grow and consolidate their sacred and secular sources of power, the key role of war canoes in late pre-contact Māʻohi society cannot be overstated.

Yet the symbolic association of the ʻOro war cult, high-status chiefs, and canoes likely had as great an import as the functional associations of ocean-going canoes with transport, tribute, and warfare. That large royal canoes in the Society Islands were named and had memories connected to them suggests they served as inalienable objects. That royal canoes and ʻOro canoes were decorated to be visually stunning and that their size required great labor investments indicates that such vessels served as highly visible symbols of elite wealth and sanctity. For example, like the ʻOro god figures, high status chiefs had "state canoes" called *anuanua*, glossed as the rainbow (Henry, 1928, p. 39; Handy, 1930, pp. 120, 190; see also Oliver, 1974, p. 787), reflecting the chiefs' close association with the gods who lived in the skies. Given their symbolic power, it is thus unsurprising that many steps in the manufacture of royal or ʻOro state canoes were highly ritualized (Henry, 1928, p. 119).

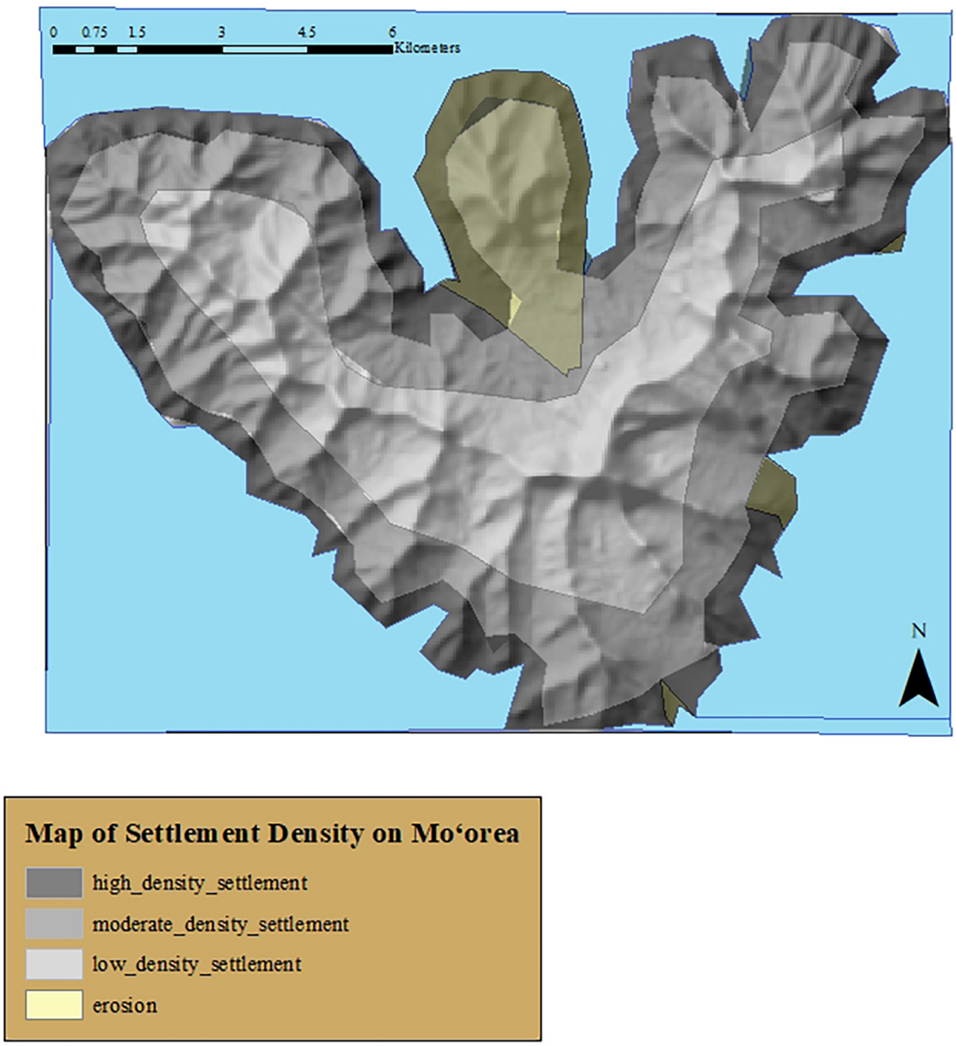

FIGURE 5 | Visualization of archaeological site densities and elevation for the Island of Moʻorea.

In sum, ethnohistoric and linguistic data demonstrate how the Society Islands, like other societies of Eastern Polynesia, used canoes as powerful metaphors for daily social relations, ritual practices, and cosmological worldviews. Equally important, the manufacture and use of large double-hulled canoes in many archipelagoes indexed clear socio-economic boundaries related to social hierarchy (chief vs. commoner), gender (male vs. female), and occupational specialization (fisher/farmer vs. craft specialists, specialized fisherman, priests, *ʻarioi*, warriors, etc.). In the most complex of Eastern Polynesian chiefdoms, such as the Society Islands, and archaic states, such as the Hawaiian Islands, large double-hulled canoes were prestige items expressly under the control of Paramount chiefs and Divine kings, used for both intra-archipelago elite travel and for military campaigns. Such data speaks to large ocean-going canoes having multi-faceted importance and to their role as highly valued prestige goods. Now we must turn to other proxy data concerning factors limiting the availability of large timber for large double-hulled canoe construction.

Settlement Pattern Densities, Landscape Elevation, Erosion, and Local Ecologies as Constraining Factors

As previously discussed, in Eastern Polynesia timber accessibility is key to canoe form, as the size of a canoe is based on the availability of large trees. This is all the more important when constructing a double-hulled canoe, as vessels for ocean-going voyaging were large in size. Given that certain islands and archipelagoes only had a few key tree species conducive to the manufacture of large double-hulled canoes, we can query to what extent island ecology and habitat, in addition to localized settlement patterns and settlement densities, put constraints on the production of ocean-going canoes.

Figure 5 provides a visualization of Moʻorea pre-contact settlement densities as mapped onto island elevation. Three categories are represented. High settlement density extends from c. 2 msl from the coast to lower to mid-valley reaches c. 100 msl. Moderately high settlement densities are found in the upper slopes of interior valleys c. 101–200 msl, where slope tends to be more severe and where land has to be more highly terraformed for ritual, residential, or agricultural use. Finally, the highest portions of the upper valley (c. 201–300 msl) have the lowest settlement densities, yet sometimes ritual mortuary, agricultural, and fortified sites are found in these upper elevations and rarely at even higher elevations (Kahn, 2005). If we assume that the Gambiers and the Societies had similar pre-contact settlement densities, the fact that Mangareva, the most elevated island in the Gambiers at 441 m, is one-quarter the height of Moʻorea is significant. As human populations increased on Mangareva, they had less vertical room to expand. This likely led to a situation where upper valley reaches in the Gambiers were more heavily settled and cultivated than those in the Societies.

Figures 6A,B visually model the ecological range of *Tamanu* and *Mara*, slow-growing hardwood trees used by the Māʻohi to fashion large double-hulled canoes. It also depicts areas on Moʻorea island with high erosion, as derived from data reported in excavated archaeological sites. In some locations, excavations revealed significant volumes of colluvium overlaying prior living surfaces (ranging from 0.03 m in the upper limits of the ʻOpunohu valley to 2.75 m in the bottom-most slopes

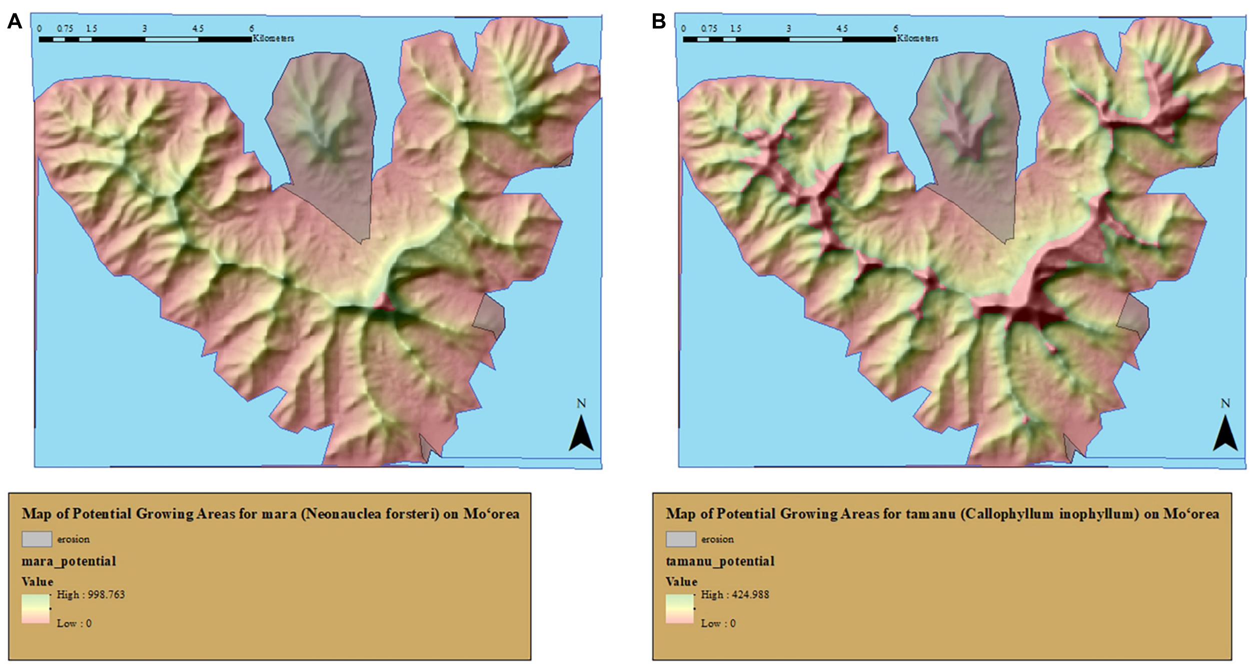

FIGURE 6 | (A) Visual habitat suitability model for *Tamanu* on the Island of Moʻorea; **(B)** visual habitat suitability model for *Mara* on the island of Moʻorea.

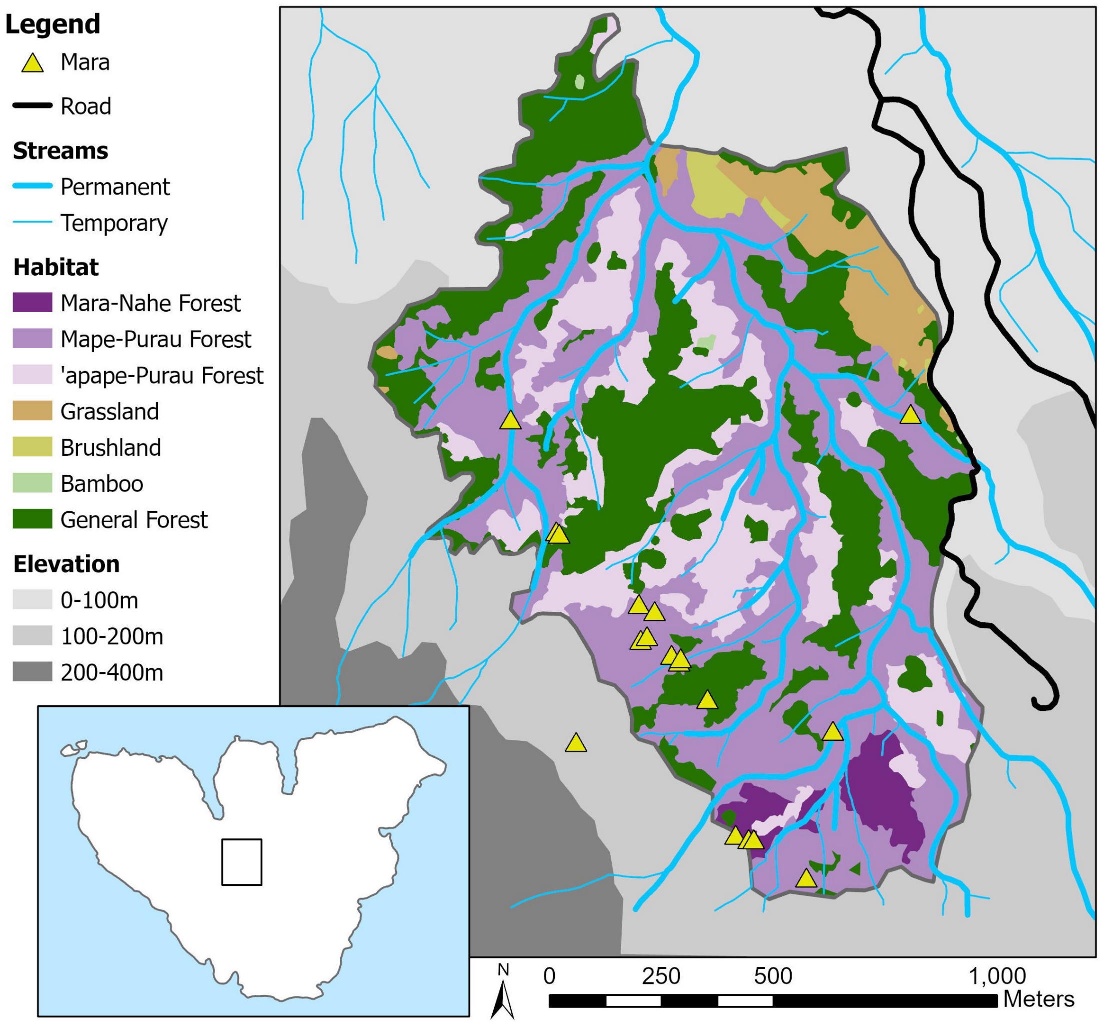

FIGURE 7 | Modern botanical survey of the middle sector of the ʻOpunohu Valley with *Mara-Nahe* forest elevational distribution and *Mara* isolates.

of the valley), supplying evidence for the heavy impact of swidden agriculture during the first few centuries following island settlement (c. 950 CE). We theorized that this process, which appears to have generally ceased around 1250–1400 CE, would have impacted the regrowth potential of large trees preferred for *vaʻa* hulls. This is because in addition to elevational limits for these trees (425 m for *Tamanu*, 1,000 m for *Mara*), there are also pH and soil type limits (4.0–7.4 in sandy well-draining soils for *Tamanu* and hydrophilic forests with well-drained soils for *Mara*). At the ecological limits for these trees, even if trees are viable, their growth potential may be impacted resulting in smaller statured trees. *Tamanu* in particular is a fairly slow-growing tree, which takes seven to eight years to mature, meaning harvesting the tree too early can result in lower re-seeding potential.

As can be seen in **Figures 6A,B**, *Tamanu* grows best at lower elevations than *Mara*. On Moʻorea, *Tamanu* habitats more closely overlap with areas of moderate settlement density, while *Mara* habitats are found at higher elevations associated with low-density settlement. The latter is well-illustrated in **Figure 7**, which provides results from a recent botanical survey in the Middle sector of the ʻOpunohu Valley (see JACG, 2011). Areas with the densest remnant *Mara-Nahe* (fern) forest are situated in upper elevations at the back of the valley (c. 200 msl), yet *Mara* trees are found growing as isolates at lower elevations. When comparing erosion patterns, settlement density, and preferred tree habitats, we can infer that it is highly likely that anthropogenically caused erosion impacted *Tamanu* growth rates on Moʻorea in the pre-contact era. In contrast, suitable habitats for *Mara* were likely less impacted, both by human-induced erosion and human settlement. As previously mentioned, Mangareva lacks *Mara* trees. Given the island's lower elevation, *Tamanu* growth on this island was likely more severely impacted by human-induced erosion and human settlement, likely contributing to generalized deforestation and the inability to sustain large double-hulled canoe manufacture.

CONCLUSION

Our canoe use web illustrates that in terms of technology, we should view ocean-going canoes as one of the most, if not the most, complex technologies found in Eastern Polynesia. In the Society Islands, such canoe construction and use required considerable raw material resources, expert knowledge for their construction, use, and maintenance, and the provisioning of expert boat builders and other community members during the course of their work. Clearly, social, economic, symbolic, and ritual actions were entangled in double-hull canoe manufacture, maintenance, use, and repair. Conventional narratives viewing ocean-going canoes as solely economic vessels used in voyaging, transport, and exchange fail to see their important use as wealth and prestige items of the elite class. Furthermore, we cannot ignore that their sustained production and use was a result of significant communal and specialized labor, nor that their symbolic links to the gods was one aspect of Māʻohi chiefs' social and ritual power.

Following this, in the complex chiefdoms of the Society Islands we view the continued construction and use of double-hulled canoes at European contact as implicated in critical facets of chiefly economic, sociopolitical, and ideological power. While use of canoes as proxies for chiefly symbolic power may have positioned Māʻohi communities to better safeguard the specific tree species used in their manufacture, island ecology and habitats in the geologically youthful high islands of the Society archipelago likewise positioned its residents to having more resilient habitats for long growing hard wood trees used in ocean-going canoe construction. In contrast, in the Open chiefdoms of Mangareva, local topography and ecology worked against sustainable harvesting of canoe species over the long term. We might also query whether double-hulled canoes never reached quite the same apogee of use as visual symbols of chiefly ideological and economic power in this archipelago, thereby negating some of the social forcing factors sustaining ocean-going canoe use in the Society Islands.

Since the 1970s, Polynesian societies have been deeply engaged in reviving their long-distance canoe cultures as a means of invigorating their cultural identity and pride. These efforts also serve as a means of returning to sustainable non-fossil fuel sea transport in the modern era (Nuttall, 2012), key issues in sea transport policy and financing in the region (Newell et al., 2017). By proxy, archaeologists have long established that the construction and use of large double-hulled voyaging canoes was directly responsible for supporting human population dispersals into Eastern Polynesia from a homeland in Western Polynesia. Likewise, a Central Eastern Polynesia interaction sphere lasting some 400–500 years after initial colonization of the region depended on the use of large ocean-going canoes. Yet, while Weisler (2002) documented a Mangarevan-Pitcairn group interaction sphere undoubtedly supported by ocean-going canoes, these networks of trade were abandoned in the fifteenth century. As we and others have argued, deforestation on Mangareva and a lack of timber for ocean-going canoe construction appears to have had regional impacts beyond Mangareva, likely serving as one cause leading to the abandonment of Pitcairn and Henderson islands (Weisler, 2002). Thus, we must view ocean-going canoes as critical items in the maintenance of pre-contact intra-archipelago social networks in Eastern Polynesia, all the more important as archipelagoes here are further distant from each other than in Western Polynesia, thus leading to greater island isolation.

As we argue, the dearth of direct archaeological evidence for canoe technologies has contributed to an under-representation of the processes surrounding the manufacture and voyaging of canoes and their impact on the structure of Eastern Polynesian settlement patterns, social hierarchies, and economic interactions as well as intra-archipelago interactions involving the exchange of material goods and ideas over eight centuries of pre-contact settlement. As we have demonstrated, ethnohistoric and linguistic data illustrate how some archipelagoes of Eastern Polynesia, like the Society Islands, used canoes as powerful metaphors for daily social relations, ritual practices, and cosmological worldviews. Equally important, the manufacture and use of large double-hulled canoes indexed clear socio-economic boundaries related to social hierarchy (chief vs. commoner), gender (male vs. female), and occupational specialization (fisher/farmer vs. craft specialists, specialized fisherman, priests, warriors, etc.). Like our ethnohistoric analysis, our canoe use webs illustrate how in the most complex of Eastern Polynesian chiefdoms, as with the Society Islands, large-double-hulled canoes were prestige items expressly under the control of Paramount chiefs, used for both intra-archipelago elite travel, military campaigns, and the amassing of tribute. Our network analysis reveals a highly connected set of interactions among elite social personae like chiefs and canoe builders for the chiefs, plants, and animals in the process of manufacturing and using large double-hulled-canoes. This is consonant with expectations for highly valued prestige items.

In returning to our larger question of why did some Eastern Polynesian societies retain the use of large ocean-going canoes, while others did not, we argue there are complex issues when managing forests today, as in the past (Vogt, 2006). Varied factors, like island height and isolation, island-wide settlement pattern densities, erosion patterns, and suitable habitats for canoe timber likely all played a role in the maintenance, or lack thereof, of double-hulled canoe technologies. As such, we posit that social processes as well as environmental factors constrained canoe manufacture and use in some Eastern Polynesian contexts, yet permitted double-hulled canoe manufacture in others. We end by acknowledging that future studies might investigate suitable habitats for other tree species used to fashion other types of canoes, such as *Artocarpus altilis* (breadfruit), and *Terminalia* sp. Furthermore, other aspects of canoe use, like the labor and skill needed for their production as derived from modern experimental studies, might be incorporated into future models examining large ocean-going canoes as wealth items in Eastern Polynesia.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/**Supplementary Material**.

AUTHOR CONTRIBUTIONS

JK, AB, CE, and SC contributed to conception and design of the study. JK, AB, and CE organized the database. AB performed the network analysis. JK wrote the first draft of the manuscript. JK and AB wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2021.750351/full#supplementary-material

Supplementary Table 1 | Use Categories for Human-Centered Interaction Networks database. Entries after Verhagen et al. (2021, **Table 2**), excepting Cosmology, which is specific to the Society Island-Gambier Island HCIN databases and Ornamental, whose meaning has been modified in the current paper.

Supplementary Table 2 | Canoe Network Node Data Used in the Network Analysis.

Supplementary Table 3 | Details of select Eastern Polynesian societies and canoe types at the time of European Contact, after Forester, 1777; Wilkes, 1845; Roggeveen, 1908; Morrison, 1935; Haddon and Hornell, 1936; Lamb, 1984; Finney, 1994; Van Tilburg, 1994; Rolett, 2002; Howe, 2004; Irwin, 2006; Irwin and Flay, 2015; Thomas et al., 2016; Anderson, 2017; Irwin et al., 2017.

Supplementary Data Sheet 1 | R Code Used in the Network Analysis.

REFERENCES

Anderson, A. (2008). Traditionalism, interaction, and long-distance seafaring in Polynesia. *J. Island Coast. Archaeol.* 3, 240–250. doi: 10.1080/15564890802340000

Anderson, A. (2017). Changing perspectives. upon Māori colonisation voyaging. *J. R. Soc. N. Zeal.* 47, 222–231. doi: 10.1080/03036758.2017.1334674

Anderson, A., Conte, E., Smith, I., and Szabó, K. (2019). New excavations at Fa'ahia (Huahine, Society Islands) and chronologies of colonization in central east Polynesia. *J. Pac. Archaeol.* 10, 1–14.

Babadzan, A. (1993). *Les Dépouilles de Dieux: Essai sur la Religion Tahitienne à L'époque de la Découverte*. Paris: Editions de La Maison des Sciences de L'Homme.

Banack, S. A., and Cox, P. A. (1987). Ethnobotany of ocean-going canoes in Lau, Fiji. *Econ. Bot.* 41, 148–162. doi: 10.1007/BF02858961

Banks, J. (1896). *Journal of the Right Hon, Sir Joseph Banks*, ed. S. J. D. Hooker (London: Macmillian & Company, Limited).

Beaglehole, J. C. (1955/1961/1967). *The Journals of Captain Cook on his Voyage of Discovery*, Vol. 2. Cambridge: Cambridge University Press for the Hakylut Society.

Beechey, F. W. (1831). *Narrative of a Voyage to the Pacific and Beering's Strait: To Co-Operate with the Polar Expeditions. Under the Command of Captain FW Beechey*. London: H. Colburn & R. Bentley.

Biggs, B. G. (2006). *Kimihia te Mea Ngaro - Seek That Which is Lost*. Auckland: The Polynesian Society.

Brandtstädter, J. (2007). "Action perspectives on human development," in *Theoretical Models of Human Development*, 6 Edn. Vol. 1, ed. R. M. Lerner (New York, NY: Wiley), 516–568.

Conte, E., and Kirch, P. V. (2004). *Archaeological Investigations in the Mangareva Islands (Gambier Archipelago), French Polynesia*. University of California Archaeological Research Facility, No. 62. Los Angeles, CA: University of California.

Cook, J. (1893). *Captain Cook's Journal During his First Voyage Round the World Made in H.M. Bark "Endeavour" 1768-71*. London: E. Stock.

Corney, B. G. (1913/1914/1918). *The Quest and Occupation of Tahiti by Emissaries of Spain During the Years 1772-76*, Vol. 3. London: The Hakluyt Society.

Davies, J. (1991). *A Tahitian and English Dictionary With Introductory Remarks on the Polynesian Language and a Short Grammar of the Tahitian Dialect with an Appendix*, Second Edn. Papeete: Haere Po No Tahiti.

Diamond, J. (2014). "Easter's end," in *Science and Society: an Anthology for Readers and Writers*, eds C. Nelson-McDermott, L. Buzzard, and D. LePan (Peterborough, ON: Boardview Press), 25–35.

Ellis, W. (1829). *Polynesian Researches During a Residence of Nearly Eight Years in the Society and Sandwich Islands*, Vol. 4. London: Fisher, Son, & Jackson.

Finney, B. (1993). Voyaging and isolation in Rapa Nui prehistory. *Rapa Nui J.* 7, 1–6.

Finney, B. (1994). The other one-third of the globe. *J. World Hist.* 5, 273–297.

Finney, B. (2006). "Ocean sailing canoes," in *Vaka Moana: Voyages of the Ancestors. The Discovery and Settlement of the Pacific*, ed. K. R. Howe (Auckland: David Bateman), 102–153.

Forester, G. (1777). *A Voyage Round the World, in His Britannic Majesty's Sloop Resolution, Commanded by Capt. James Cook*. London: B. White.

Forster, J. R. (1778). *Observations Made During a Voyage Around the World in Physical Geography, Natural History, and Ethic Philosophy. Especially on: 1. The Earth and Its Strata; 2. Water and The Ocean; 3. The Atmosphere; 4. The Changes of the Globe; 5. Organic Bodies; and 6. The Human Species*. London: G. Robinson.

Goldman, I. (1970). *Ancient Polynesian Society*. Chicago, IL: University of Chicago Press.

Green, R. C., Green, K., Rappaport, R., Rappaport, A., and Davidson, J. (1967). Archaeology on the island of Moʻorea, French Polynesia. *Anthropol. Pap. Am. Mus. Nat. Hist.* 51, 111–230.

Guiot, H. (2001). La construction navale polynésienne traditionnelle. Dimension culturelle d'un processus technique. *Tech. Cult.* 35–36, 445–478. doi: 10.4000/tc.306

Guiot, H. (2006). "Forêts sacrées de Polynésie: l'exemple de ʻUvea-Wallis," in *Cahiers des Thèmes Transversaux ArScAn 2004 – 2005*, Vol. VI. (Paris: CNRS, University Paris I, Panthéon-Sorbonne), 187–193.

Haddon, J., and Hornell, A. (1936). *Canoes of Oceania*. Honolulu, HI: Bishop Museum Press.

Handy, E. S. C. (1930). *History and Culture in the Society Islands*. Honolulu, HI: Bishop Museum.

Henry, T. (1928). *Ancient Tahiti*. Honolulu, HI: Bishop Museum.

Hermann, A., Molle, G., Maury, R., Liorzou, C., and Mcalister, A. (2019). Geochemical sourcing of volcanic materials imported into Teti'aroa Atoll shows multiple long-distance interactions in the Windward Society Islands, French Polynesia. *Archaeol. Ocean.* 54, 184–199. doi: 10.1002/arco.5187

Hommon, R. J. (2013). *The Ancient Hawaiian State: Origins of a Political Society*. New York, NY: Oxford University Press.

Howe, K. R. (2004). "Tales from several coves," in *Pacific Places, Pacific Histories*, (Honolulu, HI: University of Hawaii Press), 42–52.

Hunter-Anderson, R. L., and Zan, Y. (1996). Demystifying the Sawei, a traditional interisland exchange system. *ISLA* 4, 1–15.

Irwin, G. (2006). "Voyaging and settlement," in *Vaka Moana: Voyages of the Ancestors*, ed. K. R. Howe (Auckland: Bateman), 55–91.

Irwin, G., and Flay, R. G. J. (2015). Pacific colonisation and canoe performance: experiments in the science of sailing. *J. Polyn. Soc.* 124, 419–443. doi: 10.3316/informit.801482755650285

Irwin, G., Johns, D., Flay, R. G. J., Munaro, F., Sung, Y., and Mackrell, T. (2017). A review of archaeological Māori canoes (Waka) reveals changes in sailing technology and maritime communications in Aotearoa/New Zealand, AD 1300–1800. *J. Pac. Archaeol.* 8, 31–43.

JACG (2011). *Etude de la Vegetation du Projet de Parcelles Agricoles à Vocation Commerciale (PAVOC 2) du Domaine Opunohu à Moorea (Communes Moorea – Maiao). Unpublished Report*. Papara: Service du Développement Rural.

Johns, D. A., Irwin, G. J., and Sung, Y. K. (2014). An early sophisticated East Polynesian voyaging canoe discovered on New Zealand's coast. *Proc. Natl. Acad. Sci. U.S.A.* 111, 14728–14733. doi: 10.1073/pnas.1408491111

Kahn, J. G. (in press). *Fare and Fenua, Marae and Mana: Social Complexity in the Pre-Contact Society Island Chiefdoms*. Honolulu, HI: University of Hawaii Press.

Kahn, J. G. (2005). *Household and Community Organization in the Late Prehistoric Society Island Chiefdoms (French Polynesia)*. Doctoral Dissertation. Berkeley, CA: University of California.

Kahn, J. G. (2010). A spatio-temporal analysis of ʻOro Cult Marae in the ʻOpunohu Valley, Moʻorea, society islands. *Archaeol. Ocean.* 45, 103–110. doi: 10.1002/j.1834-4453.2010.tb00085.x

Kahn, J. G. (2012). Coastal occupation at the GS-1 site, Cook's Bay, Moʻorea, society islands. *J. Pac. Archaeol.* 3, 1–10.

Kahn, J. G. (2018). "Colonization, settlement, and process in central eastern Polynesia," in *Handbook of Prehistoric Oceania*, eds T. Hunt and E. E. Cochrane (Oxford: Oxford Press), 351–405.

Kahn, J. G. (2020). Maʻohi Hinterlands: investigating regional variability and multi-scalar socio-economic networks in the pre-contact society islands. *J. Pac. Archaeol.* 11, 41–52.

Kahn, J. G., Crabtree, S., Buffington, A., Crabtree, S., Wood, S., Hansen, D., et al. (forthcoming). *Do Environmental or Social Factors Generate Internal Variation Amongst Eastern Polynesian Chiefdoms? A Comparison of Society Island and Gambier Island Human-Centered Use Webs*.

Kahn, J. G., and Escue, C. (2021). Supplementary material for society island human-centered Canoe-web database. *Arts Sci. Data*. doi: 10.21220/qwvb-fq33

Kahn, J. G., and Kirch, P. V. (2011). Monumentality and the materialization of ideology in central eastern Polynesia. *Archaeol. Ocean.* 46, 93–104. doi: 10.1002/j.1834-4453.2011.tb00104.x

Kahn, J. G., and Kirch, P. V. (2014). Monumentality and ritual materialization in the society islands. *Bishop Museum Bull. Anthropol.* 13.

Kahn, J. G., Nickelsen, C., Stephenson, J., Porch, N., Dotte, E., Christensen, C. C., et al. (2015). Mid- to late holocene landscape change and anthropogenic transformation on Moʻorea, society islands: a multi-proxy approach. *Holocene* 25, 333–347.

Kirch, P. V. (1984). *The Evolution of the Polynesian Chiefdoms*. Cambridge: Cambridge University Press.

Kirch, P. V. (2010). *How Chiefs Became Kings: Divine Kingship and the Rise of Archaic States in Ancient Hawaiʻi*. Berkeley, CA: University of California Press.

Kirch, P. V., and Green, R. C. (2001). *Hawaiki, Ancestral Polynesia: Essays in Historical Anthropology*. Cambridge: Cambridge University Press.

Klem, J. M.-A. (2017). *Shells and Stones: A Functional Examination of the Tuamotus Adze Kit*. Master's thesis. Honolulu, HI: University of Hawaiʻi at Mānoa.

Lamb, W. K. (ed.) (1984). *A Voyage of Discovery to the North Pacific Ocean and Round the World, 1791-1795*. London: The Hakluyt Society.

Lepofsky, D. (1994). *Prehistoric Agricultural Intensification in Society Islands, French Polynesia*. Doctoral Dissertation. Berkeley, CA: University of California.

Lepofsky, D., and Kahn, J. G. (2011). Cultivating an ecological and social balance: elite demands and commoner knowledge in ancient Maʻohi agriculture, society islands. *Am. Anthropol.* 113, 319–335. doi: 10.1111/j.1548-1433.2011.01333.x

Mathews, D. L., and Turner, N. J. (2017). "Ocean cultures: northwest coast ecosystems and indigenous management systems," in *Conservation for the Anthropocene Ocean*, eds P. Levin and M. Poe (Seattle, WAS: Academic Press), 169–206.

Medeiros, A. C., Davenport, C. F., and Chimera, C. G. (n.d.). *Auwahi: Ethnobotany of a Hawaiian Dryland Forest. Technical Report 117*. Honolulu, HI: Cooperative National Park Resources Studies Unit, University of Hawaii at Manoa.

Moerenhout, J.-A. (1837). *Voyages aux Iles du Grand Océan, Contenant des Documents Nouveaux sur la Géographie Physique et Politique, la Langue, la Littérature, la Religion, les Moeurs, les Usages et les Coutumes de Leurs Habitants; et des Considérations Générales sur Leur Commerce, Leur Histoire et Leur Gouvernement, Dupuis les Temps les Plus Reculés Jusqu'à Nos Jours*, Vol. 2. Paris: A. Bertrand.

Molle, G., Hermann, A., Lagarde, L., and Stoll, B. (2019). The long-term history of Teti'aroa (Society Islands, French Polynesia): new archaeological and ethnohistorical investigations. *J. Pac. Archaeol.* 10, 55–62.

Morrison, J. (1935). *The Journal of James Morrison, Boatswain's Mate of the Bounty Describing the Mutiny and Subsequent Misfortunes of the Mutineers, Together With an Account of the Island of Tahiti*, ed. O. Rutter (London: The Golden Cockerel Press).

Mulloy, W. (1975). Double canoes on Easter Islandʻ *APAO* 10, 181–184.

Newell, A., Nuttall, P., Prasad, B., and Veitayaki, J. (2017). Turning the tide: the need for sustainable sea transport in the Pacific. *Mar. Policy* 75, 249–259. doi: 10.1016/j.marpol.2016.01.009

Nuttall, P. (2012). Steering a course for the future with sticks, stones, grass and a little sharkskin: the case for revitalisation of sail technology and sailing culture as a practical sea-transport response to climate change and fossil fuel dependence and supply issues in Fiji. *J. Pac. Stud.* 32, 163–175.

Oliver, D. L. (1974). *Ancient Tahitian Society*. Honolulu, HI: University of Hawaii Press.

Orliac, C. (1982). *Matériaux Pour L'étude des Habitations Protohistoriques à Tahiti, Polynésie Française*. Doctoral Dissertation. Sorbonne: Université de Paris I.

Orliac, C. (2000). *Fare et Habitat à Tahiti – Habitat Traditionnel de Polynésie*, ed. C. Gleizal (Marseille: Editions Parenthèses).

Ranney, K. E. (2018). *The Polynesian Voyaging Canoe: The Regionalization of Seafaring Technologies*. Doctoral Dissertation. Eugene, OR: University of Oregon.

Rogers, D. S., and Ehrlich, P. R. (2008). Natural selection and cultural rates of change. *Proc. Natl. Acad. Sci. U.S.A.* 105, 3416–3420. doi: 10.1073/pnas.0711802105

Roggeveen, J. (1908). *The Voyage of Captain Don Felipe González: in the Ship of the Line San Lorenzo, with the Frigate Santa Rosalia in Company, to Easter Island in 1770-1. Preceded by an Extract from Mynheer Jacob Roggeveen's Official Log of His Discovery of and Visit to Easter Island in 1722*. London: Hakluyt Society.

Rolett, B. V. (2002). Voyaging and interaction in ancient East Polynesia. *Asian Perspect.* 41, 182–194.

Sahlins, M. D. (1958). *Social Stratification in Polynesia*. Seattle, WAS: University of Washington Press.

Salmon, T. (1910). On Ari'is in Tahiti. *J. Polyn. Soc.* 19, 39–46.

Salmond, M. (2009). *Aphrodite's Island: The European Discovery of Tahiti*. Berkeley, CA: University of California Press.

Shearn, I. (2020). Canoe societies in the Caribbean: ethnography, archaeology, and ecology of precolonial canoe manufacturing and voyaging. *J. Anthropol. Archaeol.* 57, 101–140.

Sinoto, Y. (1979). Excavations in Huahine, French Polynesia. *Pac. Stud.* 39, 1–40.

Sinoto, Y. (1988). "A waterlogged site on Huahine Island, French Polynesia," in *Wet Site Archaeology*, ed. B. Purdy (Boca Raton, FL: CRC Press), 113–130.

Sinoto, Y. H., and McCoy, M. (1975). Report on the preliminary excavation of an early habitation site on Huahine, society islands. *J. Soc. Océan.* 47, 143–186. doi: 10.3406/jso.1975.2699

Sinoto, Y., and Han, T. L. (1985). *Interim Report on the Final Excavation of Section 3, Zone A, Fa'ahia Site, Huahine Island, French Polynesia*. Honolulu, HI: B. P. Bishop Museum.

Taomia, J. M. E. (2000). Household units in the analysis of prehistoric social complexity, Southern Cook Islands. *Asian Perspect.* 39, 139–164.

Thomas, N., Adams, J., Lythberg, B., Nuku, M., and Salmond, A. (2016). *Artefacts of Encounter: Cook's Voyages, Colonial Collecting and Museum Histories*. Dunedin: Otago University Press.

Van Tilburg, J. (1994). *Easter Island: Archaeology, Ecology, and Culture*. Washington, DC: Smithsonian Institution Press.

Verhagen, P., Crabtree, S. A., Peeters, H., and Raemaekers, D. (2021). Reconstructing human-centered interaction networks of the swifterbant culture in the Dutch wetlands: an example from the archaeoecology project. *Appl. Sci.* 11:4860. doi: 10.3390/app11114860

Vogt, K. A. (2006). *Forests and Society: Sustainability and Life Cycles of Forests in Human Landscapes*. Oxfordshire: CABI.

Weisler, M. I. (1994). The settlement of marginal Polynesia: new evidence from Henderson Island. *J. Field Archaeol.* 21, 83–102. doi: 10.1179/jfa.1994.21.1.83

Weisler, M. I. (2002). "Centrality and the collapse of long-distance voyaging in East Polynesia," in *Geochemical Evidence for Long-Distance Exchange*, ed. M. Glascock (London: Bergin and Garvey), 257–273.

Wilkes, C. (1845). *Narrative of the United States' Exploring Expedition: During the Years 1838, 1839, 1840, 1841, 1842*, Vol. 1. London: Whittaker.

Wilson, J. (1799). *A Missionary Voyage to the Southern Pacific Ocean, Performed in the Years 1796, 1797, 1798, in the Ship Duff, Commanded by Captain James Wilson*. London: T. Chapman.

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Land Use Change in a Pericolonial Society: Intensification and Diversification in Ifugao, Philippines Between 1570 and 1800 CE

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Land use modelling is increasingly used by archaeologists and palaeoecologists seeking to quantify and compare the changing influence of humans on the environment. In Southeast Asia, the intensification of rice agriculture and the arrival of European colonizers have both been seen as major catalysts for deforestation, soil erosion, and biodiversity change. Here we consider the Tuwali-Ifugao people of the Cordillera Central (Luzon, Philippines), who resisted Spanish colonial subjugation from the 16th to the mid-nineteenth century, in part through the development of a world-renowned system of intensive wet-rice terrace agriculture. To quantify changes in how the Tuwali-Ifugao used their environment, we model land use in Old Kiyyangan Village, a long-inhabited settlement, at two timepoints: circa 1570 CE, prior to the Spanish arrival in Luzon, and circa 1800 CE, before the village was sacked by Spanish military expeditions. Our model demonstrates that between 1570 and 1800 the adoption of rice as a staple and the corresponding expansion in terrace agriculture, along with a general diversification of diet and land use, enabled the village's population to double without increasing total land use area. Further, this major intensification led to the solidification of social hierarchies and occurred without a proportional increase in deforestation.

Keywords: ifugao, circle diagrams, land use modelling, pericolonialism, Philippines, socio-ecology

INTRODUCTION

There is growing recognition that past human societies may have modified tropical landscapes, with implications for vegetation cover and local and regional climates that have left legacies lasting into the present (Willis et al., 2004; Roberts et al., 2018; Koch et al., 2019). In tropical Southeast Asia, an area of immense endemic biodiversity, a key driver of past land use change was rice agriculture, and the expansion of this crop—as well as other intensively grown grains around the world—has been linked to major deforestation and significant changes in methane emissions as early as the middle Holocene (Fuller et al., 2011; Ma et al., 2020; Zheng et al., 2021). Additionally, in Southeast Asia more specifically, the arrival of European colonial administrations, settlement patterns, and economic

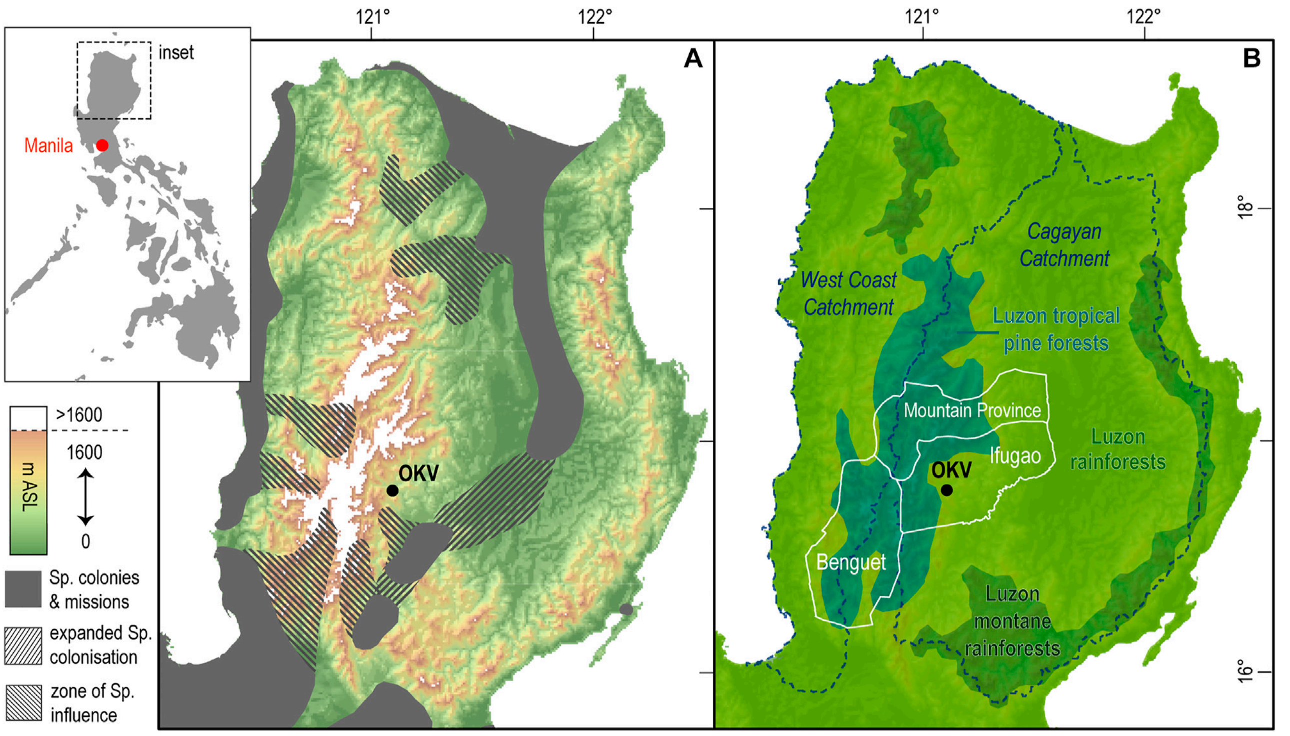

FIGURE 1 | Maps of Northern Luzon detailing **(A)** topography and the extent of Spanish colonization circa 1780 CE and **(B)** the outline of modern Ifugao province, the three ecotypes of Northern Luzon, and water catchments. Old Kiyyangan Village (OKV) is identified in both maps. The extent of Spanish colonization in the 18th century, shown in panel A, is reproduced from Conklin (1980, 98).

strategies from the 16th century CE may have had considerable impacts on tropical forests in the form of deforestation, the marginalization of Indigenous land use, and the introduction of exotic plants and animals (Amano et al., 2020; Hamilton et al., 2020).

These major transformations heavily impacted the Philippine Archipelago, whose 7,100 islands are all characterized by significant ecological, ethno-linguistic, and cultural diversity. The islands contain river valleys, littoral plains, and mountain chains, with the lattermost creating highly variable microclimates (Wernstedt and Spencer, 1967) as well as distinctive forests replete with endemic species (Olson and Dinerstein, 2002; Dinerstein et al., 2017). This varied geography, as well as historic migrations, not only shaped pre-colonial socio-ecologies (Bankoff, 2013; Amano et al., 2020) but also helped to create non-uniform experiences of colonialism during the Spanish, American, and Japanese periods (Costa, 1967; Phelan, 1967; Newson, 2009). As a result, the Philippines today harbors a wide variety of unique land use strategies iconic of the archipelago's Indigenous peoples. Perhaps the most well-known are the rice terraces of the Ifugao peoples, whose eponymous modern administrative province is located in the southeast Cordillera (**Figure 1**).

These terraced highland landscapes, now recognized as a UNESCO world heritage site (UNESCO, 1995), were initially assumed by scholars to be two-thousand to three-thousand years old (Barton, 1919; Barton, 1922; Beyer, 1955) and to represent a vivid example of the sweeping impact of past intensive agriculture on tropical forest environments, particularly in montane areas. However, post-1950s research in ethnography (Keesing, 1962; Scott, 1966), linguistics (Reid, 1994), oral tradition (Lambrecht, 1967; Conklin, 1980), and archaeology (Maher, 1973; Conklin, 1980; Acabado S. B. 2012; Acabado S. 2012; Acabado, 2017; Acabado, 2018) all suggest the terraces are relatively young (see **Supplementary Material**). Rather than being millennia old, they were likely constructed between the 16th and 18th centuries after the Spanish first conquered northern Luzon's lowlands in 1572–74 CE (Blair and Robertson, 1909). Acabado (2017) has argued that the terraces allowed the Ifugao to function as a "pericolonial society," as a people influenced by Spain's conquest of the Luzon lowlands who nonetheless maintained their independence, grew in number, and developed more rigid social hierarchies *outside* of the colonial system. Furthermore, key to this pericolonial society's growth, ethnographic and palaeoecological research suggests, was a highly integrated agroforestry system that employed carefully managed woodlots (*muyong*), swidden fields (*uma*), and wet-field terraces (*payo*) that enabled long-term, sustainable cultivation of rice, root crops, and usable tree species. Woodlots were fully incorporated into the Ifugao peoples' agricultural system, guaranteeing forests were preserved or possibly expanded alongside the intensively cultivated rice terraces (Sajor, 1999; Hayama, 2003; Serrano and Cadaweng, 2005).

Modelling Ifugao land use in the Philippines' pre-colonial and colonial periods is an opportunity to apply multidisciplinary data to visualize how a burgeoning system of rice agriculture, and its associated population growth, affected local forest cover and how Indigenous socio-ecodynamics responded to a neighboring, aggressive colonizer. Scholars' capacity to quantify the land use and demographic changes that occurred during this period, however, has historically been limited by a lack of written documents describing the region. The first written sources to mention the terraces were composed in the 19th century, and the earliest academic studies on the region transpired in the 20th. Comprehending past land use strategies in Ifugao therefore requires an interdisciplinary approach that draws upon history, ethnography, archaeology, anthropology, linguistics, ecology, and geography (Wilson, 1998; Izdebski et al., 2016; Rick and Sandweiss, 2020). Recently, an interdisciplinary community effort has emerged (Kay and Kaplan, 2015; Morrison et al., 2018; Kay et al., 2019; Morrison et al., 2021) to synthesize and quantify the longstanding interconnectivity of human and climate history first expounded by Ladurie (1971) and Lamb (1997; see also Harrison et al., 2018; Gaillard et al., 2018; Widgren, 2018).

Here, we quantify historic land use change in the Ifugao region using a simple spreadsheet-modeling approach, which we then visualize through "circle diagrams" (described in Kay and Kaplan, 2015; Hughes et al., 2018). To create these models, we calculate the land required for a settlement with a predetermined population (based on the available archaeological and historical data) to subsist for a single year, presuming no atypical disruptions (i.e. severe natural hazards or invasions), and classify different types of land use according to their intensity. We quantify land use for a principal settlement of the Tuwali-Ifugao people, Old Kiyyangan Village (OKV), which was inhabited from 900 CE until the mid-nineteenth century when it was razed by a Spanish military expedition. We design our models according to Acabado's (2017) pericolonialism hypothesis, which states that lowland migrants avoiding Spanish dominion swelled the Cordillera's population, leading to the rapid expansion of rice terraces and the adoption of wet-rice as one of Ifugao's primary starches. This enables us to explore the potential ramifications of rice intensification and demographic growth. We model OKV land use at two timepoints. The first timepoint, 1570 CE, depicts OKV prior to the Spaniards' subjugation of parts of Luzon's lowlands. The second timepoint, 1800 CE, describes OKV just before the first Spanish accounts of the village and its terraces (Scott, 1974). We also present models demonstrating the typical land use of Ifugao's two predominant social tiers: the *kadangyan* (elite who frequently consumed rice) and the *nawotwot* (the poor, whose name literally translates to "root eaters"; Acabado, 2017).

METHODOLOGY

Models in Ifugao: The History and Socio-Ecology of the Region

The shift from taro (*Colocasia esculenta*) to rice (*Oryza sativa*) cultivation and consumption between 1570 CE and 1800 CE was a remarkable transformation in Ifugao's socio-ecology. To convey the scope of this transformation, this section offers a brief history of Ifugao province and OKV during the Spanish colonial period. It then describes Ifugao society circa 1570 and 1800, focusing on the emergence of Ifugao's distinctive agroforestry complex, which emerged as a response to both Ifugao's geography and the Spanish occupation of the surrounding lowlands. We refer to this as the *muyong-uma-payo* complex (see **Table 1**).

Contemporary Ifugao province, which approximates the Ifugao cultural region, is enclosed by the Magat River to its south and the Cordillera Gran's steepest mountains to its north and west (Wernstedt and Spencer, 1967; Conklin, 1980; see **Figure 1**). As a result, the province's topography is defined by deep river valleys where rice cannot grow except in constructed environments like terraces. Terraced rice is able to grow up to 1,600 m above sea level (m ASL), and, not coincidentally, the average elevation of the province's inhabited regions ranges from 1,000 to 1,500 m ASL (Conklin, 1980). The region above 1500 m ASL comprises broadleaved montane forest interdigitated with Benguet pine- (*Pinus kesiya* Royle ex Gordon) dominated coniferous forests on steep slopes and ridges as well as in frequently burnt zones (Kowal, 1966; Jain, 1992; Olson et al., 2001; Rabena et al., 2015; Lamoreax, 2021). We refer to this holistically as coniferous montane forest for brevity. Land use in Ifugao settlements—the *payo,* but also the *uma* and *muyong*—take full advantage of this complex geography and the transitional zone (ecotone) from mid-to high-elevation (**Figure 2**).

Spanish colonizers became aware of the Ifugao region after establishing control over lowland Luzon in a series of campaigns between 1572 and 1574 CE. Cash-strapped colonial administrators and Spain's kings were attracted by rumors of gold mines in the western and southern Cordillera, but Ifugao lacked these precious metals (Blair and Robertson, vol. 20, 1909; Morga, 1971; Scott, 1974). As a result, regular contact between the Spanish and Ifugao peoples did not take place until the mid-eighteenth century with the establishment of Ituy and Paniqui provinces (Antolin and Scott, 1970; see **Figure 1**). Works from that period by friars Antolin in 1789 (see ibid) and Molano in 1801 (cited in Scott, 1974) offer some of the earliest written descriptions of Ifugao. Molano's account is of special interest since he was the first Westerner to visit OKV, the largest settlement of the Tuwali-Ifugao, and to describe Ifugao's unique rice terraces (see **Figure 2**).

Although Molano may not have been aware, OKV held mythic significance to the Tuwali-Ifugao and was an unusually large settlement with fertile land. Oral tradition indicates OKV was the birthplace of rice terrace farming and its associated rituals (Maher, 1984). Writing of the village in the late 20th century, Maher said, "What remains of it can be found there in the Barangay Bullaga surrounded by pond fields on the flood plain of the Ibulao River. The surface is flat, requiring no terracing, and water is abundant and accessible" (p. 119). This corresponds with Antolin's 1789 descriptions of "Kiangan (Kiyyangan)" and Tuwali-Ifugao lands as fertile compared to other parts of the Cordillera (Antolin and Scott, 1970, 237). However, the village's size also made it a target. In 1832 CE, a Spanish expedition led by Commander Galvey sacked the village and much of the region. By the 1860s, the village was abandoned (Scott, 1974; Scott, 1982).

TABLE 1 | Ifugao land use terminology as it applies to our land use modelling. The leftmost column names seven types of land use typical to Ifugao. The middle column provides the Tuwali-Ifugao (Kiangan Region) terms for these forms of land use (Acabado and Martin, 2016). The rightmost column assigns each form of land use to an Intensity Tier, reflecting how transformative of the landscape that activity is relative to others. These Intensity Tiers determine where each form of land use is depicted on a circle diagram. This table is inspired by similar tables presented in Conklin's *Ethnographic Atlas of Ifugao* (1980) and uses his terms, "Grassland" and "Caneland," to describe fields overtaken by primary and secondary growth.

Type of land use	Tuwali-ifugao terminology Acabado and Martin (2016)	Assigned intensity tier for circle diagrams
Settlement Terrace	Latangan/boble/kubu	1 (Highest Intensity)
Rice Terrace	Payo	2
Swidden Field	Habal/Uma	3
Fallow Swidden Fields/Caneland	Mabilau	4
Pasture/Grassland	Magulun	4
Private Forest	Muyong	5
Public Forest	Inalahan	6 (Lowest Intensity)

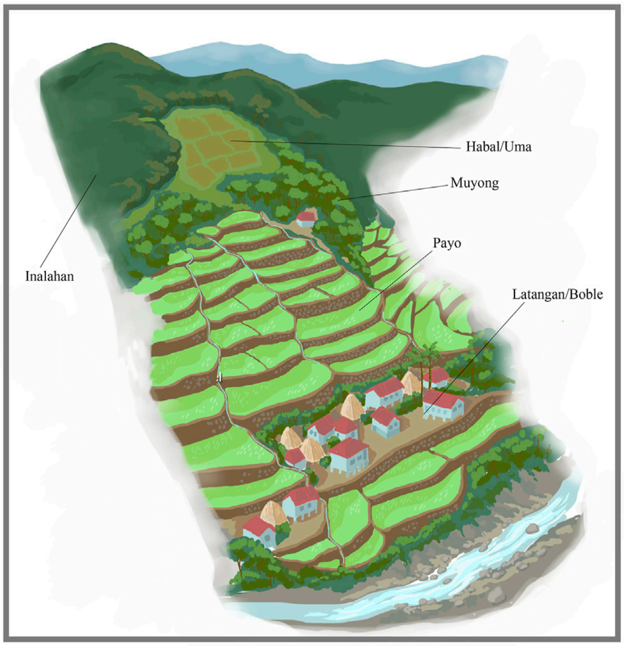

FIGURE 2 | A drawing of OKV and its associated land use, with labels. The forms of land use are arranged as they exist in 20th and 21st century Ifugao settlements.

OKV's relative prominence in Spanish documents and its mythological importance to the Ifugao make it an ideal site for land use modelling. Multiple Spanish interactions with the village mean it is relatively well-documented compared to other Ifugao settlements. Furthermore, because of the village's mythological importance, it has been thoroughly investigated by the Ifugao Archaeological Project (IAP, see[1]) and is one of the best-researched sites in the province. It therefore is one of the few sites in Ifugao province where historic land use modelling may be attempted, although the village's exceptional size and fertility mean it is not necessarily a template for the whole province. Nonetheless it is the supposed birthplace of the terrace-based rice cultivation that radically transformed Ifugao between 1570 (pre-Spanish) and 1800 (pre-conquest), and it is therefore an important site for understanding Ifugao agriculture.

Based on Molano's written accounts (see Scott, 1974), the pre-conquest socio-ecology of OKV was defined by the *payo*. The *payo,* though, were only the most visible aspect of a highly integrated agroforestry system, the *muyong-uma-payo* complex (see **Figure 2**). The payo were also a basis for social differentiation among the Ifugao (see **Table 1**). They were constructed in the absence of a central administrative state, but gave rise to a "petty plutocracy" (Scott, 1982, p. 135) where communal labor maintained and expanded terraces owned by the *kadangyan*, whose regular consumption of difficult-to-grow rice was a primary signifier of their elite status. Complementing the *payo* were the *muyong*, carefully managed woodlots that contained as many as 200 plant species that were used for food, construction, fuel, and medicine (Sajor, 1999). Located uphill of terraces, *muyong* supported rice cultivation by hindering runoff and erosion, simultaneously protecting the terraces and ensuring regular access to water. Finally, *kadangyan* who did not own many terraces as well as Ifugao who did not own terraces, the *nawotwot*, consumed root crops such as *iuktu* (*ubi,* purple yams, *Dioscorea alata*) or, more recently, *gattuk* (*camote,* sweet potatoes, *Ipomoea batatas*) grown in *uma* (swidden fields). *Uma* were typically located near *muyong* uphill of *payo* on arable land unsuitable for rice cultivation (Conklin, 1980; Sajor, 1999).

Less is known about the pre-Spanish socio-ecology of Ifugao. Palaeobotanical evidence suggests rice was entirely absent, that taro and root crops were OKV's primary starches before 1570, and that these crops were grown in less-extensive terraces and swidden fields (Acabado S. B. 2012; Acabado S. 2012; Horrocks et al., 2018). Studies employing radiocarbon dating indicate terracing substantially increased in the 17th and early 18th centuries, after the Spanish arrived in the Philippines (Maher, 1973; Conklin, 1980; Acabado et al., 2019). Based on research performed by the IAP in OKV, Acabado theorizes that increased terracing was attributable to population growth partially caused by an influx of migrants from the lowlands where rice cultivation was practiced. This population increase catalyzed both the rapid expansion of pre-existing terraces and the adoption of rice, a more productive staple, amongst social elites (Bray, 1994; Acabado S. B. 2012; Acabado S. 2012; Eusebio et al., 2015;

[1]https://www.ifugao-archaeological-project.org/.

Acabado, 2017). The shift to wet rice cultivation, Acabado asserts, provided the basis for pronounced social differentiation amongst the Ifugao, helped them resist multiple Spanish incursions and ultimately helped create a pericolonial society (Acabado, 2017; Acabado, 2018).

The Historical Land Use Model

We use a historical land use model to quantify the amount and type of land used by the residents of OKV. The model, first conceptualized by Gregg (1988) and elaborated in subsequent studies (Kay and Kaplan, 2015; Weiberg et al., 2019), posits that land use is a function of the properties of the physical environment and the socio-cultural characteristics of the people who use the land. The former includes topography, climate, soils, and vegetation and can be reconstructed for the past based on modern survey and paleoenvironmental proxies. The latter consists of the most significant components of a population's diet and their methods of agriculture, agroforestry, animal husbandry, hunting and gathering, pottery production, and metallurgy. Reconstructing the socio-cultural characteristics of past societies draws upon published archaeological, ethnographic, and anthropological research.

Hughes et al. (2018) describe the past land use modeling process in detail, and term the socio-cultural characteristics "livelihoods". These livelihoods describe the human inputs to food production that, along with the properties of the physical environment, are used to determine the yield of the principle food crops and animal products. With an initial estimate of the size of the human population, the land use model is used to approximate the amount of land required for a settlement to subsist for a single year.

Here, our model quantifies land use for an imagined year where no significant demographic change, famine, or abnormal disruptions transpire. Since natural hazards are frequent in the Philippines, our model assumes moderate damage from typhoons and earthquakes, and therefore expanded land use associated with repairs, was part of a typical year (Bankoff, 2009). However, since statistics on all but the most exceptional historic typhoons and earthquakes are rare, particularly in the Cordillera region, we are forced to make generalized assumptions about the damage they caused every year (see Bankoff, 2003). It is also essential to note that our model attempts to quantify land use at specific points in time, but does not make any assumption on how or when change transpired. As a result, our models of OKV at two timepoints only identify changes that happened in intervening years, not their cause or tempo.

Following Kay and Kaplan (2015), we recognize that different forms of land use lead to different transformations of the physical environment. For example, a village or garden would represent an obvious anthropogenic modification of the natural landscape, while a forest in which hunting and gathering takes place might only be appreciated by someone intimately familiar with the local environment. Thus, land use leads to a hierarchy of impacts on the landscape. For Ifugao, we pre-define the types of land use calculated by the model and their relative intensities (**Table 1**).

The land use model is coded in an Excel spreadsheet and contains user-definable parameters describing both livelihood and properties of the physical environment that can be adjusted based on uncertainties in diet, inputs, climate, population size, etc. The model output consists of a table of the area in hectares required for each type of land use.

In order to aid in the rapid interpretation of the model results and facilitate comparison between outputs using varying underlying assumptions or for different periods, we use the circle diagram (Kay and Kaplan, 2015; Hughes et al., 2018). A circle diagram presents the land use model output as a series of colored concentric rings, where each ring represents a specific land use at a certain hierarchical level (**Table 1**). Where two or more land uses have the same relative intensity, both are shown as distinct sectors in the ring at that level. The integrated area of each ring/sector represents the area required for that particular land use. We use a custom script for the Generic Mapping Tools software (Wessel et al., 2019) to take the tabular output from the land use model and plot the circle diagrams. The full plotting code and model output used in this paper are published on Zenodo (Kaplan, 2022).

Model Calculations for OKV

Our models for OKV in 1800 rely on 20th century ethnographic research supplemented by palaeoecological and archaeological research in Ifugao, especially the on-site investigations at the OKV by the IAP. We assume 20th century ethnographic research is useable for the 1800 timepoint based on archaeological evidence and Ifugao oral tradition, which indicate the terraces and their associated social institutions are at least ten generations old (Lambrecht, 1967; Maher, 1973; Conklin, 1980; Acabado, 2017). We acknowledge that relying on ethnographic evidence assembled in the previous century is potentially problematic as Ifugao society was and is dynamic. However, the lack of regular historic documentation of Ifugao forces us to make these assumptions. For the 1570 timepoint, for which no written historical documents exist, we rely exclusively on archaeological and palaeoecological evidence and assert that OKV in 1570 CE grew taro as its primary subsistence crop to support a smaller population. As a result, both our pre-Spanish and pre-conquest models are built upon several informed assumptions, which are a source of uncertainty in our models. To explore how these uncertainties can produce significant variations in our model results, we also run a series of simulations (or "sensitivity tests") covering a range of input values.

The remainder of this Methodology section is dedicated to describing the information we use to assemble our model calculations with a focus on our template or initial models. These models represent what we believe to be the probable land use of OKV at our two timepoints. This section is organized according to the three broad categories of data used in land use modelling: population, "livelihood," and yields and nutrition. Throughout, we summarize the data we gathered and the assumptions we made. When necessary, more detailed descriptions of our data are included in the **Supplementary Material**. We also allude to points of uncertainty in our templates and how we test the potential error introduced by these uncertainties. These are discussed in detail in the

Supplementary Material, where we demonstrate they do not alter our primary conclusion: that intensification, particularly expanded terracing, and the initiation of widespread rice cultivation allowed OKV to have lower per capita land use in 1800 than in 1570, even though the village's population in 1800 was double what it was in 1570.

Population and *Boble* (Settled Area) at OKV

There is no census or comparable document describing OKV in 1800 CE or 1570 CE, nor are there any surviving, precise descriptions of OKV's size at either of these times. Further, because the Ifugao peoples' settlement patterns are intricately linked to their *payo,* one cannot determine per capita land use and from that extrapolate the settlement's size based on empirically observed relationships between population and settlement size (see Ortman et al., 2014). As a result of these complicating factors, how we determine the settlement's size is inextricably connected to what we expect OKV's population was. A full explanation of how we derived the estimates for population and settlement size that we provide below can be found in our **Supplementary Material**.

For the 1800 timepoint, we estimated the population and size of the settled area using a combination of Molano's 1801 account of OKV (Scott, 1974), Maher's (1973) observations on how *payo* can be repurposed as "settlement terraces," Conklin's (1980) observations on the Ifugao hamlet of Buble, and Acabado (2017) and the IAP's research fieldwork at OKV. We presume OKV contained 284 houses (Scott, 1974), with the majority occupying a 3.39 ha nucleated settlement and the others dispersed throughout the *payo* (see section 3.3.2). Assuming that *bale* (houses) held on average 3–4 individuals, we expect OKV's population in 1800 was at minimum 852 and at maximum 1,136. We use the maximum expected population in our templates. Given population densities reported by Conklin (1980) that were also supported by Barton (1922), and using Molano's description of OKV's satellite villages as a guide (Scott, 1974), we calculate that OKV in 1800 would have required ~5.55 ha of "settled area" for 1,136 people.

For the 1570 timepoint, there are no contemporaneous written accounts that indicate the full extent or population of OKV. However, as per the pericolonialism theory and research led by the IAP and Acabado, it is known that the nucleated settlement was 1.70 ha, half the size it would be in 1800 (Acabado, 2017). It is also known that taro, a less productive crop than rice or sweet potatoes, was the primary staple that was grown in both swidden field and terraces (Acabado S. B. 2012; Acabado S. 2012). So, because we expect Ifugao settlements were dispersed in 1570 as well, we conclude that OKV's settled area in 1570 was half of its size in 1800: ~2.78 ha. Since we lack any information on OKV's population in 1570, we assume OKV's population was also half its future maximum size and contained 568 people. Again, because we assume OKV's settled area included various dispersed hamlets, we do not use Ortman et al.'s (2014) observed relationship between nucleated settlement size and population. However, we must emphasize that this estimate for total population is a rough estimate and cannot be proven or disproven based on existing evidence from the OKV site.

Payo (Terraces)

Despite the labor expended on rice cultivation and its cultural significance, rice only met approximately 25–33% of OKV's carbohydrate requirements circa 1800 CE (Barton, 1922; Acabado et al., 2018). Because rice and a small quantity of taro were grown in *payo,* we determine the area terraced for rice cultivation by calculating how much rice the village's population would have required to produce a surplus, to be used either in trade or as a precaution against hazards. We then add on the amount of land required to grow the small amount of taro consumed annually.

For the 1570 CE timepoint, since terrace agriculture was less extensive than in 1800 and was primarily used for taro cultivation, which can occur in either wet or dry fields, we presume a much smaller amount of land was terraced. Given the labor requirements of *payo,* the size of OKV in 1570, and the premises of the pericolonialism hypothesis, we expect ~13.4 ha of land were terraced for growing taro in OKV in 1570 (see **Supplementary Material** section 3.3.1).

Before continuing, we should note that terraces were routinely damaged and repaired. However, these repairs do not contribute to land use in our model for three reasons. First, a high proportion of terrace walls in the Tuwali-Ifugao are built of earth, not stone. Second, the sandstone used in stone walls was often gathered from cleared *uma, muyong,* or other sites uphill of the terraces, which permitted villagers to move these heavy materials downhill with water. If no stones were available uphill, the villagers of OKV would have used stones and boulders from the nearby Ibulao River instead. Third, Ifugao quarrying, when it did transpire, was not especially transformative of the landscape; boulders were not dug up, but instead were gathered, broken apart using other rocks, and then hauled to the terraces. For these reasons, we do not measure quarrying in our models and presume terrace repair had a negligible effect on land use (Conklin, 1980).

Uma (Swidden Fields)

In contemporary Ifugao, swidden fields are positioned on fertile land unsuitable for terracing, are often close to *muyong,* and are relatively distant from villages and hamlets. Today, swidden farming is used to primarily grow sweet potatoes, though taro can also be grown in wetter years. Swidden fields are prepared during the dry season by first cutting cane or woodland and enacting a controlled burn; wood or cane that does not burn fully can be saved for fuel (Conklin, 1980). A swidden plot is cultivated for 2–3 years, with each year experiencing successively smaller yields. It is then left to lie fallow for 5–6 years, at which point primary growth is cleared again or the field is cultivated as a woodlot. In years when rice harvests are expected to be poor, swidden agriculture can be rapidly expanded into unclaimed forests or fields (Conklin, 1980).

Ethnohistorical accounts by Antolin indicate *gattuk* (sweet potato), *aba* (taro), and *iuktu* (purple yams) were grown in swidden fields circa 1800 CE (Antolin and Scott, 1970), and Barton indicates that, by the 20th century, sweet potato had entirely replaced yams in Ifugao diets. Given this information, we assume *gattuk* and *iuktu* were grown simultaneously in *uma* circa

1800, with a small amount of *aba* also being grown. In our template diagram, we presume *iuktu* and *gattuk* were equal components of OKV's diet.

For 1570 CE, swidden crops, particularly *aba* and *iuktu*, are presumed to have been OKV's primary source of energy based on archaeobotanical and archaeological evidence (Acabado S. B. 2012; Moran, 2015). For both timepoints, we expect vegetables such as squash, were also grown in swidden fields or along the bunding atop terrace walls (Antolin and Scott, 1970; Conklin, 1980; Amano et al., 2020). In 1800, we assume the most common squash was *kalabasa* (*Cucurbita maxima*). However, since *kalabasa* was first introduced to the Philippines from the Americas during the Spanish period, it would not have been present in OKV in 1570. Instead, similar vegetables such as squashes indigenous to East and Southeast Asia would have been grown. Our models assume these vegetables had similar productivity to *kalabasa*.

Muyong (Private Forests)

Historically, edible plants grown in *muyong* included mangoes and bananas, with the latter being the most prevalent (Antolin and Scott, 1970). It is also possible, though not confirmed, that breadfruit was cultivated in woodlots (Acabado et al., 2018). Tobacco, a plant originally imported from the Americas, may also have been cultivated in personal gardens, *muyong*, or *uma* in 1800 CE, though we do not discuss its cultivation in our models.

In 1800, *kadangyan* and *nawotwot* alike obtained their fuel and resources from *kadangyans*' *muyong*. Typically, *nawotwot* were permitted to gather dead branches and even chop down dead trees in exchange for laboring to maintain *kadangyans*' *muyong* (Conklin, 1980; Hayama, 2003; Serrano and Cadaweng, 2005). These *muyong* would have contained hardwoods for *bale* (house) construction (Scott, 1966), which we find did not significantly contribute to land use (see **Supplementary Material**).

We have little information on forestry practices in 1570, prior to increased terrace building. As terraces were still present, we assume managed forests were also maintained uphill of those terraces and their size was primarily determined by the village's food and fuel requirements (see Kay and Kaplan, 2015).

Domesticated Animals

In contemporary Ifugao, domesticated animals including carabao (water-buffalo, *Bubalus bubalis*), pigs, and chickens are sacrificed at various stages of rice cultivation. Notably, only domesticated animals are considered suitable for sacrifice (Lapeña and Acabado, 2017). Chickens are most frequently sacrificed, followed by pigs, and then carabao, which are only sacrificed during the harvest period (Conklin, 1980; Conklin, 2002). Among these animals, pigs and especially carabao are prestige animals. They are owned by *kadangyan,* and they are sacrificed and distributed during communal feasts (Conklin, 1980; Brosius, 1988; Lapeña and Acabado, 2017). However, carabao are only shared among other *kadangyan,* while pig parts are more widely distributed with various parts considered more prestigious gifts than others. By contrast, chickens and their eggs are an easily accessible source of protein and are commonly raised throughout settlements (Conklin, 2002). When chickens are ritualistically sacrificed, they are consumed by the ritual leader (*mumbaki*), but the meat is not distributed (Barretto-Tesoro, 2007).

For 1800 CE, zooarchaeological evidence from OKV indicates four domesticated animals were common: dogs (*Canis familiaris*), chickens (*Gallus gallus*), pigs (*Sus scofra*), and water buffalo or carabao (Ledesma et al., 2015). Although no remains were found, it is also possible goats were present in OKV, presumably in small numbers (Amano et al., 2020). While our template diagram does not account for goats, we do discuss what effects they might have had in our **Supplementary Material**.

Of the animals confirmed to be present in 1800 CE, carabao—these are large grazing animals averaging over 400 kg in size—would have had the most significant effect per animal on land use. It is unclear, though, whether very small carabao herds were kept or if these animals were purchased from the lowlands (Ledesma et al., 2015). For our template models, we assume a small herd of ~22 animals was kept at OKV, and we detail other possible herd sizes in our **Supplementary Material**.

Domestic pigs were the most common large animal, though ethnographic evidence indicates they had a very small effect on land use in OKV. This is because pigs, like chickens, were raised within settlement terraces near homes. Further, pigs' caloric needs could have been met with plant and animal waste generated from farming and hunting as well as from human waste (Conklin, 1980; Gregg, 1988; Conklin, 2002; Huynh et al., 2007). Nevertheless, for nutritional reasons, we assume 10% of pigs' caloric needs were met by browsing in forests. Browsing occurred in *muyong* or public forests between the rice harvest and the reseeding of the terraces (Conklin, 1980).

The same suite of domestic animals was present in 1570 CE, except possibly carabao (Acabado, 2017). Based on existing zooarchaeological evidence we expect that fewer domestic pigs and no carabao were present (Ledesma et al., 2015; Acabado, 2017). Therefore, we calculate animal-associated land use in 1570 was significantly less than it was in 1800.

Hunting, Foraging, and Fishing

Zooarchaeological evidence indicates that, in both 1570 and 1800 CE, a substantial portion of OKV's dietary needs were met through hunting and gathering. According to Antolin, Ifugao and other highland peoples hunted in the foothills of the Cordillera, particularly in wooded regions where larger mammals proliferated (Antolin and Scott, 1970). Zooarchaeological reconstructions of faunal assemblages (Number of Identified Specimens-NISP, Minimum Number of Individuals-MNI) undertaken by Ledesma et al. (2015) indicate wild deer (*Rusa marianna*) were the most consumed animal in Ifugao, followed by wild pigs (*Sus philippensis*). Various bones attributed to different small game were also preserved at OKV. Lastly, a small percentage of bones at OKV were attributed to mudfish (*Channa striata*), a freshwater fish common in the Ibulao River (Ledesma et al., 2015). In modern times, this fish and various shellfish from the river are often introduced and maintained in terraces, where they promote soil fertility and are an easily obtained source of protein (Conklin, 1980).

Given the known biases of NISP and MNI counts against small animal bones and fish bones as well as the relative dearth of studies undertaken at OKV, we suspect small game and mudfish and other freshwater life comprised a larger fraction of historic diets than suggested by Ledesma et al. (2015; see also Barton, 1922; Conklin, 1980). Additionally, for both 1800 and 1570 CE, we assume residents of OKV consumed wild game more frequently than domesticated animals, and large animals like wild deer and pigs were shared among families and villages once slaughtered.

Fuel and Resource Extraction

Ethnographic evidence suggests the primary fuel source for the Cordillera and parts of Ifugao was Benguet Pine, which could be gathered in *muyong* or while clearing swidden fields (Antolin and Scott, 1970; Scott, 1975; Conklin, 1980; Manuta, 1993; Jang and Salcedo, 2013). However, Benguet Pines grow best at elevations between 1,000 and 2,500 m ASL and likely would have been interspersed with tropical montane oaks and other broadleaved trees in OKV's *muyong* (Dinerstein et al., 2017; Lamoreax, 2021). Since most societies do not limit themselves to one type of tree, but instead gather wood from various species as long as they lack religious or cultural significance, we assume Ifugao peoples in both 1570 and 1800 CE relied on several tree species for fuel (Picornell-Gelabert, 2020). The species they selected would likely have included Benguet Pines, molave oaks, and species that released as little smoke as possible. Given these criteria and the species available near OKV, our model postulates that local fuel-woods had an average energy content of approximately 20 MJ/kg (Bhatt and Tomar, 2002; Kay and Kaplan, 2015).

For both 1570 and 1800 CE, we calculate that OKV's annual fuel consumption was approximately 476 kg per capita (Donovan, 1981; de S. Wijesinghe, 1984; Kay and Kaplan, 2015). Because individuals who did not own a *muyong* were often permitted to gather fallen trees for firewood by *kadangyan* in exchange for their labor (Manuta, 1993; Hayama, 2003), we expect *kadangyan* and *nawotwot* alike gathered fuel exclusively from *muyong* in 1800. In 1570, we likewise presume firewood was gathered from managed woodlots.

Pottery and metallurgy can significantly increase the demand for fuel and other resources. Pottery production in Ifugao, according to Acabado et al. (2018), did not experience substantial change and remained decentralized (occurring in each household as per a family's need) between 1570 and 1800. We therefore assume pottery requirements for each person in 1570 were near identical to those in 1800 (Lauer and Acabado, 2015). Critically, Ifugao traditional pottery is fired by filling the earthenware pot with twigs and grasses that are then combusted with the container doubling as a heat trap (Maher, 1984). Therefore, we conclude neither the gathering of clays nor fuel for firing had a significant effect on land use.

Ifugao, unlike all other regions of the southern Cordillera, did not practice extensive mining in 1570 or in 1800. However, Antolin noted that the Ifugao frequently purchased iron waste from lowlanders, which they would then melt to create new tools and weapons (Antolin and Scott, 1970). As a result, we conclude gathering ore in Ifugao required no significant land use. Friar Antolin also observed highlanders from neighboring regions (Benguet) using hollowed tree stumps as furnaces to melt and reshape the metal, suggesting fuel-use for these furnaces would have been significant (Antolin and Scott, 1970). To calculate annual fuel-use associated with iron for both timepoints, we employ the procedure designed by Kay and Kaplan (2015): we assume each individual person, regardless of age, required 1.5 kg of iron per year on average, which necessitated 492 kg of fuel per year per capita.

Commerce

Antolin reported that the Ifugao would primarily trade rice with lowlanders in exchange for worked iron pieces and various animals, including domesticated pigs and carabao (Antolin and Scott, 1970). Furthermore, recent research undertaken by the IAP indicates prestige goods, such as Chinese ceramics, were desired by *kadangyan* (Yakal, 2017). Since we do not know the extent of this commerce, we cannot precisely calculate its effect on land use. However, we presume commerce was primarily undertaken by (or for the sake of) *kadangyan* and that a surplus of rice was produced most years—set to 30% in our models, an amount that would permit poorer harvests to not affect *kadangyan* diets—of which a portion was used for trade. The land dedicated to surplus rice production would therefore also be the most significant form of land use associated with commerce.

It must be noted that our model does not describe tobacco production in OKV. The Galvey expedition of 1832 CE was, in part, triggered by the sale of Ifugao tobacco in the lowland Philippines (Scott, 1974). At the time, the Spanish were attempting to enforce a tobacco monopoly, established in the late-eighteenth century, to increase the Philippine colony's profitability (de Jesus, 1998) and begrudged the Ifugao for undermining that monopoly. Unfortunately, estimating the amount of tobacco grown in OKV and sold in the lowlands as contraband circa 1800 CE is exceedingly difficult. Based on anecdotal evidence and the severity of the colonial administration's 19th century expeditions to Ifugao, we can assume the amount of tobacco grown was not insubstantial (Scott, 1974). However, we lack sufficient data to make an informed estimate at this time.

Agricultural Productivity and Nutritional Value

Extensive records of historic crop productivity do not exist for Ifugao prior to the 20th century, so we instead rely on agricultural research performed in the province and the Philippines in the past 6 decades, which often discusses traditional yields in comparison to high productivity crops (see Tulin, 2014). Using such material, we assemble a range of viable historic yields for each crop, and then employ the average yield in our models. If a reliable historic range cannot be established for a specific crop, we instead establish a range of modern yields for that crop and assume the minimum corresponds to the historic average production (see **Supplementary Material**). Furthermore, we assume yields for all crops did not change between 1570 and

1800 CE. In this way, we establish probable historic productivities based on the limited evidence available, and we utilize these productivities in our template models. We discuss yield as a source of uncertainty in our **Supplementary Material**.

Similar to historic yields, there is no accurate account of foods' historic nutritional value in Ifugao. We instead rely on analysis performed by the CINE group at McGill University (Centre for Indigenous People's Nutrition and Environment) on the diets of the Aetas of Morong, Bataan in Luzon (Santos-Acuin et al., 1997; Kuhnlein et al., 2006), supplemented by publicly available nutritional values published by the United States Department of Agriculture (USDA). Unlike productivity, it can be safely assumed that the caloric content of species found in Bataan and Ifugao do not significantly differ. We expect no significant change in foods' nutritional and caloric content between 1570 and 1800.

Dietary Proportions

Our model does not currently explicitly enforce a balanced diet, only a minimum total caloric intake. Therefore, to ensure realistic dietary proportions, we assume Ifugao peoples in both 1570 and 1800 CE consumed starches, proteins, and vitamins in similar ratios to those observed by Barton (1922) and Conklin (1980). Of the two, we prioritize Barton, whose quantitative descriptions of Kiangan, Ifugao diets are among the earliest available. However, there is no guarantee diets did not change between 1800 and the 20th century, and the peri-colonialism hypothesis asserts diets changed profoundly between 1570 and 1800 (Moran, 2015). Therefore, the dietary proportions we use in our template models are informed estimates, reflecting what we believe is a probable scenario for past diets (the inherent uncertainty of this approach is discussed in the **Supplementary Material**).

In our template models for both timepoints, we suggest starches constituted approximately 76% of annual diets with all other foods comprising the remaining 24%. This remaining percentage, we posit, was primarily comprised of vegetables and fruits, fish, and hunted game (especially small game). We expect domesticated animals did not account for more than 4% of annual diets. Variations in the consumption of various plants and animals between 1570 and 1800 transpire within these constraints, which reflect Conklin and Barton's observations.

RESULTS

Our results are presented in three sections. The first presents our template diagram for 1800 CE. This diagram presents what we maintain is a probable pattern of land use, given existing evidence. The second section offers a similar template diagram for 1570 CE. The final section presents the imagined land use of a hypothetical *kadangyan* family that only consumed rice as a starch and a hypothetical *nawotwot* family that only consumed tubers as starches. In all three sections, we present our results using circle diagrams, a series of concentric circles representing different types of land use differentiated by intensity. The settlement is plotted as the centermost circle. Surrounding the

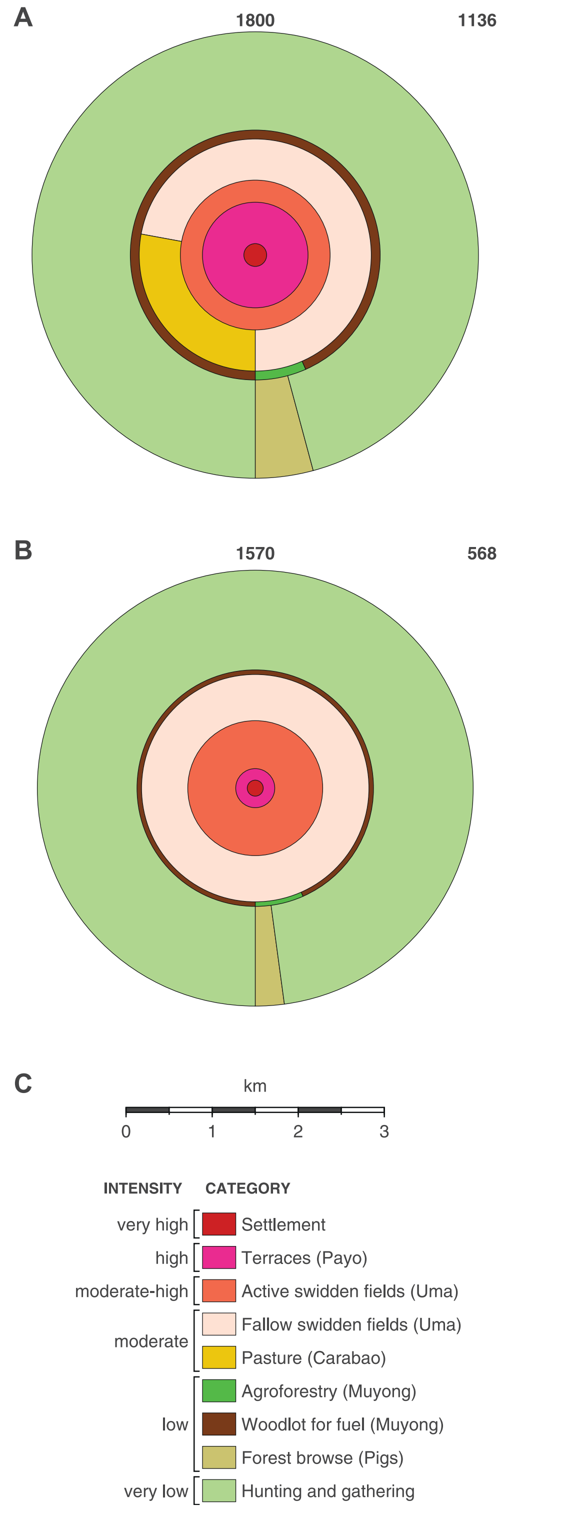

FIGURE 3 | Template circle diagrams for OKV in 1800 **(**Panel **A)** and in 1570 **(**Panel **B)**. The figure also includes a legend **(**Panel **C)** with a scale. The legend lists all types of land use and their intensity relative to one another. In each panel, the number in the upper right corner represents the population whose land use is being modelled.

settlement are five rings. They contain, in order of descending intensity: terraces; active swidden fields; fallow swidden fields and pastureland; agroforestry and woodlots; forested land for pigs to browse and hunting space.

1800

Our template diagram for OKV in 1800 CE is presented in **Figure 3**. We assume the village contained 284 houses and 1,136 individuals, the maximum population we allowed for in *Population and Boble (Settled Area) at OKV*. As per our Methodology (Section 3.3), we expect that *iuktu* (purple yam) and *gattuk* (sweet potato) comprised equal portions of diets at OKV; that a small herd of carabao (~22 animals) were present in the village; and that goats were absent from the village. Lastly, for the sake of clarity, all land use numbers presented here, excepting the Settlement, are approximations. For more precise numbers, see the datasheets included in the **Supplementary Material**.

We calculate that a village of this size, operating within the constraints listed above, would require ~2,113 ha of land to subsist for a single year, with the majority of this land being hunting land. Hunting would require 1,390 ha, while all other forms of land use would require ~723 ha of land. Assuming that the historic yield of rice was 1650 kg ha^{-1}; that historic taro's yield was 2000 kg ha^{-1}; and that the village produced 30% more rice than required for subsistence, the village would have required ~112 ha for *payo* (terraces). Of this terraced land, ~15 ha would have been required to grow taro, despite it only comprising 2.2% of annual diets in our template model (compared to rice, which represented 32% of annual diets).

Furthermore, we expect houses and hamlets were scattered among these terraces (see section 3.3.1), so the 5.55 ha of land comprising the settlement circle was not consolidated around a single nucleus. This lowered population density and maximized individual access to the terrace paths and bunding, so the whole village's *kalabasa* (squash) and other garden vegetables could have been grown in personal gardens or along terrace bunding and pathways (Conklin, 1980). In this way, *kalabasa* or garden vegetables were fully integrated into other forms of land use.

In addition to the *payo*, our model asserts that OKV required ~120 ha of active *uma* (swidden fields) to grow *iuktu* and *gattuk* each year, as well as ~240 ha of fallow land. Additionally, as discussed in section 3.1, supporting the *payo* and *uma* were the *muyong,* the indispensable managed forests. We calculate that OKV would have required ~6 ha of *muyong* for fruits and another ~85 ha for fuel and other essential resources. Therefore, the village as a whole would have required ~91 ha of *muyong* in total to support 1,136 individuals circa 1800.

Based on the community of 1,136 individuals' caloric needs as well as the physical requirements and breeding habits of pigs and carabao, we expect OKV would have contained ~391 pigs and ~22 carabao. The carabao, as grazing animals, would have required ~93 ha of pastureland (Conklin, 1980). We expect pigs, as foraging omnivores, were primarily fed agricultural waste—failed tubers and the green material from various crops—and human waste products (Gregg, 1988; Conklin, 2002). The 10% of their diet derived from forest browse would have required ~61 ha annually. Conklin's (1980) research on ritual sacrifice suggests these herds would have been too small to meet OKV's ceremonial obligations, and therefore commerce with the lowlands to obtain additional pigs and carabao was essential, which agrees with all ethnohistorical evidence (Scott, 1966; Scott, 1974; Scott, 1982).

1570

By using Acabado's pericolonialism theory to argue that widespread terracing transpired only after the Spanish arrived in Luzon, we can create a feasible model for OKV in 1570 CE. This model describes a configuration of pre-Spanish land use in Ifugao that can be tested in future research. Our template diagram for OKV in 1570 is presented in **Figure 3**. This diagram assumes the population was 568, and the settlement circle was ~2.7 ha, half the size of the settlement in 1800, and no rice was grown in the village as per the pericolonialism hypothesis (see also Horrocks et al., 2018). Instead, terraces were used to grow a portion of OKV's taro. We assume taro constituted 32% of annual diets, while yams comprised 44.3% of annual diets (sweet potatoes not having been introduced yet constituted 0% of diets). We expect 12% of taro was grown in terraces while the remaining taro and all yams were grown in swidden fields. This would require ~177 ha of active fields, ~354 ha of fallow fields, and ~13.3 ha of terraces (meaning the agricultural and residential terraces together amounted to ~16 ha of land). Additionally, our model calculations predict half as much highly managed forest would have been needed for a population of 568, so OKV in 1570 would have required ~46 ha of *muyong* (3.02 ha for fruits, 42.60 ha for fuel). And lastly, our model expects ~30 ha of unmanaged forests were used for pigs to browse.

Zooarchaeological evidence is inconclusive on whether OKV in 1570 possessed or consumed carabao. For this model, as per Acabado's hypothesis (2017), we assume carabao were not consumed or raised in OKV in 1570. We do expect OKV raised and consumed domesticated chickens and pigs as well as hunted game in similar proportions to OKV in 1800. However, because the Ifugao region's population density would have been lower (half what it was in 1800, based on our models' existing assumptions), the amount of land available for hunting would have been greater in 1570 than in 1800.

In total, our model concludes OKV circa 1570 would have required ~2,013 ha of land. Of this land, 623 ha of land would have been dedicated to all activities except hunting. This is in contrast to OKV in 1800, which required ~2,113 ha of land, of which only ~723 ha were dedicated to all activities aside from hunting. Therefore, our models suggest increased terracing and the switch from taro to rice, as well as the introduction of sweet potato, permitted OKV's population to double without greatly increasing the amount of land devoted to starch production. Further, even the addition of grazing animals like carabao by 1800 does not change or challenge this conclusion. This minimization of high intensity agricultural activity undoubtedly helped OKV preserve wild deer and pigs' habitats and therefore continue to practice widespread hunting. This, and the highly sustainable *muyong-uma-payo* system of integrated agriculture all indicate historic Ifugao society was premised on a stable pattern of land use that, when bolstered by commerce with the lowlands,

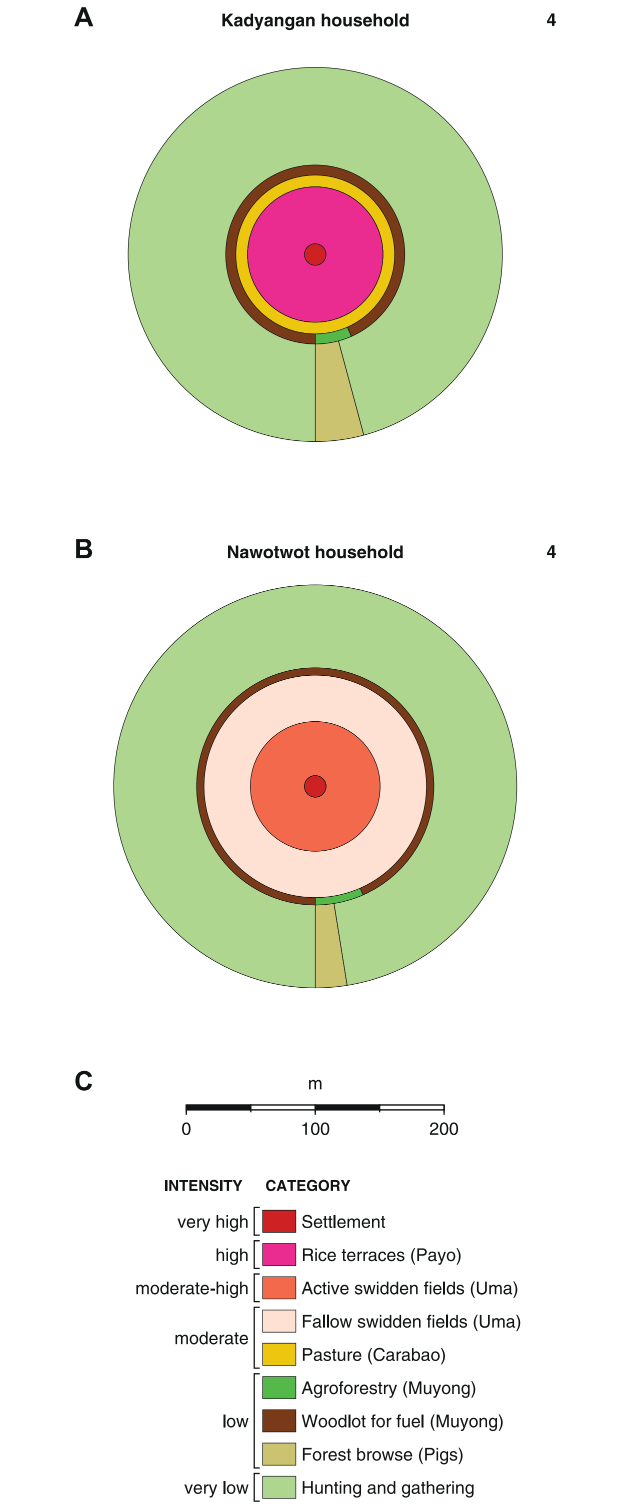

FIGURE 4 | Circle diagrams describing the hypothetical land use of a *kadangyan* family of 4 **(**Panel **A)** and a *nawotwot* family of 4 **(**Panel **B)**. As with **Figure 3**, a legend with a scale is also included **(**Panel **C)**. In each panel, the number in the upper right corner represents the population whose land use is being modelled.

permitted large populations to survive and maintain independence in the Cordillera.

The points of uncertainty in our model, discussed in the methodology, do not challenge this conclusion. In the **Supplementary Material**, we model scenarios for the 1800 CE timepoint with the potential to change our conclusion. We do not model for 1570 because less palaeoecological data is available for this timepoint, and our model for it is primarily based upon the pericolonialism hypothesis. Our scenarios for the 1800 timepoint include: varying the population of OKV; varying the daily caloric intake of individuals at OKV; varying the amount of *gattuk* and *iuktu* grown at OKV; removing the carabao herd at OKV; adding a goat herd to OKV; modelling a failed rice harvest at OKV caused by a strong typhoon or similar natural hazard; and modelling how hunting ranges could be affected by Ifugao's historic population density. These scenarios confirm the amount of land used for all activities except hunting varied from 543 ha at minimum to ~998 ha at maximum. All confirm intensive land use would not have increased proportionally with population, suggesting Ifugao land use in 1800 was markedly more consolidated than in 1570; was remarkably efficient; and did not rely on extensive deforestation but instead maintained *muyong* as well as public forests and hunting grounds.

Exploring Social Difference: *Kadangyan* and *Nawotwot* Land Use in 1800

The land used to feed a family of *kadangyan* was distinct from the land used to feed a family of *nawotwot,* and the land use model calculations can reflect this (Hughes et al., 2018). In **Figure 4**, we present two circle diagrams depicting the land use associated with two families of four individuals. Panel A depicts *kadangyan* land use and panel B depicts *nawotwot* land use. For this diagram, we gave each family an idealized diet, representing the wealthiest *kadangyan* family possible and the poorest *nawotwot* family possible. The *kadangyan* in this diagram are imagined to have consumed only rice and taro as starches, while the *nawotwot* consumed only yams and sweet potatoes as starches. Both imagined families, however, are presumed to consume the same proportion of starches annually (~76.2% of their total diet). Additionally, the *kadangyan* in our scenario consumed carabao and a larger proportion of domesticated pigs than the *nawotwot,* who would have owned and sacrificed fewer pigs and no carabao (see section 3.3.5).

Our models indicate that a *kadangyan* family of four, given these parameters, would require 6.62 ha of land to subsist for a year. That land would be divided as follows: 0.02 ha for living space, 0.84 ha for terraces, 0.33 ha for pastureland, 0.32 ha for *muyong*, 0.21 ha of forest for pigs to browse, and 4.89 ha for hunting. By contrast, the *nawotwot* family would require the same amount of land for hunting, *muyong*, and living space, but no land for terraces or pasture for carabao. Instead, they would require 0.77 ha of active *uma,* 1.55 ha of fallow *uma,* and 0.13 ha forest for pigs to browse. Altogether then, the *nawotwot* family would need 2.79 ha of actively modified land per year to subsist, while the *kadangyan* family of the same size would require 1.73 ha of land.

The diagrams presented in **Figure 4** help explain how land use in the 1800 timepoint did not double from 1570, despite the population doubling. *Payo*, a hallmark of the *kadangyan* class, use less land than *uma*. In a village like OKV, which evidence suggests was more suitable to rice agriculture than most of Ifugao (Barton, 1922), this means a high proportion of the population could have utilized *payo,* and their consumption of rice would have helped decrease land use even as the population grew. Nonetheless, it should be noted that a *kadangyan* family of four could not exist in a vacuum. While terrace construction does not require generations of laborers as once supposed (Acabado et al., 2019), building and maintaining them does take a village. As Conklin (1980) observed, a hectare of highland terrace requires 630 human days of labor per year to maintain, while a swidden field of the same size only requires 250 days. Therefore, without a large population, the Ifugao terraces would not be viable. The same principal applies to hunting for both *kadangyan* and *nawotwot*. Hunting was not undertaken by family units but instead was a community endeavor. Again, the hypothetical families we model here did not exist in a vacuum, but were instead part of a community that enabled them to enact this specific land use pattern.

DISCUSSION

In this study, we modelled land use in OKV in 1570 and 1800 CE. Using data gathered from ethnography, anthropology, archaeology, and history, our model calculations quantify how population growth and social differentiation affected land use in OKV circa 1800 CE, reaffirming that land use modelling can be used successfully to quantify how social status affects a society's ecological impact (Hughes et al., 2018). Furthermore, by applying the pericolonialism hypothesis advanced by Acabado (2017), we were able to estimate land use in OKV circa 1570 CE. Our calculations show that the adoption of intensive rice agriculture and widespread terracing, as well as the adoption of sweet potato, could have permitted OKV's population in 1800 to be double what it was in 1570 without experiencing a proportional increase in intensive land use and deforestation.

Our models confirm, as several earlier studies suggested, that the *muyong-uma-payo* complex was a highly efficient and sustainable land use system. It is often assumed that societies will abandon extensive agriculture (i.e., swidden techniques) for intensive agriculture (i.e., terracing) as their populations increase (for examples, see Geertz, 1963; Boserup, 1965; Chrisholm, 2007) and that this in turn, will have deleterious impacts on the landscape in the form of forest clearance, biodiversity declines, and soil nutrient losses. Historic Ifugao's tandem agriculture not only contradicts this theory but also developed in a non-state society where status was derived from prestige crops and feasting. Our model calculations instead confirm the value of an agricultural system reliant on both terracing and swidden techniques. Ifugao's distinctive agroforestry system also sustained OKV and the Tuwali-Ifugao during their prolonged resistance to imperial subjugation by maintaining widespread forests that provided essential resources and a habitat for wild game. The necessity of extensive *muyong* and public forests suggests population increase would not have led inexorably to deforestation or the denuding of mountain sides. Further, unlike lowland paddy fields, rice terraces would not have contributed to soil degradation due to a combination of traditional "green fertilizer" (mulch) and the rigorously maintained irrigation system used to replenish the ponds' water and soil (Sione et al., 2017). Instead, the effects of increased population were likely more subtle and could have included the deliberate or unintended favoring of trees that grew faster at higher elevations (e.g., pioneer forest taxa) or the increased growth of usable tree species. Alternatively, certain utilizable species might have been depleted faster, causing them to become rarer in the Ifugao highlands, similar to how deforestation progressed in the Spanish-colonized lowlands (Bankoff, 2013). Our models, which do not model specific trees, cannot discern which outcome was more likely.

Ultimately, then, the *muyong-uma-payo* complex provided the basis for an alternative lifestyle to the colonial lowlands, which were increasingly subject to commercialized, extractive world systems in the 19th century (Wallerstein, 1989; Acabado et al., 2019). Instead, labor-intensive rice production provided a physical basis for social cohesion (Acabado, 2018; Acabado et al., 2019) that was also integrated with Ifugao spirituality and myth (Eliade et al., 1959; Conklin, 1980), ultimately providing a venue for Ifugao society to produce and reproduce itself through annual cultivation and terracing (Merchant, 1980). Our model calculations cannot explain how the Ifugao peoples resisted conquest for centuries, but they do elucidate the underlying socio-ecological regime that permitted this pericolonial society to thrive. Its apparent success, especially in a highland environment often imagined as less productive than lowland plains, evokes comparisons to the Indigenous Maya *milpa* system (Ford and Nigh, 2015), the Inka of the Andes (Chepstow-Lusty and Jonsson, 2000), and swidden farmers in the highlands of mainland Southeast Asia (especially the Zomia region denoted by Scott, 2009; see also Hamilton et al., 2020). Like the Ifugao, Indigenous populations in these areas practiced, and still practice, highly innovative, sustainable, and integrated forms of agriculture and agroforestry that contrast strongly with modern techniques that emphasize high productivity and clearance.

The limitations in our calculations suggest ways historical land use models might be improved in the future. First, they could better incorporate nutritional data and thereby incorporate research from historical ecology and associated fields (see, for instance, Moran, 2015). Second, our models do not account for commerce, even though it was Ifugao's production and trade in tobacco that ultimately precipitated Galvey's expedition (Scott, 1974). Providing a more in-depth account of trade will be essential, then, to improving these models and applying them to less well-studied Philippine societies and provinces where dietary proportions are not known. Lastly, our models may be further developed using GIS to map our diagrams onto physical landscapes to create complete land use maps that visualize how specific villages and towns could have developed over time. Alternatively, an adjusted form of this model might be applied through GIS to chart the impact of anthropogenic land use on forest cover throughout Ifugao and the southeast Cordillera, akin to work performed by Kay et al. (2019) and the LandCover6k project (Morrison et al., 2021).

As these lacunae are filled, it will be possible to generate historical land use model calculations for other Philippine provinces, both in the pre-Spanish period and during the colonial eras (1565–1946). This quantification, especially once validated by palaeoecological and archival records, will facilitate comparisons between different ethno-linguistic groups' land use strategies and help illustrate historic differences between Philippine societies, such as: customs regarding ownership of land and animals, status differentiation, apportionment of labor, and the penetration of regional market and commercial pressures into Philippine villages in the 18th and 19th centuries (Larkin, 1982). Furthermore, land use models applied to specific landscapes can inform research into historic deforestation, especially in provinces where written records are scarce. Such diagrams could serve as a launching point for historic and anthropological investigations, archaeological fieldwork, and historical ecology and geography, ultimately furthering research into regional and global estimates of past human impacts on landscapes (Pongratz et al., 2008; Kaplan et al., 2009; Kaplan et al. 2011; Kaplan et al. 2012; Kaplan et al. 2017; Klein Goldjewijk et al., 2011; Mahli et al., 2014; Kay et al., 2019). Last of all, if diagrams akin to the ones presented in this paper were expanded to cover even the remainder of the Cordillera, they could help visualize for the first time the diverse socio-ecological histories of numerous peoples as well as the spatial scales of human-environment interactions in this part of the tropics.

DATA AVAILABILITY STATEMENT

The input data and land use model used in this study are contained in the **Supplementary Material**, and the model output and plotting scripts are archived in Kaplan (2022).

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2022.680926/full#supplementary-material

REFERENCES

Acabado, S., Barretto-Tesoro, G., and Amano, N. (2018). Status Differentiation, Agricultural Intensification, and Pottery Production in Precapitalist Kiyyangan, Ifugao, Philippines. *Archaeological Res. Asia* 15, 55–69. doi:10.1016/j.ara.2017.10.004

Acabado, S. B., Koller, J. M., Liu, C.-h., Lauer, A. J., Farahani, A., Barretto-Tesoro, G., et al. (2019). The Short History of the Ifugao Rice Terraces: A Local Response to the Spanish Conquest. *J. Field Archaeology* 44, 195–214. doi:10.1080/00934690.2019.1574159

Acabado, S. B. (2012a). Taro before Rice Terraces: Implications of Radiocarbon Determinations, Ethnohistoric Reconstructions, and Ethnography in Dating the Ifugao Terraces. *Senri Ethnological Ser.* 78, 285–305.

Acabado, S. (2013). Defining Ifugao Social Organization: "House," Field, and Self-Organizing Principles in the Northern Philippines. *Asian Perspect.* 52 (2), 161–189. doi:10.1353/asi.2013.0009

Acabado, S., and Martin, M. (2016). The Sacred and the Secular: Practical Applications of Water Rituals in the Ifugao Agricultural System. *TRaNS* 4 (2), 307–327. doi:10.1017/trn.2016.7

Acabado, S. (2017). The Archaeology of Pericolonialism: Responses of the "Unconquered" to Spanish Conquest and Colonialism in Ifugao, Philippines. *Int. J. Histor Archaeol* 21, 1–26. doi:10.1007/s10761-016-0342-9

Acabado, S. (2012b). The Ifugao Agricultural Landscapes: Agro-Cultural Complexes and the Intensification Debate. *J. Southeast. Asian Stud.* 43 (3), 500–522. doi:10.1017/s0022463412000367

Acabado, S. (2018). Zones of Refuge: Resisting Conquest in the Northern Philippine highlands through Environmental Practice. *J. Anthropological Archaeology* 52, 180–195. doi:10.1016/j.jaa.2018.05.005

Ali, N. A. N. G., Abdullah, M. L., Nor, S. A. M., Pau, T. M., Kulaimi, N. A. M., and Naim, D. M. (2021). A Review of the Genus Rusa in the Indo-Malayan Archipelago and Conservation Efforts. *Saudi J. Biol. Sci.* 28, 10–26. doi:10.1016/j.sjbs.2020.08.024

Amano, N., Bankoff, G., Findley, D. M., Barretto-Tesoro, G., and Roberts, P. (2020). Archaeological and Historical Insights into the Ecological Impacts of Pre-colonial and Colonial Introductions into the Philippine Archipelago. *The Holocene* 31 (2), 313–330. doi:10.1177/0959683620941152

Antolin, F., and Scott, W. H. (1970). Notices of the Pagan Igorots in 1789. *Asian Folklore Stud.* 29, 177–249. doi:10.2307/1177612

Bacquira, P. B. (2012). *Ubi Production Guide*. Manila: Department of Agriculture Philippines.

Bankoff, G. (2013). "Deep Forestry": Shapers of the Philippine Forests. *Environ. Hist.* 18, 523–556. doi:10.1093/envhis/emt037

Bankoff, G. (2009). "Cultures of Disaster, Cultures of Coping: Hazard as a Frequent Life Experience in the Philippines," in *Natural Disasters, Cultural Responses: Case Studies toward a Global Environmental History*. Editors C. Mauch and C. Pfister (Plymouth, UK: Lexington Books), 265–284.

Bankoff, G. (2003). *Cultures of Disaster: Society and Natural Hazards in the Philippines*. London and New York: Routledge.

Barretto-Tesoro, G. (2007). Symbols of an Ifugao Thanksgiving Ritual. *Chronicle. Univ. Philippines Archaeological Stud. Program* 11, 13–15.

Barton, R. F. (1922). *Ifugao Economics*. Berkeley: University of California.

Barton, R. F. (1919). Ifugao Law. *Univ. Calif. Publications Am. Archaeology Ethnology* 15, 1–186.

Beyer, H. O. (1955). The Origins and History of the Philippine rice Terraces*Proc. Eighth Pac. Sci. Congress*, 1953. Quezon City: National Research Council, 387–398.

Bhatt, B. P., and Tomar, J. M. S. (2002). Firewood Properties of Some Indian Mountain Tree and Shrub Species. *Biomass and Bioenergy* 23, 257–260. doi:10.1016/s0961-9534(02)00057-0

Binford, L. (2001). *Constructing Frames of Reference: An Analytical Method for Archaeological Theory Building Using Hunter-gatherer and Environmental Data Sets*. Berkeley and Los Angeles: University of California Press.

Blair, E. H., and Robertson, J. A. (1909). *The Philippine Islands, 1493-1898, Volumes I-LV*. Cleveland, Ohio: Arthur H. Clark.

Boserup, E. (1965). *The Conditions of Agricultural Growth: The Economics of Agrarian Change under Population Pressure*. Chicago: Aldine Publishing.

Bray, F. (1994). *The Rice Economies: Technology and Development in Asian Societies*. Berkeley, Los Angeles, and London: University of California.

Brosius, J. P. (1988). Significance and Social Being in Ifugao Agricultural Production. *Ethnology* 27 (1), 97–110. doi:10.2307/3773563

Chepstow-Lusty, A., and Jonsson, P. (2000). Inca Agroforestry: Lessons from the Past. *AMBIO: A J. Hum. Environ.* 29 (6), 322–328. doi:10.1579/0044-7447-29.6.322

Chrisholm, M. (2007). *Rural Settlements and Land Use*. First Edition. London: Routledge.

Conklin, H. C. (1980). *Ethnographic Atlas of Ifugao: A Study of Environment, Culture, and Society in Northern Luzon*. New Haven and London: Yale University.

Conklin, J. M. (2002). *An Ifugao Notebook*. US: The Author.

Costa, H. de. la. (1967). *The Jesuits in the Philippines*. Cambridge, U.S.A.: Harvard University, 1581–1768.

Cushman, G. T. (2013). *Guano and the Opening of the Pacific World: A Global Ecological History*. Cambridge: Cambridge University.

de Jesus, E. C. (1998). *The Tobacco Monopoly in the Philippines: Bureaucratic Enterprise and Social Change*. Third Edition. Manila: Ateneo de Manila, 1766–1880.

de S. Wijesinghe, L. C. A. (1984). A Sample Study of Biomass Fuel Consumption in Sri Lanka Households. *Biomass* 5, 261–282. doi:10.1016/0144-4565(84)90073-8

Dinerstein, E., Olson, D., Joshi, A., Vynne, C., Burgess, N. D., Wikramanayake, E., et al. (2017). An Ecoregion-Based Approach to Protecting Half the Terrestrial Realm. *Bioscience* 67 (6), 534–545. doi:10.1093/biosci/bix014

Donovan, D. J. (1981). *Fuelwood: How Much Do We Need?* Hanover NH): Institute of Current World Affairs, 1–23.

Eliade, M., transand Trask, W. R. (1959). *The Sacred and the Profane: The Nature of Religion*. New York and London: Harvest/Harcourt Brace Jovanovich.

Espino, R. R. C., Jamaluddin, S. H., Silayoi, B., and Nasution, R. E. (1991). "Musa L. (Edible Cultivars)," in *On Proseabase*. Editors E. W. M. Verheij, R. E. Coronel, and Bogor (Indonesia: PROSEA. . http://www.proseanet.org (Accessed Feb. 16, 2021).

Eusebio, M. S., Ceron, J. R., Acabado, S. B., and Krigbaum, J. (2015). Rice Pots or Not? Exploring Ancient Ifugao Foodways through Organic Residue Analysis and Paleoethnobotany. *Nat. Mus. J. Cult. Her.* 1 (1), 11–20.

Food and Agriculture Organization(2021). FAOSTAT. Available at: http://www.fao.org/faostat/en/#home (Accessed Jan. 20, 2021).

Ford, A., and Nigh, R. (2015). *The Maya Forest Garden: Eight Millennia of Sustainable Cultivation of the Tropical Woodlands*. London: Routledge.

Fuller, D. Q., Van Etten, J., Manning, K., Castillo, C., Kingwell-Banham, E., Weisskopf, A., et al. (2011). The Contribution Of Rice Agriculture And Livestock Pastoralism To Prehistoric Methane Levels: An Archaeological Assessment. *The Holocene* 21 (5), 743–759.

Gaillard, M-J., Morrison, K. D., Madella, M., and Whitehouse, N. (2018). Past Land-Use and Land-Cover Change: The challenge of Quantification at the Subcontinental to Global Scales. *Past Glob. Changes Mag.* 26 (1), 3. doi:10.22498/pages.26.1.3

Geertz, C. (1963). *Agricultural Involution: The Processes of Ecological Change in Indonesia*. Berkeley: University of California.

Greenland, D. J. (1997). *The Sustainability of Rice Farming*. Wallingford, U.K.: CAB International.

Gregg, S. A. (1988). *Foragers and Farmers: Population Interaction and Agricultural Expansion in Prehistoric Europe*. Chicago and London: University of Chicago.

Hamilton, R., Penny, D., and Hall, T. L. (2020). Forest, Fire & Monsoon: Investigating the Long-Term Threshold Dynamics of South-East Asia's Seasonally Dry Tropical Forests. *Quat. Sci. Rev.* 238, 106334. doi:10.1016/j.quascirev.2020.106334

Harrison, S. P., Stocker, B. D., Goldewijk, K. K., Kaplan, J. O., and Braconnet, P. (2018). Do we Need to Include Anthropogenic Land-Use and Land-Cover Changes in Paleoclimate Simulations? *Past Glob. Changes Mag.* 26 (1), 4–5. doi:10.22498/pages.26.1.4

Hartemink, A. E., Johnston, M., O'Sullivan, J. N., and Poloma, S. (2000). Nitrogen Use Efficiency of Taro and Sweet Potato in the Humid Lowlands of Papua New Guinea. *Agric. Ecosyst. Environ.* 79, 271–280. doi:10.1016/s0167-8809(00)00138-9

Hayama, A. (2003). "Local Forest Management in the Rice Terrace Area of Banaue, the Philippines," in *People and Forest—Policy and Local Reality in Southeast Asia, the Russian Far East, and Japan*. Editors M. Inoeu and H. Isozaki (Tokyo: Springer Science and Business), 275–286. doi:10.1007/978-94-017-2554-5_18

Horrocks, M., Acabado, S., and Peterson, J. (2018). Plant Microfossil Results from Old Kiyyangan Village: Looking for the Introduction and Expansion of Wet-Field Rice (*Oryza Sativa*) Cultivation in the Ifugao Rice Terraces, Philippine Cordilleras. *Asian Perspect.* 57 (1), 159–176. doi:10.1353/asi.2018.0005

Hughes, R., Weiberg, E., Bonnier, A., Finné, M., and Kaplan, J. (2018). Quantifying Land Use in Past Societies from Cultural Practice and Archaeological Data. *Land* 7, 9. Land 7. doi:10.3390/land7010009

Huynh, T. T. T., Aarnink, A. J. A., Drucker, A., and Verstegen, M. W. A. (2007). Pig Production in Cambodia, Laos, Philippines, and Vietnam: A Review. *Asian J. Agric. Dev.* 3 (1-2), 69–87.

Ipac-Alarcon, N. (1991). *Philippine Architecture during the Pre-Spanish and Spanish Periods*. Manila: Santo Tomas University.

Izdebski, A., Holmgren, K., Weiberg, E., Stocker, S. R., Büntgen, U., Florenzano, A., et al. (2016). Realising Consilience: How Better Communication between Archaeologists, Historians and Natural Scientists Can Transform the Study of Past Climate Change in the Mediterranean. *Quat. Sci. Rev.* 136, 5–22. doi:10.1016/j.quascirev.2015.10.038

Jang, J. W., and Salcedo, S. (2013). "The Socio-Political Structure That Regulates The Ifugao Forest Maintenance," In Proceedings of the 4th International Conference on Biology, Environment and Chemistry (IPCBEE), Phuket, Thailand 58, 85–94.

Kaplan, J., Krumhardt, K., Gaillard, M.-J., Sugita, S., Trondman, A.-K., Fyfe, R., et al. (2017). Constraining the Deforestation History of Europe: Evaluation of Historical Land Use Scenarios with Pollen-Based Land Cover Reconstructions. *Land* 6, 91. doi:10.3390/land6040091

Kaplan, J. O. (2022). *ARVE-Research/circlediagram: Pericolonial Ifugao (v1.0.1)*. Zenodo. doi:10.5281/zenodo.5991796

Kaplan, J. O., Krumhardt, K. M., Ellis, E. C., Ruddiman, W. F., Lemmen, C., and Goldewijk, K. K. (2011). Holocene Carbon Emissions as a Result of Anthropogenic Land Cover Change. *The Holocene* 21, 775–791. doi:10.1177/0959683610386983

Kaplan, J. O., Krumhardt, K. M., and Zimmermann, N. E. (2012). The Effects of Land Use and Climate Change on the Carbon Cycle of E Urope over the Past 500 Years. *Glob. Change Biol.* 18, 902–914. doi:10.1111/j.1365-2486.2011.02580.x

Kaplan, J. O., Krumhardt, K. M., and Zimmermann, N. (2009). The Prehistoric and Preindustrial Deforestation of Europe. *Quat. Sci. Rev.* 28, 3016–3034. doi:10.1016/j.quascirev.2009.09.028

Kay, A. U., Fuller, D. Q., Neumann, K., Eichhorn, B., Höhn, A., Morin-Rivat, J., et al. (2019). Diversification, Intensification and Specialization: Changing Land Use in Western Africa from 1800 BC to AD 1500. *J. World Prehist.* 32, 179–228. doi:10.1007/s10963-019-09131-2

Kay, A. U., and Kaplan, J. O. (2015). Human Subsistence and Land Use in Sub-saharan Africa, 1000BC to AD1500: A Review, Quantification, and Classification. *Anthropocene* 9, 14–32. doi:10.1016/j.ancene.2015.05.001

Keesing, F. M. (1962). *The Ethnohistory of Northern Luzon*. Stanford, CA: Stanford University.

Klein Goldjewijk, K., Beusen, A., Van Drecht, G., and De Vos, M. (2011). The Hyde 3.1 Spatially Explicit Database of Human-Induced Global Land-Use over the Past 12,000 Years. *Glob. Ecol. Biogeogr.* 20, 73–86.

Koch, A., Brierley, C., Maslin, M. M, and Lewis, S. L. (2019). Earth System Impacts of the European Arrival and Great Dying in the Americas after 1492. *Quat. Sci. Rev.* 207, 13–36.

Kowal, N. E. (1966). Shifting Cultivation, Fire, and pine forest in the Cordillera Central, Luzon, Philippines. *Ecol. Monogr.* 36 (4), 389–419. doi:10.2307/1942374

Kuhnlein, H. V., Smitasiri, S., Yesudas, S., Bhattacharjee, L., Dan, L., and Ahmed, S. (2006). *Documenting Traditional Food Systems of Indigenous Peoples: International Case Studies, Guidelines for Procedures*. Montreal: Center for Indigenous Peoples Nutrition and Environment, FAO.

Kumar Jain, R. (1992). Fuelwood Characteristics of Certain Hardwood and Softwood Tree Species of India. *Bioresour. Tech.* 41, 129–133. doi:10.1016/0960-8524(92)90182-w

Ladurie, E. L. R. (1971). *Times of Feast, Times of Famine: A History of Climate since the Year 1000, Trans. B. Bray*. London: George Allen and Unwin.

Lamb, H. H. (1997). *Climate, History, and the Modern World*. 2nd Edition. London and New York City: Routledge.

Lambrecht, F. (1954). Genealogical Trees of Kiangan, Ifugao. *JEAS* 3, 366–369.

Lambrecht, F. (1953). Genealogical Trees of Mayawyaw. *JEAS* 2, 21–28.

Lambrecht, F. (1967). The Hudhud of Dinulawan and Bugan at Gonhadan. *Saint Louis Q.* 5, 267–713.

Lamoreax, J. (2021). Southeast Asia: Island of Luzon in the Philippines. Available at: https://www.worldwildlife.org/ecoregions/im0302 (accessed Feb. 2, 2021).

Lapeña, Q. G., and Acabado, S. B. (2017). Resistance through Rituals: The Role of Philippine "Native Pig" (*Sus scrofa*) in Ifugao Feasting and Socio-Political Organization. *J. Archaeol Sci. Rep.* 13, 583–594.

Larkin, J. A. (1982). Philippine History Reconsidered: A Socioeconomic Perspective. *Am. Hist. Rev.* 87 (3), 595–628. doi:10.2307/1864158

Lauer, J., and Acabado, S. B. (2015). Infant Death and Burial Practices in Late Prehistoric Kiyyangan Village, Ifugao. *Natl. Mus. J. Cult. Heritage* 1 (1), 31–38.

Ledesma, C. P., Amano, N., and Acabado, S. B. (2015). Faunal Remains Recovered from the Old Kiyyangan Village, Kiangan, Ifugao. *Nat. Mus. J. Cult. Her.* 1 (1), 21–29.

Ma, T., Rolett, B. V., Zheng, Z., and Zong, Y. (2020). Holocene Coastal Evolution Preceded the Expansion of Paddy Field rice Farming. *Proc. Natl. Acad. Sci. USA* 117, 24138–24143. doi:10.1073/pnas.1919217117

MacRae, G. (2016). Food Sovereignty and the Anthropology of Food: Ethnographic Approaches to Policy and Practice. *Anthropological Forum* 26 (3), 227–232. doi:10.1080/00664677.2016.1201456

Maher, R. F. (1973). Archaeological Investigations in Central Ifugao. *Asian Perspect.* 16 (1), 39–71.

Maher, R. F. (1984). Kiyyangan Village of Ifugao Province, Philippines. *Philipp. Q. Cult. Soc.* 12 (2), 116–127.

Mahli, Y., Gardner, T. A., Goldsmith, G. R., Silman, M. R., and Zelazowski, P. (2014). Tropical Forests in the Anthropocene. *Annu. Rev. Environ. Resour.* 39, 125–159.

Manuta, J. B. (1993). Tenurial Arrangements and Forest Resource Management in Halicap, Kiangan, Ifugao, Northern Philippines. Doctoral dissertation Los Banos: University of the Philippines.

Merchant, C. (1980). *The Death of Nature: Women, Ecology, and the Scientific Revolution*. New York City: Harper.

Moran, M. (2015). Nutritional Ecology in Old Kiyyangan Village. *Philipp. Q. Cult. Soc.* 43 (3-4), 322–338.

Morga, A. (1971). "J.S. Cummins.," in *Sucesos de las Islas Filipinas, trans* (Cambridge: Cambridge University).

Morrison, K. D., Hammer, E., Boles, O., Madella, M., Whitehouse, N., Gaillard, M.-J., et al. (2021). Mapping Past Human Land Use Using Archaeological Data: A New Classification for Global Land Use Synthesis and Data Harmonization. *PLoS ONE* 16 (4), e0246662. doi:10.1371/journal.pone.0246662

Morrison, K. D., Hammer, E., Popova, L., Madella, M., Whitehouse, N., Gaillard, M-J., et al. (2018). Global-scale Comparisons of Human Land Use: Developing Shared Terminology for Land-Use Practices for Global Change. *Past Glob. Changes Mag.* 26 (1), 8–9. doi:10.22498/pages.26.1.8

Newson, L. (2009). *Conquest and Pestilence in the Early Spanish Philippines*. Honolulu: University of Hawai'i.

Olson, D. M., and Dinerstein, E. (2002). The Global 200: Priority Ecoregions for Global Conservation. *Ann. Mo. Bot. Garden* 89 (2), 199–224. doi:10.2307/3298564

Olson, D. M., Dinerstein, E., Wikramanayake, E. D., Burgess, N. D., Powell, G. V. N., Underwood, E. C., et al. (2001). Terrestrial Ecoregions of the World: A New Map of Life on Earth. *BioScience* 51 (11), 933–938. doi:10.1641/0006-3568(2001)051[0933:teotwa]2.0.co;2

Ortman, S. G., Cabaniss, A. H. F., Sturm, J. O., and Bettencourt, L. M. A. (2014). The Pre-history of Urban Scaling. *PLoS ONE* 9 (2), e87902. doi:10.1371/journal.pone.0087902

Peralta, J. T. (1982). "I'wak Alternative Strategies for Subsistence: A Micro-economic Study," in *The I'wak of Boyasyas, Nueva Vizcaya, Philippines*. Manila: National Museum of the Philippines.

Phelan, J. L. (1967). *The Hispanization of the Philippines: Spanish Aims and Filipino Responses*. Second Edition. Madison, Wisconsin: University of Wisconsin, 1565–1700.

Philippine Statistics Authority (2018). *Crop Statistics of the Philippines, 2013-2017*. Quezon City: Philippine Statistics Authority.

Picornell-Gelabert, L. (2020). An Archaeological Approach to People-Tree Interactions: The Ethnoarchaeology of Firewood Procurement and Consumption Among the Benga People of the Island of Mandji (Corisco, Equatorial Guinea, Central Africa). *J. Archaeological Sci. Rep.* 34, 102591. doi:10.1016/j.jasrep.2020.102591

Pongratz, J., Reick, C., Raddatz, T., and Claussen, M. (2008). A Reconstruction Of Global Agricultural Areas And Land Cover For The Last Millennium. *Global Biogeochem. Cycles* 22 (3).

Rabena, M. A. F., Macandog, D. M., Cuevas, V. C., and Espaldon, V. O. (2015). A Vegetation Inventory of a Traditional Secondary forest (*Muyong*) in Kinakin, Banaue, Ifugao, Northern Luzon, Philippines. *Phil. J. Syst. Bio.* 9, 10–32.

Reid, L. A. (1994). "Terms for Rice Agriculture and Terrace Building in Some Cordilleran Languages of the Philippines," in *Austronesian Terminologies: Continuity and Change (Pacific Linguistics C-127)*. Editors A. K. Pawley and M. D. Ross (Canberra: Australian National University), 363–388.

Reuter, T. A. (2018). "Seeds of Life, Seeds of Hunger: Corporate Agendas, Agricultural Development Policy and the Struggle for Seed Sovereignty," in *Anthropology of Food* (East Timor, Indonesia. http://journals.openedition.org/aof/8135.

Rick, T. C., and Sandweiss, D. H. (2020). Archaeology, Climate, and Global Change in the Age of Humans. *Proc. Natl. Acad. Sci. USA* 117 (15), 8250–8253. doi:10.1073/pnas.2003612117

Roberts, P., Boivin, N., and Kaplan, J. O. (2018). Finding the Anthropocene in Tropical Forests. *Anthropocene* 23, 5–16. doi:10.1016/j.ancene.2018.07.002

Sajor, E. (1999). "Cutting Trees and the Dynamics of Social Change: The Case of the Ifugao Muyong in the Philippine Uplands," in *The Hague: Working Papers* (Institute of Social Sciences Series No), 294.

Santos-Acuin, C., Gepte, A. T. I. V., and Dedace, M. J. (1997). *Community Food Sources Journal. The Aetas of Morong, Bataan, Philippines*. Manila: The Research Institute of Tropical Medicine.

Scott, J. C. (2009). *The Art of Not Being Governed*. New Haven: Yale University Press.

Scott, W. H. (1982). *Cracks in the Parchment Curtain and Other Essays in Philippine History*. New Day: Quezon City.

Scott, W. H. (1975). *German Travellers on the Cordillera (1860-1890)*. Manila: The Filipiniana Book Guild.

Scott, W. H. (1970). Igorot Responses to Spanish Aims 1576-1896. *Philipp. Stud.* 18 (4), 695–717. doi:10.1136/bmj.3.5724.695-a

Scott, W. H. (1966). *On the Cordillera: A Look at the Peoples and Culture of the Mountain Province*. Manila: MCS Enterprises Inc.

Scott, W. H. (1974). *The Discovery of the Igorots: Spanish Contacts with the Pagans of Northern Luzon*. Revised edition. New Day: Quezon City.

Serrano, R. C., and Cadaweng, E. A. (2005). "The Ifugao Muyong: Sustaining Water, Culture and Life," in *In the Search of Excellence: Exemplary Forest Management in Asia and the Pacific*. Editors P. B. Durst, C. Brown, H. D. Tacio, and M. Ishikawa (Bangkok: FAO), 103–112.

Sione, S. M. J., Wilson, M. G., Lado, M., and González, A. P. (2017). Evaluation of Soil Degradation Produced by rice Crop Systems in a Vertisol, Using a Soil Quality index. *Catena* 150, 79–86. doi:10.1016/j.catena.2016.11.011

Tepper, L. M. (2013). *Squash Production Guide*. Los Baños, Philippines: Department of Agriculture Bureau of Plant Industry.

Tulin, A. B. (2014). Enhancing Productivity, Profitability, and Quality of Root Crops and Vegetables through Macro- and Micronutrient Fertilization. *Searca Agric. Dev. Discussion Paper Ser.* 2014-2, 1–60.

Tulin, A. (2009). Improvement of the Growth, Yield, and Tuber Quality of Purple Yam through Macro and Micronutrient Fertilization. *Atr* 31 (2), 95–119. doi:10.32945/atr3125.2009

UNESCO (1995). Rice Terraces of the Philippine Cordilleras. Available at: https://whc.unesco.org/en/list/722 (Accessed Jan. 24, 2021).

Valmayor, R. V., Espino, R. R. C., and Pascua, O. C. (2002). *The Wild and Cultivated Bananas of the Philippines*. Los Baños, Philippines: PARRFI.

Valmayor, R. V., Jamaluddin, S. H., Silayoi, B., Kusumo, S., Danh, L. D., Pascua, O. C., et al. (2000). *Banana Cultivar Names and Synonyms in Southeast Asia*. Montpellier, France: INIBAP.

Vandermeer, C. (1967). Population Patterns on the Island of Cebu, the Philippines: 1500 to 1900. *Ann. Assoc. Am. Geogr.* 57 (2), 315–337. doi:10.1111/j.1467-8306.1967.tb00606.x

Wallerstein, I. (1989). "The Modern World-System, Vol. III," in *The Second Great Expansion of the Capitalist World-Economy* (San Diego: Academic Press), 1730–1840s.

Weiberg, E., Hughes, R. E., Finné, M., Bonnier, A., and Kaplan, J. O. (2019). Mediterranean Land Use Systems from Prehistory to Antiquity: a Case Study from Peloponnese (Greece). *J. Land Use Sci.* 14 (1), 1–20. doi:10.1080/1747423x.2019.1639836

Wernstedt, F. L., and Spencer, J. E. (1967). *The Philippine Island World*. Berkeley: University of California.

Wessel, P., Luis, J. F., Uieda, L., Scharroo, R., Wobbe, F., Smith, W. H. F., et al. (2019). The Generic Mapping Tools Version 6. *Geochem. Geophys. Geosyst.* 20 (11), 5556–5564. doi:10.1029/2019gc008515

Widgren, M. (2018). Towards a Global History of Agricultural Systems. *Past Glob. Changes Mag.* 26 (1), 18–19. doi:10.22498/pages.26.1.18

Wilson, E. O. (1998). *The Unity of Knowledge*. New York City: Vintage Books.

Wilson, J. E., and Siemonsma, J. S. (1996). in *Colocasia Esculenta (L.) Schott" from Proseabase*. Editors M. Flach and F. Rumawas (Bogor, Indonesia: PROSEA Foundation). http://www.proseanet.org (Accessed Feb 16, 2021).

Willis, K. J., and Van Andel, T. H. (2004). Trees or No Trees? The Environments of Central And Eastern Europe During the Last Glaciation. *Quat. Sci. Rev.* 23 (23–24), 2369–2387.

Yakal, M. A. (2017). *Exotic Beads and Jar Burials: Social Status in the Old Kiyyangan Village, Ifugao, Philippines*. [Los Angeles]: University of California Los Angeles. [master's thesis].

Zheng, Z., Ma, T., Roberts, P., Li, Z., Yue, Y., Peng, H., et al. (2021). Anthropogenic Impacts on Late Holocene Land-Cover Change and Floristic Biodiversity Loss in Tropical southeastern Asia. *Proc. Natl. Acad. Sci. USA* 118, 40e2022210118. doi:10.1073/pnas.2022210118

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The reviewer NG declared a past co-authorship with several of the authors AK, JK.

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