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Early urban impact on vegetation dynamics: Palaeoecological reconstruction from pollen records at the Dongzhao site, Henan Province, China

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A R T I C L E I N F O

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A B S T R A C T

Archaeologists have focused on the social conditions surrounding the development of urbanism around the world; however, the environmental impact of these ancient cities remains unclear. In this paper, we present palynological data from the early Bronze Age city of Dongzhao, Henan Province, China. Our data indicate that vegetation change and the development of early urban settlements are closely linked, with the advent of urban development significantly accelerating deforestation and altering the composition of local vegetation communities. The pollen record from Dongzhao provides new evidence to support the claim that urban expansion, coupled with a drying climate and the expansion of agriculture, dramatically reconfigured the landscapes of Bronze Age China.

1. Introduction

Archaeological assessment of the environmental impact of early cities can provide a baseline for thinking about the complex challenges of contemporary urban living. Current research on urbanism has resulted in two divergent views on the environmental consequences of city living. One perspective contends that the dense population of cities which requires a large amount of natural resources provokes an "urban penalty" resulting in environmental degradation beyond the city, as well as the concentration of harmful diseases and pollutants within the city (Brown, 2009; Ehrlich and Ehrlich, 2013; Elmqvist et al., 2013; Grimm et al., 2008; Seto et al., 2012). The Bronze Age site of Akko (Acre) in Israel has provided evidence for this "urban penalty" in antiquity (Kaniewski et al., 2013).

Proponents of the second view argue that cities actually provide an "urban advantage", because they are environmentally efficient. That is, cities can produce positive feedback from social interactions that generates more economic value relative to resource consumption (Bettencourt, 2013; Bettencourt et al., 2007; Dodman, 2009; Meyer, 2013; Schlapfer et al., 2014). This perspective has similarly been applied to archaeological contexts, where the longevity of many premodern cities is also credited to environmental advantages conferred by the landscape-transforming activities of urban settlements (Isendahl and Smith, 2013).

Despite these notable applications, archaeological research on cities and urbanism has tended to focus on the political, economic, and social origins and contexts of cities, as well as their roles in broader society (Cowgill, 2004; Marcus and Sabloff, 2008; Smith, 2003, 2007, 2010). There are far fewer archaeological studies on the relationship between cities and their environments, and the majority of work on this topic placed the emphasis on urban systems sustained by agricultural systems that were typical to Mesoamerica or Southeast Asia (Barthel and Isendahl, 2013; Elmqvist et al., 2013; Fletcher, 2009, 2012; Isendahl, 2010; Isendahl and Smith, 2013; Sinclair et al., 2010). In contrast to such low-density systems in Mesoamerica or Southeast Asia, early Chinese cities are characterized by high-density settlements supported by intensive land use practices. As such, early Chinese cities provide an important context that more closely resembles modern cities (von

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Faukenhausen, 2008; Yang, 2004).

In this paper we investigate the sustainability of cities in the past by examining urban impact on the environment in Bronze Age China, as revealed from the archaeological site of Dongzhao in Henan Province. This urban settlement features qualities associated with the “penalties” as well as with “advantages” of urban systems (Gu, 2015; Lei et al., 2016; Hao and Zhang, 2016). Using geoarchaeological, chronometric, and palynological data from Dongzhao site in Henan Province, we test the “urban advantage” and “urban penalty” models within a densely-populated and intensive agricultural land-use system.

The rapid expansion of modern cities and associated environmental changes witnessed in the present underscore the importance of this line of research; however, the environmental consequences of urbanism are poorly understood (Fletcher, 2012). By providing an archaeological example of urban activities and their effects on local vegetation dynamics of the past, we can contribute to the broader scholarly endeavor of discerning what makes societies sustainable or vulnerable in the face of environmental challenges.

2. Study site

The Dongzhao site (113°29′38″E, 34°46′56″N) is located to the west of Zhengzhou City in Henan Province. It lies within the broad region known as the Central Plains (Zhongyuan) that has traditionally been called the “Cradle of Chinese Civilization” (Yan, 1987; Zhao, 2000) and is within close proximity to a number of other important Bronze Age urban settlement sites (Fig. 1). Geographically, Dongzhao is bounded by the Yellow River to the north and the Songshan Mountains to the southwest (Fig. 1). It is situated on the northeastern piedmont of Mount Tan and has an altitude of approximately 125 m above sea level. The nearby Suo and Xushui rivers flow to the east into the upper reaches of the Huai River. In terms of geomorphology, the dominant landform of the study area is a loess platform composed of re-deposited Pleistocene and Holocene loess (Lu et al., 2014). The Songshan Mountains to the southwest of the site are primarily composed of limestone, dolomite, and siltstone (Webb et al., 2007).

Regional vegetation is characterized by coniferous-deciduous forests and shrubs found in nearby mountainous areas, including *Pinus armandii*, *Pinus massoniana*, *Abies chensiensis*, and *Betula albo-sinensis*. At lower elevations, *Ulmus pumila*, *Populus tomentosa*, and *Salix matsudana* are common, with *Salix sinopurpurea* and *Typha* spp. common in wetlands (Wang et al., 1989; Zhang et al., 2018). At present, the landscape is dominated by agricultural fields that have almost entirely replaced the natural vegetation. The annual mean temperature is 14.4 °C, and the annual mean precipitation is about 650 mm with the majority occurring from May to September (Zhengzhou Committee of Chorography, 1999).

Previous studies have provided basic evidence of vegetation shifts in the Central Plains from middle to late Holocene (Yan et al., 1986; Wang et al., 2004; J. Xu et al., 2013). Pollen analysis from the Sihenan profile in the Luoyang Basin, Henan Province, shows a forest steppe landscape dominated by *Pinus* spp. and *Artemisia* in the period of 4580–3545 yr BP, followed by a period (3545–3090 yr BP) of rapid increase in Amaranthaceae/Chenopodiaceae pollen percentage (Sun and Xia, 2005). Evidence from Anyang in northern Henan Province has shown that mixed deciduous and evergreen broad-leaved forests were dominant between 8200 and 3400 cal. BP and the component of evergreen broad-leaved forests decreased sharply after 3400 cal. BP (Xu et al., 2010; Cao et al., 2010).

Since 2014, the Dongzhao site has been extensively excavated by the Zhengzhou Municipal Institute of Relics and Archaeology and the School of Archaeology and Museology of Peking University. The site area is about 1 km^2 and contains three urban settlements that are dated to the early period of the Xinzhai Culture (ca. 1870–1790 BC), the early period of the Erlitou Culture (ca. 1735–1565 BC), and the eastern Zhou Dynasty (770–256 BC), respectively (Gu, 2015; Lei et al., 2016; X. Zhang et al., 2007). Recent excavations at Dongzhao have unearthed house foundations, burials, sacrificial remains, ditches, wells, ash pits, as well as a large number of artifacts including oracle bones, ceramics, and various grains (Gu, 2015; Lei et al., 2016). The site features multiple periods of large-scale urban settlement, which are punctuated by intervals of smaller-scale and less socio-economically complex occupations. This provides the opportunity to see how vegetation around Dongzhao responded to site-wide socio-economic dynamics.

3. Materials and methods

3.1. Field work and particle size analysis

Excavators from the Zhengzhou Municipal Institute of Relics and Archaeology and Peking University (including authors W.F. Gu, X.S.

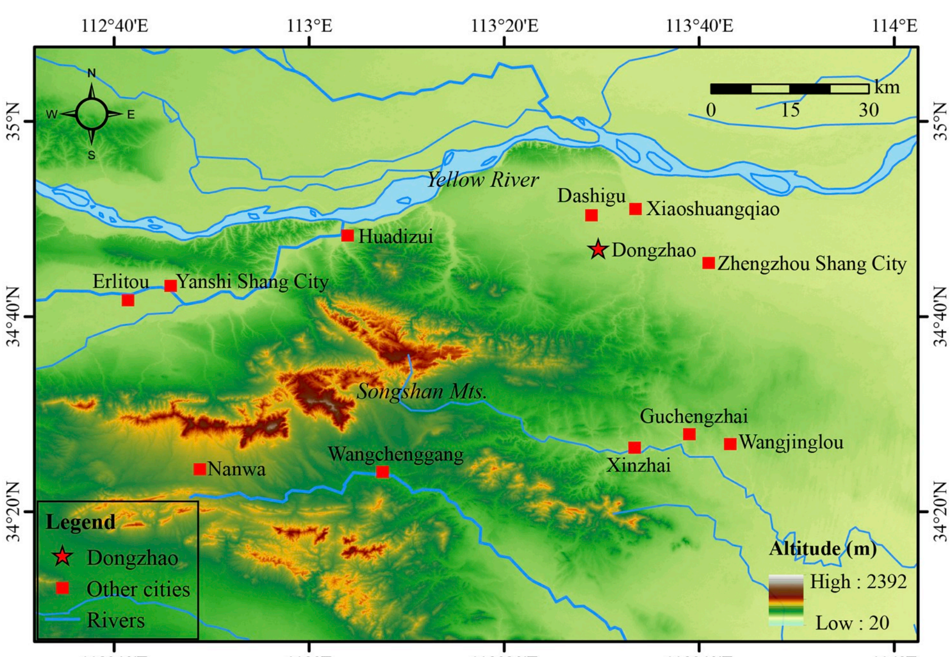

Fig. 1. Topographical map showing the location of the Dongzhao site, and selected urban settlements in Henan Province, China, during the early Bronze Age. The data set of the background map is provided by *International Scientific & Technical Data Mirror Site, Computer Network Information Center, Chinese Academy of Sciences (*http://www.gscloud.cn*)*.

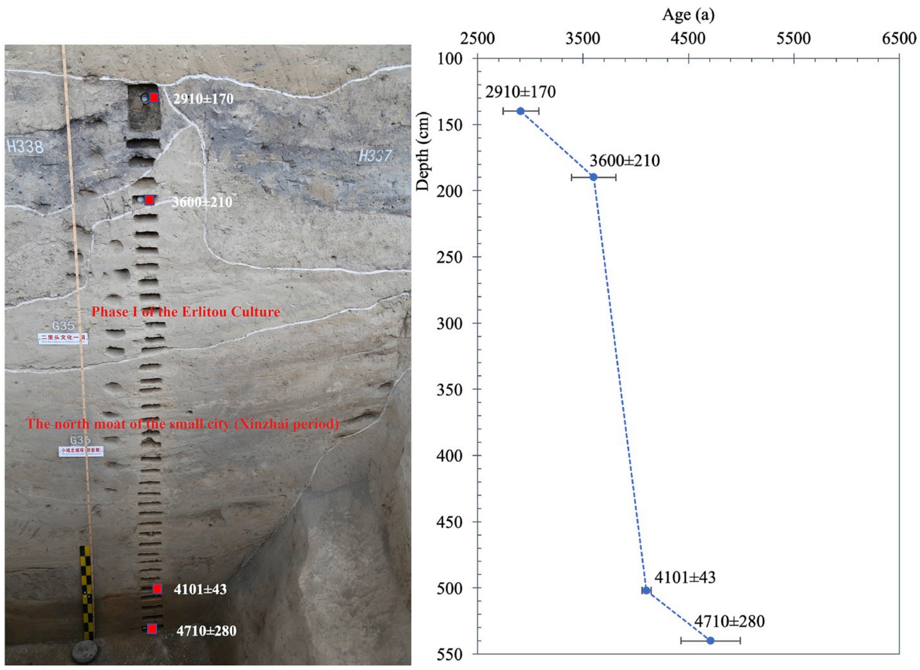

Fig. 2. Picture and age-depth relationship of the T3 profile based on linear interpolation. The radiocarbon date from 502 cm depth is calibrated using CalPal (http://www.calpal-online.de).

Lei, and J.Q. Zhang) excavated a trench, designated as T3, within the northern moat at the Dongzhao site. The west-facing profile of trench T3 was sampled at 10 cm intervals (Fig. 2). The sediments from the T3 profile come mainly from the deposits of fluvial origin. These sediments exhibit little evidence of human disturbance, but human activities are likely to have affected the moat and the depositional processes to some extent. We also conducted particle size analysis at the College of Urban and Environmental Sciences, Peking University. Samples were pretreated in a 30% H_2O_2 and 10% HCl solution respectively for organic and carbonate removals. Particle size was measured by a Malvern Mastersizer 2000 laser diffraction particle size analyzer.

The profile sampled was 420 cm deep and can be divided into four lithologic layers based on colour and texture (Fig. 3).

Lithologic layers:

(1) 550-295 cm, a dark yellowish brown (10 YR 4/6) or yellowish brown (10 YR 5/4) silt loam layer, containing some redox features and organics. It is interpreted to be waterlogged deposits.
(2) 295-195 cm, a yellowish brown (10 YR 5/4) silt loam layer, containing some redox features and organics. It is interpreted to be high-energy water-transported deposits. Notably, the percentage of sand reaches its peak of the entire profile (Fig. 3).
(3) 195-175 cm, a brown (10 YR 5/3) silt loam layer with some redox features and organics. It is interpreted to be low-energy water-transported deposits.
(4) 175-130 cm, a dark grayish brown (10 YR 4/2) or dark gray (10 YR 4/1) silt loam layer with some redox features and many organics, filled with red fired clay and small pieces of charcoal. It is interpreted as an anthropogenic ash pit from the Erligang period.

3.2. OSL and radiocarbon dating

Three OSL samples (Table 1) were processed at the Environmental Archaeology Laboratory of the Institute of Geographical Sciences, Henan Academy of Sciences, China, using the SAR (single aliquot regenerative-dose) method on quartz grains sized from 4 to 11 μm (Murray and Wintle, 2000, 2003). Elemental contents of U, Th and K in samples were analyzed using neutron activation analysis (NAA) at the China Institute of Atomic Energy. Water content was set to 10 ± 5% by weighing samples before and after drying in the laboratory. The elemental concentrations were converted into the equivalent dose rate (*De*) with the AGE program (Grun, 2009), using revised dose-rate conversion factors (Adamiec and Aitken, 1998). The AGE program was used to calculate the cosmic dose rate (Gy) based on the latitude and depth of the samples.

We also collected one sample for accelerator mass spectrometry (AMS) radiocarbon dating. It was dated at the Department of Archaeology at Peking University.

3.3. Pollen analysis

35 sediment samples from the T3 profile were also selected for pollen analysis. Sample preparation followed the standard Hydrofluoric acid (HF) method (Fægri and Iversen, 1989; Moore et al., 1991). One exotic tablet of Lycopodium-spore containing 8295 grains served as a marker and was added into each sample in order to calculate pollen concentration. At least 100 pollen grains were counted for each sample. Poaceae pollen grains were divided into two categories based on diameter size: < 40 μm and > 40 μm. Poaceae pollen with diameters of > 40 μm were treated as cultivated species (Tweddle et al., 2005; Shu et al., 2010; Li et al., 2012). Pollen concentration and percentage diagrams were constructed using the Grapher (version 13.2, published in 2018) and TILIA (version 2.0.4, published in 2013) software.

4. Results

4.1. Chronology and particle size distribution

The T3 profile yielded a total of three OSL ages and one AMS radiocarbon date (Table 1, Table 2). The chronology established by these four dates generally agrees with typological dates from archaeological relics from the same profile and are corroborated by AMS dates from other stratigraphic sequences within the site. (Yang et al., 2017). Thus, an age-depth model can be established through linear interpolation of the three OSL dates and one AMS date (Fig. 2).

Particle size distribution was categorized by following the standard

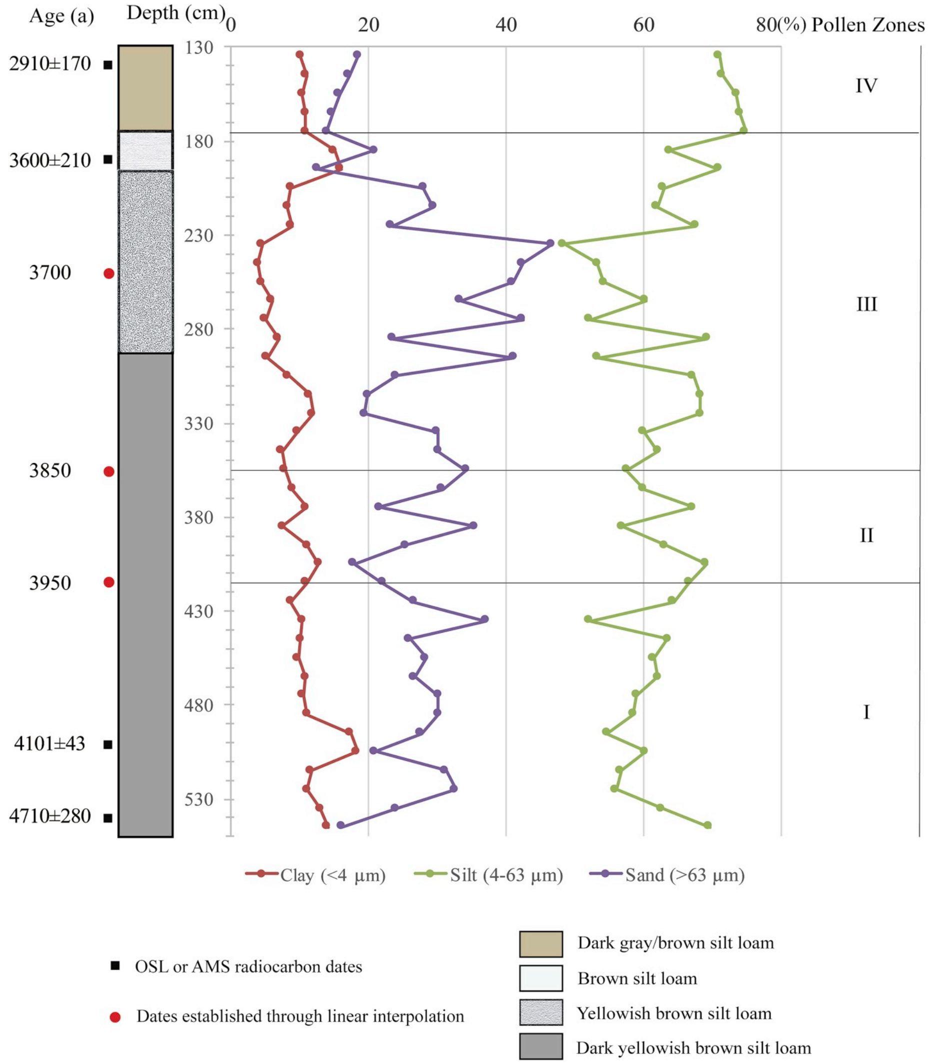

Fig. 3. Grain size distribution of T3 profile, Dongzhao site. Please note that the dates at 250, 355, 415 cm (red dots) are generated from the age-depth model established through linear interpolation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

classification system described by the Chengdu College of Geosciences (1978). Particles ranging from 4 to 63 μm were grouped into the silt category, and silt-sized particles were dominant throughout the entire profile (Fig. 3). The percentage of sand was higher in our samples than what would be expected from typical loess deposits, indicating that some of the sediment was transported by water.

The percentage of clay reaches its peak (18.5%) around 4100 yr BP and then decreases gradually until ca. 3700 yr BP. In contrast, the percentage of sand fluctuates and increases from 18% to 47% over the same time period (ca. 4100–3700 yr BP), indicating a high-energy water-transporting process of the sediments. However, a notable decrease in sand percentage and an increase in clay percentage during ca. 3700–3600 yr BP demonstrate a low-energy water-transporting process of the sediments. The high-amplitude fluctuation and the increasing percentage of sand seen between ca. 3800 and 3700 yr BP may reflect more human disturbance of the landscape at this stage. Finally, very minor changes seen in particle size distribution after ca. 3400 yr BP show that the moat was silting up during this period (Fig. 3).

4.2. Pollen assemblages

Based on a cluster analysis of pollen concentrations (Fig. 4) as well as relative abundance percentages (Fig. 5), the T3 profile was divided into four pollen zones.

Zone 1 (540–415 cm, ca. 4710–3950 yr BP). This zone is dominated by terrestrial herbs and grasses, such as Asteraceae (8.26–44.64%),

Table 1
Optically stimulated luminescence (OSL) dates from T3 profile, Dongzhao site.

Lab No.	Field No.	Depth, cm	NAA				Dose rate (mGy/a)	*De*, Gy	OSL age, ka
			U, ppm	Th, ppm	K, %	Rb, ppm			
L089	T3 H338	140	2.13 ± 0.09	9.45 ± 0.27	1.74 ± 0.06	89.00 ± 5.16	3.29 ± 0.18	9.58 ± 0.15	2.91 ± 0.17
L090	T3 G34	190	1.73 ± 0.08	11.70 ± 0.33	1.86 ± 0.06	83.40 ± 5.00	3.47 ± 0.20	12.46 ± 0.18	3.60 ± 0.21
L096	T3 G36-4	540	2.07 ± 0.09	8.80 ± 0.26	1.68 ± 0.06	69.40 ± 4.72	3.09 ± 0.17	14.55 ± 0.30	4.71 ± 0.28

NAA: neutron-activation analysis.

Table 2
Result of AMS-radiocarbon dating from T3 profile of Dongzhao site, calibrated with the program OxCal v4.2.4 (Bronk Ramsey, 2014), using IntCal13 atmospheric curve (Reimer et al., 2013).

Lab No.	Field No.	Dating material	Radiocarbon age (yr BP)	Calibrated age (BC)	
				1σ (68.2%)	2σ (95.4%)
BA161540	2016 ZGD T3-502 cm	Charcoal	3710 ± 25	2140 BC (18.1%) 2116 BC 2099 BC (50.1%) 2039 BC	2197 BC (11.0%) 2168 BC 2149 BC (84.4%) 2030 BC

Artemisia (4.55–19.05%), Poaceae (< 40 μm) (0–15.27%), Amaranthaceae/Chenopodiaceae (0.92–13.16%), and *Urtica* (1.83–11.43%). Arboreal taxa are predominately represented by *Pinus* (5.45–52.73%), mixed with low abundances of broadleaf trees including *Tilia*, *Quercus* and *Carpinus*.

Zone 2 (415–355 cm, ca. 3950–3850 yr BP). The lower part of this zone is marked by a sharp increase of evergreen *Pinus,* which accounts for about 92% of pollen at its peak. The middle part shows a slight decline of *Pinus* and an increase of *Artemisia*. Evergreen and broadleaf trees reach another peak in the upper part where pollen percentages of *Pinus*, *Tsuga*, *Picea* + *Abies*, *Quercus*, and *Betula* increase.

Zone 3 (355–175 cm, ca. 3850–3400 yr BP). This zone is marked by the dominance of shrubs and terrestrial herbs and grasses, including Asteraceae (4.72–61.32%), *Artemisia* (0.94–41.51%), Amaranthaceae/Chenopodiaceae (2.83–19.51%), Poaceae (< 40 μm) (0–14.05%), and *Urtica* (1.10–13.21%). The concentration of arboreal pollen such as *Pinus*, *Quercus* and *Tilia* decreases in the lower part and increases in the upper part.

Zone 4 (175–130 cm, ca. 3400–2910 yr BP). This zone is marked by the increasing dominance of Amaranthaceae/Chenopodiaceae at the expense of *Pinus*. *Quercus* also has a higher percentage in the lower part, while Ranunculaceae peaks at the topmost part.

5. Discussion

5.1. Local vegetation history

Pollen analyses of sediments from moats provide proxies for local vegetation and also for land use history (Greig, 1985). However, the pollen assemblages of sediment from moats might be altered by human activities. We have attempted to examine the degree to which human activities have influenced the integrity of the pollen results by cross-checking our data with current knowledge of occupation history at Dongzhao as well as relevant research on the pollen source area. Our cross-checking suggests that our pollen results are likely to reflect the local vegetation within a range of 2 km (Xu and Zhang, 2013). Our pollen data indicate that the local vegetation has been influenced by human activities and does not represent pristine vegetation dynamics. According to the characteristics of the pollen zones established from the T3 profile, four corresponding stages of vegetation succession can be identified:

5.1.1. Stage 1 – Pollen zone 1 (540–415 cm, ca. 4710–3950 yr BP)

This stage contains a high content of Asteraceae as well as various kinds of herbs and shrubs, implying a grassland dominated ecosystem during this time interval. *Pinus* pollen dominates the assemblage of trees and exhibits a significant variability in this stage. The pollen percentage of trees decreases around 4100 yr BP, probably reflecting widespread climatic shifts recorded in this interval (Weiss et al., 1993; Wu and Liu, 2004; Gao et al., 2007). Subsequently, woodland vegetation seems to recover as evidenced by a slight increase in the percentages and concentrations of broad-leaved deciduous tree pollen grains, including *Tilia*, *Quercus*, *Betula*, and *Carpinus*. In the upper part of this stage, the concentration of *Concentricystes* spores increases and reaches its peak of entire profile, indicating a relatively wet environment between 4000 and 3950 yr BP. In the upper part of this stage, the *Artemisia*/Chenopodiaceae (A/C) ratio increases from 1 to 10, being consistent with the increase of concentration of *Concentricystes* spores.

The appearance of some pollen taxa such as *Urtica* was reported to be related to human disturbance of the natural vegetation (Li et al., 2008; Zhang et al., 2018). The slight increase of *Urtica* pollen in the upper part of this stage may indicate an increase in human disturbance to natural vegetation during the terminal Neolithic. In addition, an increase of Poaceae pollen with diameters of > 40 μm indicates the development of farming after ca. 4020 yr BP. These data corroborate previous archaeobotanical evidence coming from carbonized plant remains, suggesting that farming of foxtail millet (*Setaria italica*) and broomcorn millet (*Panicum miliaceum*) were the dominant agricultural crops in the Dongzhao site in the late Longshan period (Yang et al., 2017).

5.1.2. Stage 2 – Pollen zone 2 (415–355 cm, ca. 3950–3850 yr BP)

At the beginning of the second stage, *Pinus* increases very rapidly. The pollen percentage of *Pinus* reaches more than 60%, giving this stage

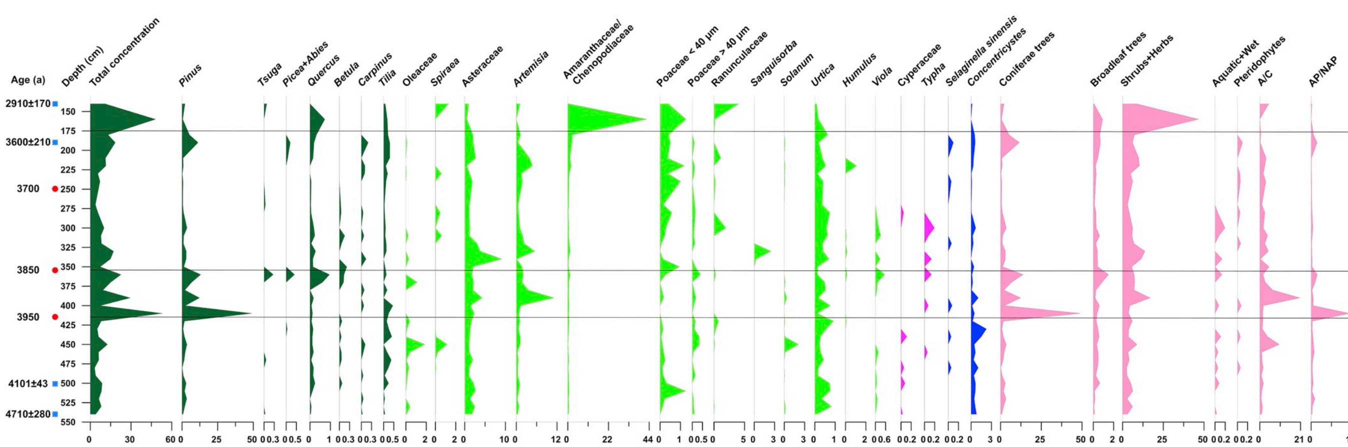

Fig. 4. Pollen concentration diagram of T3 profile, Dongzhao site.

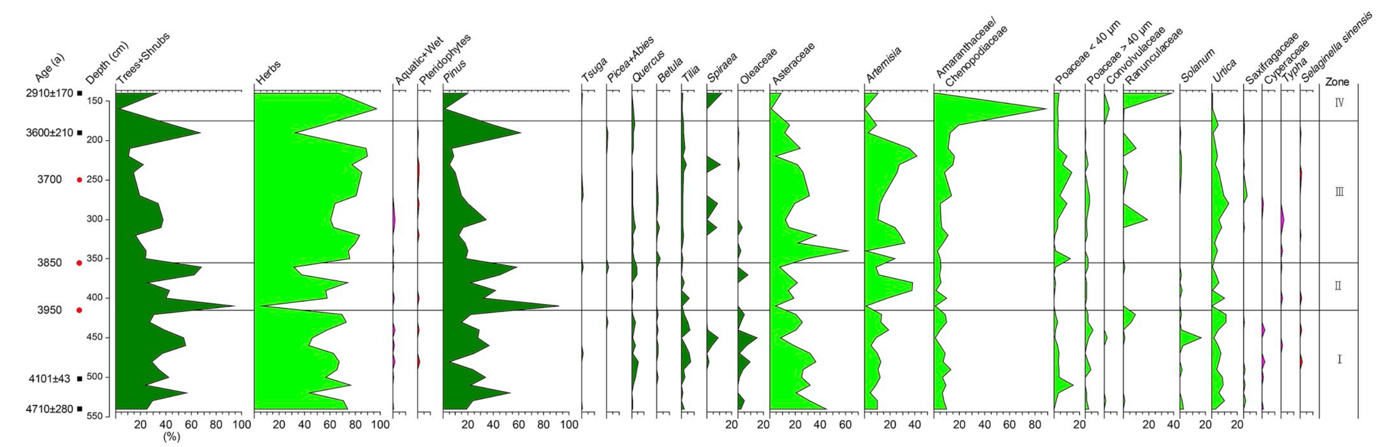

Fig. 5. Pollen percentage diagram of T3 profile, Dongzhao site.

the highest ratio of arboreal pollen to non-arboreal pollen (AP/NAP) in the entire profile. Studies of the relationship between modern pollen and vegetation have demonstrated that pine trees are typically present locally if the percentage of *Pinus* pollen is above 30% (Li and Yao, 1990; Li et al., 2005; Xu et al., 2007; Cao et al., 2010). Thus, vegetation at this stage was likely composed of a mixed coniferous-deciduous forest dominated by *Pinus*, accompanied by herbs and shrubs such as Asteraceae and *Artemisia*. This conclusion is further substantiated by pollen analysis from the Taosi site (4300–4000 yr BP) in the southern Linfen Basin of Shanxi Province (Kong and Du, 1992; T. Li et al., 2014). A relatively wet environment seems to succeed this mixed woodland landscape, as evidenced by a slight increase in *Concentricystes* pollen concentration and also by the peaked A/C ratio.

In the upper part of this stage, dating from ca. 3900 to 3850 yr BP, the concentrations and the percentages of coniferous trees (*Pinus*, *Tsuga*, and *Picea* + *Abies*) and broad-leaved deciduous trees (*Quercus*, *Betula*) increase, indicating a forest landscape dominated by *Pinus* and broad-leaved deciduous trees. This woodland landscape suggests a warm and wet climate, which may have contributed to the rise of urban settlements during the Xinzhai period. Previous palaeoecological reconstructions from the Xinzhai and Erlitou sites indicate a relatively warm and wet climate dating to the Xinzhai Culture and Phase I of the Erlitou Culture, roughly in agreement with our pollen dataset (Song et al., 2002; Yao et al., 2007).

5.1.3. Stage 3 – Pollen zone 3 (355–175 cm, ca. 3850–3400 yr BP)

In comparison with Stage 2, there is sharp decreases in both coniferous trees (*Pinus*, *Tsuga*, and *Picea* + *Abies*) and broadleaf trees (*Quercus*, *Betula*) in Stage 3. In contrast, pollen from herbaceous plants, such as Asteraceae, *Artemisia*, Poaceae, and *Urtica* increases in this stage. This shift in vegetation likely reflects the growing human influence on the environment occurring after the development of the urban settlement at Dongzhao in the Xinzhai Culture period at ca. 3850 yr BP.

In the middle part of this stage, total concentrations of tree pollen remain low. However, tree pollen content increases after ca. 3700 yr BP, suggesting that the landscape transitioned from grasslands to steppe-forests. The increase of *Pinus*, *Quercus*, and *Tilia* pollen in this stage can be interpreted as the spread of these pioneer trees (Sadovnik et al., 2014). The appearance of *Concentricystes* and *Selaginella sinensis* in the upper part of this stage indicates a wet environment, being consistent with another peak seen in the AP/NAP ratio between ca. 3600 and 3400 yr BP.

5.1.4. Stage 4 – Pollen zone 4 (175–130 cm, ca. 3400–2910 yr BP)

The final stage presents a sharp increase in Amaranthaceae/Chenopodiaceae pollen percentage at the expense of *Pinus*, *Picea* + *Abies*, *Carpinus* and *Tilia* percentages. This suggests a cooler and drier climate, as well as increased human activities. This regional change from a steppe-forest-dominated landscape under a warmer-wetter condition before 3400 yr BP to a grassland-dominated landscape under a cooler-drier condition after 3400 yr BP is further supported by the pollen assemblage from the Sihenan profile in Luoyang Basin (Sun and Xia, 2005). The disappearance of *Selaginella sinensis* pollen and decline of *Concentricystes* pollen concentration in this stage further indicates that the moat at Dongzhao was undergoing a gradual process of silting up during this period.

5.2. Human impact associated with early urban settlement

In the Chinese Central Plain and Loess Plateau, previous reconstructions of prehistoric land use have demonstrated that human-driven landscape alterations, primarily through the expansion of arable fields, occurred by at latest the middle Neolithic (Yu et al., 2012, 2016). The effects of urban development on natural vegetation in the past can also be seen beyond China in southwest Asia and in Israel (see Kaniewski et al., 2013).

The detailed reconstruction of vegetation dynamics through different periods of varying urban intensity at the Dongzhao site provides an opportunity to further explore the effects that urban disturbances would have had on vegetation in the Central Plains of China. Our pollen data indicate that human disturbance was detectable at ca. 4020 yr BP (in the later part of Pollen Stage 1) most likely due to the intensification of agricultural production at Dongzhao (Yang et al., 2017; Luo et al., 2018). However, it is only after the establishment of cities when ecological dynamics has changed dramatically and rapidly. In the Bronze Age, the rise of such cities is associated with population increases (Wang, 2011; Li et al., 2013) and also with agricultural expansion that affected local vegetation dynamics.

Our dataset from Dongzhao provides strong evidence for environmental changes resulting from human land uses associated with different phases of urban development. Notably, the distinct decrease in total tree pollen percentages seen at the end of Stage 2 and at beginning of Stage 3 at Dongzhao can be correlated with the rise of cities during the Xinzhai and Erlitou periods. At the onset of the construction of the Dongzhao enclosures (ca. 3850 yr BP), marked changes in the pollen assemblage are evident, including a sharp decrease in the concentrations and percentages of arboreal trees and notable increases in the pollen abundances of ruderal species. These data show that tree abundances declined while weedy plant species flourished in disturbed areas, being consistent with evidence for intensified anthropogenic activity at the site. This suggests that humans were having quantifiable impacts on the landscape. Conversely, a decline in human activities, due to the abandonment of the Dongzhao urban settlement by the late period of the Erlitou Culture, is evidenced by a clear increase in tree pollen percentages from ca. 3600 to 3400 yr BP toward the end of Stage 3.

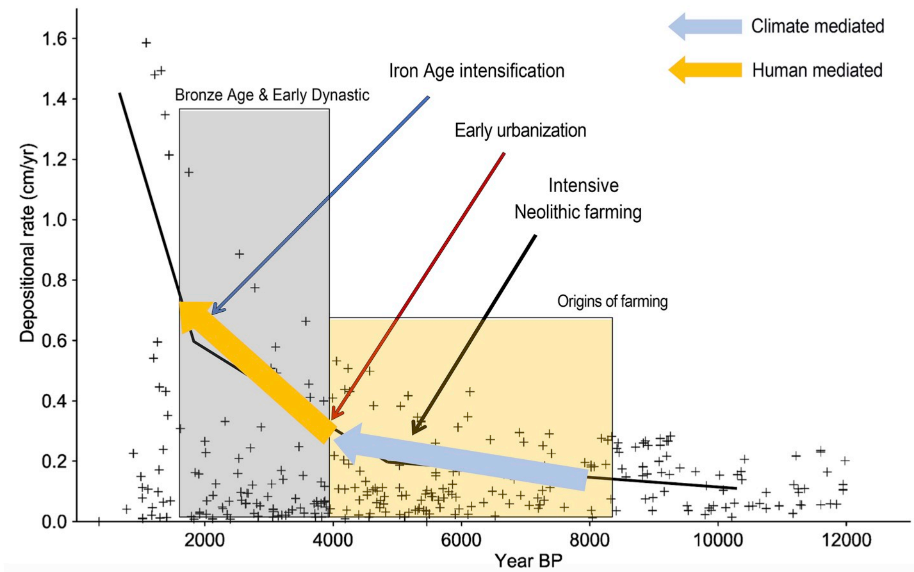

Fig. 6. Yellow River sediment deposition in the North China Plain (modified from Shi et al., 2002; Kidder and Liu, 2017; Xu, 1998, 2003). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

At the onset of Stage 4, after ca. 3400 yr BP, rapid woodland shrinkage resumed. This process is probably related to increasing aridity, as well as to a later surge in human population and the associated activities in this region during the Erligang period, evidenced by the hollow-square, rammed earth building sites of the Shang dynasty (Gu, 2015; Lei et al., 2016; Hao and Zhang, 2016). Pollen assemblages from the site of Anyang in Henan Province show the same pattern of deforestation occurring after 3400 yr BP (Z. Zhang et al., 2007; Cao et al., 2010). To sum up, the pollen records from Dongzhao and also from Anyang support the claim that human activities during the middle Bronze Age significantly accelerated forest shrinkage that was initiated by an increasingly cool and dry climate at the beginning of the late Neolithic (Zhao et al., 2009).

The growing human footprint and impact of urban settlement are also recorded in the sedimentary record. The pattern of sediment deposition within the North China Plain is characterized by a rapid increase of sedimentation rates at ca. 3900 yr BP (Fig. 6), which roughly coincides with the flourishing of early urban settlements in the Central Plains (see Fig. 1). These data suggest that from the Neolithic to the Bronze and Iron Ages, what had once been local, site specific sedimentary changes became increasingly large-scale and prominent throughout the entire Central Plains (Zhuang and Kidder, 2014; Kidder and Zhuang, 2015; Storozum et al., 2018).

These events are complex and likely reflect two inter-related processes. The first is the effect of increasing aridity as a result of the gradual weakening of the Asian monsoon in the late Holocene (Q. Li et al., 2014; Wang et al., 2014; Wen et al., 2010; Xiao et al., 2004; Chen et al., 2015; Xu et al., 2017). A reduction of moisture in the Loess Plateau and Central Plains led to reduced vegetation and a higher soil erosion rate. The second process is human land uses (including urban construction, forest and land clearance, use of fire, and cultivation) that might have increased as a consequence of increasing population. Increased aridity is implicated in a positive feedback loop involving soil erosion and land-use intensification. However, an important theoretical question still remains: at what point does this feedback loop become dominated by human landscape modifications that overtake the effects of natural processes? How did these human-induced changes affect land-use responses?

Low-density cities such as those found in the Maya world of Mesoamerica, or in some parts of Southeast Asia, were sustained over long periods with relatively few signs of significant human effects on the environments (Fletcher, 2009, 2012; Isendahl, 2010; Isendahl and Smith, 2013). In contrast, our data suggest that high-density urban settlements at Dongzhao site likely had a long-term detrimental effect on the environments. In this particular instance, deforestation around the Dongzhao site led to increased soil erosion and thus landscape instability. The deforestation-related effects might have persisted for hundreds, if not thousands, of years, shaping both geomorphological processes and human decision-making processes. It is likely that the urban penalty associated with unmanaged high-density urbanism might have initially led to a further reliance on technological solutions to deal with environmental problems like soil erosion.

6. Conclusions

Our results indicate that from the late Neolithic to the Bronze Age a steppe forest was present around the study site. Anthropogenic forest disturbance related to cereal cultivation was already occurring by the late Neolithic period (Stages 1 and 2), but the intense human impact associated with early high-density urban construction and the expansion of intensive farming is only recorded after ca. 3850 yr BP, during the Xinzhai and Erlitou cultural periods (end of Stage 2 and Stage 3). A period of forest recovery is detected after the abandonment of the Dongzhao urban settlement between ca. 3600-3400 yr BP (end of Stage 3), followed by another phase of deforestation between ca. 3400 and 2910 yr BP (Stage 4), likely due to the combination of increased aridity and intensified human landscape use.

Not all cities are alike. In China, for example, the path of urbanism led to high-density settlements supported by intensive agriculture. Similar pathways were followed in the Near East. But, in the Maya world of Mesoamerica, or in some parts of Southeast Asia, low-density urban settlements predominated. As with any form of settlement, high-density urbanism comes with costs and benefits. At Dongzhao and other early Chinese cities, there is little evidence showing that the elites and rulers of these communities placed any emphasis on limiting the environmental footprint of the communities. In China's Central Plains, the development of early urban settlements and associated human activities, notably forest clearance and selective felling, during the Bronze Age had profound effects on the composition and abundance of local vegetation communities. The Dongzhao example shows that in the case of early Chinese urbanism, the environmental penalties of unmanaged land use practices were significant and may have contributed to social vulnerability and the abandonment of the site.

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