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Synchrony of prehistoric agricultural evolution and drought events in the North China Plain

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ABSTRACT

Since the Holocene, marked transformations have occurred in patterns of human activity and modes of subsistence, with agriculture progressively becoming the principal means by which human societies modified and adapted to natural environments and sustained social development. The North China Plain (NCP) serves as the core region for the origin of millet agriculture in northern China and remains a pivotal area for understanding the genesis and evolution of Chinese civilization. By analyzing plant macrofossils from three sites—Zhujia, Dalaidian, and Wangzhuang—in the Qihe River basin (QRB), and integrating with crop assemblages from 54 representative sites across the North China Plain, this study systematically examines the synchrony between the evolution of Neolithic agricultural structures and climatic change in the region. The results demonstrate that multiple drought events had varying impacts on millet and rice agricultural systems in the NCP throughout the Neolithic period. Early communities responded to abrupt climatic perturbations by strategically adjusting agricultural structures to secure stable food supplies, thereby ensuring the sustained development of their societies. Furthermore, confronted with recurrent Neolithic drought events, prehistoric communities adopted diverse adaptive strategies, with their adaptive capacity progressively strengthening over time.

1. Introduction

The relationship between climate change and human activity has long been a central theme of academic inquiry. Climatic fluctuations, by reshaping the biosphere, hydrosphere, and atmosphere, have profoundly shaped the trajectories of human cultural development (An et al., 2004; Zhang et al., 2007). Since the onset of the Holocene, early hunter-gatherers continuously adjusted their subsistence strategies to enhance ecological adaptability. This shift facilitated the incorporation of a broader spectrum of plant and animal resources into human diets, ultimately facilitating a gradual transition of subsistence systems (Hollander and Howe, 2020). Consequently, agriculture emerged as the principal mechanism by which human societies adapted to and modified natural environments (Dong et al., 2020; Milla and Osborne, 2021). Simultaneously, abrupt cooling episodes and prolonged drought events induced by climate change also significantly impeded the development of prehistoric agricultural societies (He et al., 2022a; Li et al., 2025). Elucidating the adaptive dynamics of agricultural societies under varying climatic contexts is essential not only for understanding the processes through which prehistoric human adaptive capacities were enhanced but also for providing critical insights into the broader trajectories of early social evolution.

In recent years, with the synergistic integration of archaeology, life sciences, environmental sciences and other disciplines, the

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socioeconomic development patterns of early communities of the region, the interrelationships between changes in population size and the evolution of ecological environments, and many other studies have gradually been increasingly subsumed into a comprehensive analytical framework (Stevens et al., 2024; Zhuang and Fuller, 2024). Through multidisciplinary comparative research, systematic insights have yielded into climate change, economic development patterns of prehistoric populations, and the evolution of social structures (Li, 2013; Lu, 2017). Despite these methodological advances, integrative investigations of human–climate interactions remain geographically uneven in several regions critical to the genesis of human civilization. This constrains multi-scalar understandings of the origins, dispersal, and adaptive mechanisms of agriculture under varying climatic and ecological contexts, resulting in a lack of systematic insight into the reciprocal feedbacks between agricultural evolution and climate–environmental change.

The North China Plain (NCP) stands as a pivotal region for the origin and proliferation of millet agriculture in northern China (Liu and Chen, 2017). Since the Neolithic period, this region has yielded a wealth of archaeological remains and preserved a well-defined cultural sequence, making it an optimal setting for investigating the origins of early crops and the evolution of agricultural economic structures (Hosner et al., 2016; Liu and Chen, 2017). In addition, the Qihe River basin (QRB) located in the western part of NCP is regarded as a crucial region for the origins of Chinese Bronze Age civilization and served as an important economic and cultural center for the Pre-Shang, Shang, and Zhou dynasties (IA CASS, 2003). Numerous agricultural archaeological remains have been discovered in the QRB, spanning significant periods including the Peiligang, Yangshao, Longshan, and Shang-Zhou (HPACH, 2008). Consequently, investigating agricultural evolution in the QRB is essential for comprehending the broader development of Neolithic cultures and the genesis of Chinese civilization.

This study analyzes archaeobotanical assemblages from three sites in the QRB: Zhujia (35°46′40″N, 114°12′47″E), Wangzhuang (35°44′43″N, 114°15′16″E), and Dalaidian (35°44′14″N, 114°16′38″E) (Fig. 1). Integrating these data with archaeobotanical evidence from 54 Neolithic sites across NCP, we reconstructed the evolutionary trajectory of agricultural structures in the region. Furthermore, by incorporating available paleoclimate and paleoenvironmental records from surrounding areas, this study examines the spatiotemporal dynamics of early agriculture in the QRB and the broader NCP, and explores the synchrony between agricultural development and climatic changes.

2. Study area

Geographically, the NCP is situated between 32° – 40° N and 114°–120° E. This extensive low-lying region is characterized by a gentle gradient descending from west to east, with elevations predominantly remaining below 50 m above sea level (a.s.l.). Geomorphologically, the plain represents a typical alluvial landscape formed by the prolonged deposition of massive sediment loads transported by the Yellow, Huaihe, Haihe, and Luanhe rivers (Wu et al., 2017a). The study area lies within the warm-temperate semi-humid monsoon climate zone. It is characterized by a mean annual temperature ranging from 1.7 to 15.4 °C and mean annual precipitation between 290 and 1360 mm (http://www.geodata.cn). The regional climate exhibits pronounced seasonality, defined notably by the concurrence of high temperatures and peak precipitation. Precipitation patterns display significant interannual variability and a markedly uneven seasonal distribution. The zonal vegetation of the region is dominated by warm-temperate deciduous broadleaf forests. Mixed deciduous broadleaf forests are widely distributed across the surrounding piedmont zones, whereas temperate mixed coniferous–deciduous forests occur in the northernmost reaches of the study area (Wang et al., 2015).

The QRB lies within the transitional zone between the southeastern foothills of the Taihang Mountains and the NCP. The region is characterized by a marked elevational gradient descending from west to east, resulting in significant topographic relief. The terrain within the basin is complex, with mountainous and hilly areas comprising approximately 86 % of the total area. This topography supports a distinct vertical zonation of mountain landscapes. In the southern segment of the Taihang Mountains, vegetation belts shift sequentially along the altitudinal

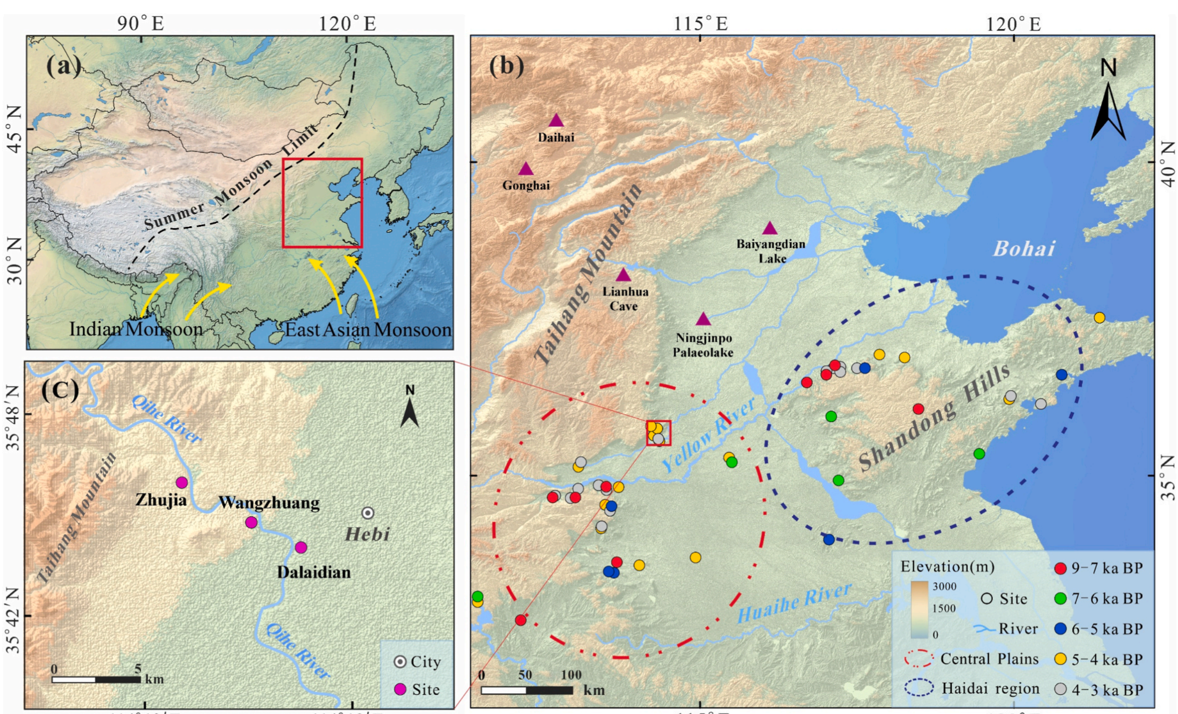

Fig. 1. Study area and the distribution of prehistoric archaeological sites. (a) Location of the study area in China. (b) Distribution of major archaeological sites in the North China Plain (NCP). (c) Distribution of archaeological sites in the Qihe River Basin (QRB).

gradient: encompassing shrub-cultivated zones at lower elevations, transitioning to deciduous broadleaf forests, mixed coniferous-broadleaf forests, and finally shrub-meadow zones at the summit. Precipitation in the basin is predominantly concentrated in summer and autumn, characterizing the region with pronounced seasonality and significant non-periodic climatic variability (Zhang et al., 2018b).

3. Materials and methods

The samples in this study were collected during archaeological survey conducted in July 2021. A total of 104 flotation samples were obtained through the implementation of targeted sampling methods, incorporating the following: A total of 42 samples were collected from cultural layers within five trial trenches at the Zhujia site; 27 samples were unearthed from cultural layers within the profile at the Dalaidian site, plus 19 samples from pits; and 16 samples were unearthed from pits at the Wangzhuang site. All flotation samples were floated using bucket flotation onsite. Charred plant macrofossils were collected using sieves with apertures of 0.5 mm (30 mesh) and 0.25 mm (60 mesh). After air-drying the floated materials in a shaded and well-ventilated area, the remains were transported to the Key Laboratory of Vertebrate Evolution and Human Origins, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, for plant species identification.

3.1. Identification and analysis of plant macrofossils

The plant macrofossils recovered from the archaeological sites were examined for species identification under the Leica M205 C stereomicroscope. Identification was primarily based on comparisons with modern seeds specimens and reference seed atlases. After identification, the charred seeds and nutlets were photographed, weighed, measured for size and quantified for statistical analysis. In addition, relatively well-preserved charred crop seeds were scanned using a micro-computed tomography scanner (GE v|tome|x m300&180) to obtain their high-resolution complete 3D models, which were used for the observation and reconstruction of their internal morphological structures.

3.2. Radiocarbon dating

A total of 11 samples were selected for AMS ^{14}C dating in this study. Two samples from Zhujia were recovered, including charred seeds from Pit 3-1 and charcoal from Pit 2–6. Eight samples were collected from Dalaidian, comprising one sediment sample (120 cm depth) from the cultural layer of Section 1-1, two charcoal samples (150 cm and 270 cm depths), one charred seed sample (220 cm depth), and four additional charred seed samples from Pits 3-1, 2–3, 1–2, and 4-1. One sample was obtained from Pit 2–4 at Wangzhuang. All samples were analyzed using AMS ^{14}C dating at Beta Analytic Laboratory, and the results were calibrated with OxCal v4.4.4 (Surovell et al., 2009; Reimer et al., 2020).

3.3. Data collection

To systematically investigate the relationship between regional agricultural evolution and climate, we collected and compiled archaeobotanical data on crops from the Central Plains and Haidai regions of NCP since the Neolithic. A total of 54 representative sites were selected, encompassing five crop types: foxtail millet (*Setaria italica*), common millet (*Panicum miliaceum*), rice (*Oryza sativa*), wheat (*Triticum aestivum*), and soybean (*Glycine max*). The dataset primarily includes two metrics: the percentage of counts and the percentage of weights. Data were mainly derived from the archaeobotanical dataset of the middle and lower reaches of the Yellow River in northern China provided by He et al. (2022b).

4. Results

4.1. Dating results

AMS ^{14}C dating of samples from the Zhujia (ZJ) site yielded a calibrated age range of 6289–6002 cal yr BP, corresponding to the middle to late phases of the Yangshao Culture. The Dalaidian (DLD) site contains cultural remains from multiple periods, with AMS ^{14}C dates ranging from 5927 to 3720 cal yr BP. These include remains from the late Yangshao Culture, the Longshan Culture, and the Xia-Shang periods. The Wangzhuang (WZ) site is dated to 3560–3390 cal yr BP based on AMS ^{14}C results and is associated with cultural remains from the Xiaqiyuan Culture to the Erligang Culture period (Fig. 2) (Supplementary Table S1).

4.2. Identification and statistics of plant macrofossils in the QRB

At the Zhujia site, flotation recovered a total of 132 plant macrofossils. Crop seeds constituted approximately 22 % of the total assemblage, comprising foxtail millet (n = 9), broomcorn millet (n = 6), rice (n = 13), and soybean (n = 1). Specifically, millets (foxtail and broomcorn combined) and rice accounted for 11.4 % and 9.8 % of the assemblage, respectively. Additionally, charred fruit kernels, including jujube (*Ziziphus jujuba* Mill.) and *Elaeagnus multiflora*, were identified (Li et al., 2024b). In contrast, the Dalaidian site recovered 43 plant macrofossils. This assemblage was dominated by crop seeds, which collectively represented approximately 77 % of the total recovery. Identified crops included foxtail millet (n = 10), broomcorn millet (n = 19), rice (n = 1), and soybean (n = 3). At Wangzhuang, 15 charred plant macrofossils were recovered. Despite the smaller sample size, the assemblage revealed diverse crop types—including wheat, soybean, broomcorn millet, and foxtail millet—alongside charred fruit kernels such as chestnut (*Castanea mollissima*), cherry (*Cerasus* sp.), and jujube (*Ziziphus jujuba* Mill.) (Fig. 3). Detailed flotation results and photographs of the charred seeds are available in the supplementary materials (Supplementary Data S1) (Supplementary Figs. S1–S6).

4.3. Quantification of crop remains in the NCP

Quantitative analysis of crop counts and weight percentages in North China between 9 and 3 ka BP reveals distinct trajectories in agricultural evolution. During the Peiligang period (9–7 ka BP), crop assemblages were characterized by relatively low diversity, with agricultural structures exhibiting significant inter-site variability. Overall, broomcorn millet served as the dominant cultivar, while rice constituted a substantial proportion at specific locations. In the transition from the Pre-Yangshao to the Early Yangshao period (7.5–6.5 ka BP), the relative proportion of rice declined, whereas broomcorn millet retained its status as the primary staple. By the Middle to Late Yangshao period (6.5–5 ka BP), foxtail millet exhibited a steady increase in abundance, eventually superseding broomcorn millet as the primary crop, while the latter showed a corresponding decline (Jia et al., 2021a; Wang et al., 2023; Yang et al., 2023). This trend intensified during the Longshan period (5–4 ka BP), where foxtail millet proportions rose further, paralleled by a continued decrease in broomcorn millet. Concurrently, soybean proportions increased, and wheat emerged at select sites (Jin, 2007; Guo and Jin, 2019). Finally, during the Bronze Age (4–3 ka BP), the dominance of dry farming crops was consolidated; the proportions of both foxtail and broomcorn millets increased, with foxtail millet occupying the preeminent position. Rice, soybean, and wheat continued to be identified alongside millets during this interval (Fig. 4).

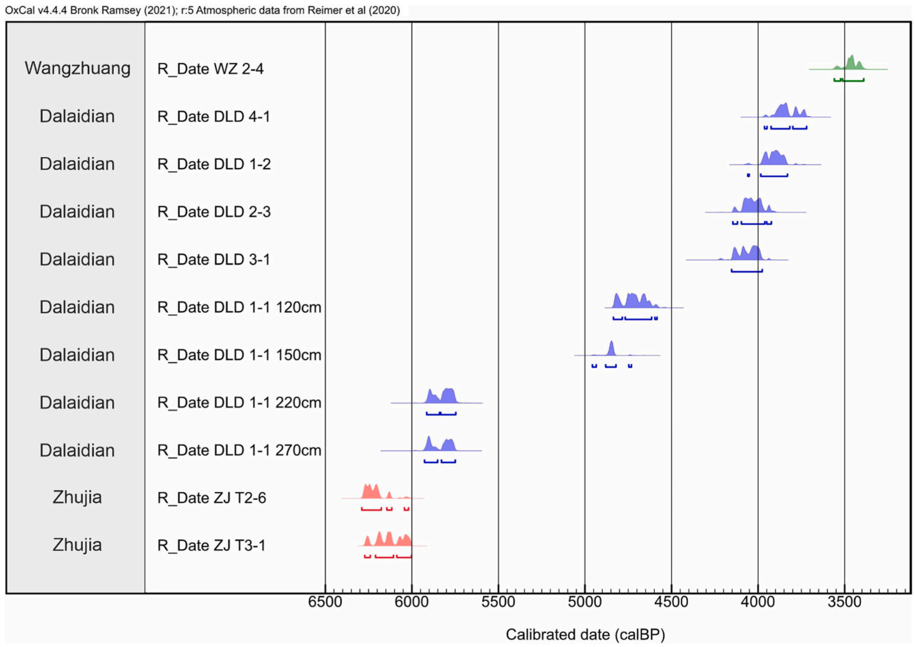

Fig. 2. AMS ^{14}C dating results from sites in the Qihe River Basin.

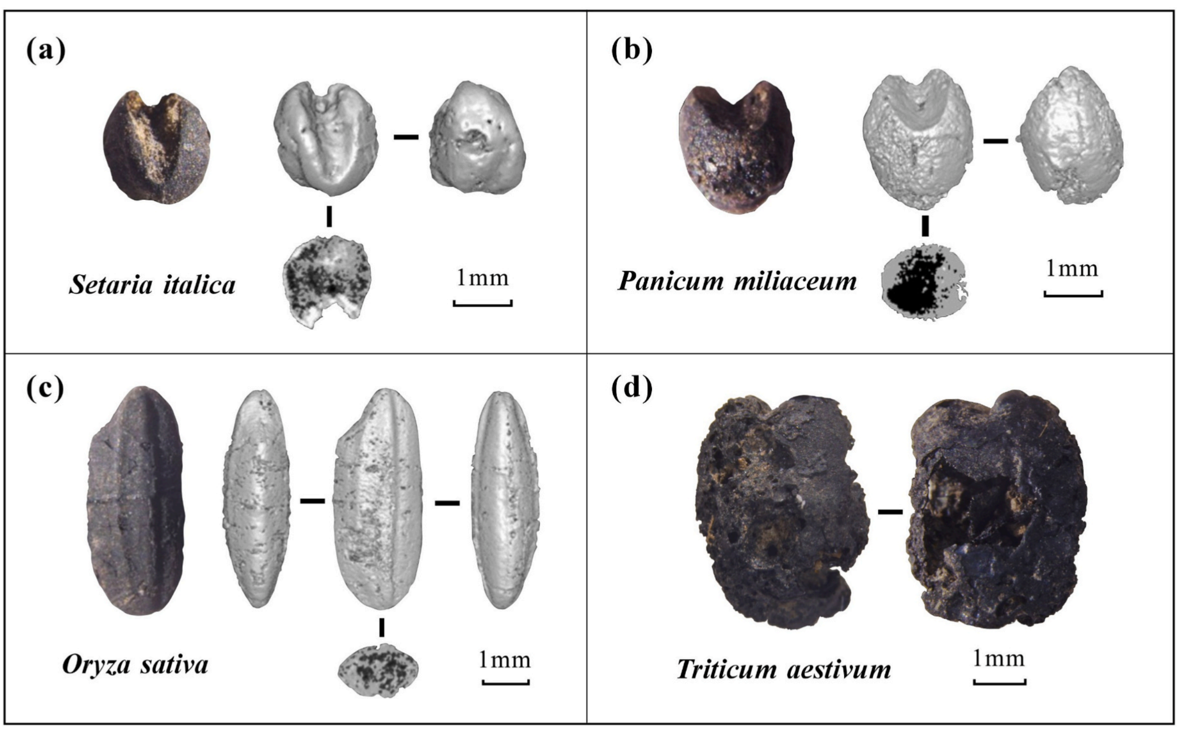

Fig. 3. Charred crop seeds and CT scan from the sites. (a) Foxtail millet from Dalaidian; (b) Broomcorn millet from Zhujia; (c) Rice from Zhujia; (d) Wheat from Wangzhuang.

5. Discussion

5.1. Records of drought events in NCP since the mid-Holocene

The Holocene represents the most recent interglacial of the Quaternary, spanning from 11.7 ka BP to the present (Sun et al., 2009). While generally characterized by relatively stable climatic conditions, this stability was nonetheless punctuated by frequent climatic fluctuations, including four major cooling episodes centered at approximately 8.2 ka BP, 7.2 ka BP, 5.5 ka BP and 4.2 ka BP (Chen et al., 2021; Hou and Wu, 2021; Hou et al., 2023; Duan et al., 2024). Hou and Fang (2012) reconstructed the temperature variation sequence in northern China by compiling multiple Holocene paleoclimate records from this region, providing a clear record of periodic climate oscillations (Fig. 5a). Furthermore, stalagmites, which serve as high-precision and high-resolution climate proxies, have been widely used in paleoclimate research (Liu et al., 2020). The speleothem $\delta^{18}O$ record from Lianhua Cave in North China reveals markedly amplified $\delta^{18}O$ variability during

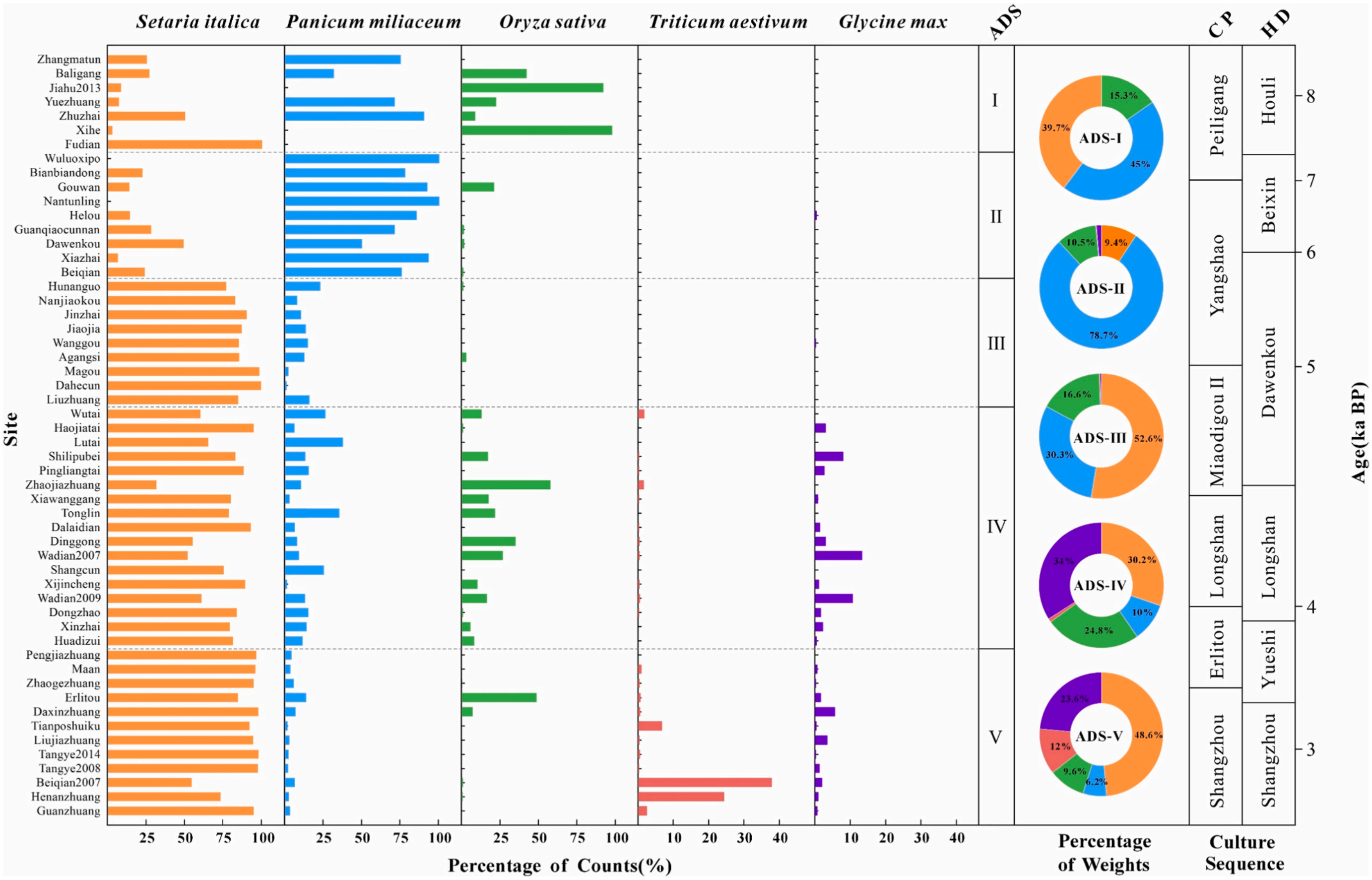

Fig. 4. The percentages of crop counts and weights in the North China Plain. According to the structure of agriculture can be roughly divided into five agricultural development stages (ADS), and the different stages corresponding to the cultural sequence of the Central Plains (CP) and the Haidai region (HD).

the intervals of 9.5–8.1 ka BP and 6.5–4.0 ka BP (Fig. 5b). Most notably, a weak monsoon event lasting approximately 150 years was identified around 8.2 ka BP (Dong et al., 2015). These weak monsoon events are corroborated by other regional paleoclimatic proxies. For instance, pollen spectra from lacustrine sediments in Daihai Lake, situated in the monsoon marginal zone (Fig. 5c), exhibit sharp declines in tree pollen percentages and significant increases in herbaceous pollen concentrations during 7.25–6.05 ka BP and 4.45–3.95 ka BP (Xiao et al., 2004). These shifts indicate substantially reduced precipitation and a transition toward colder and drier climatic conditions. Comparable trends have been documented in pollen records from other lakes across North China (Fig. 5d and e) (Jiang et al., 2006; Xu et al., 2010; Chen et al., 2015).

Besides, lake-level fluctuations within the East Asian monsoon region provide indicators of variations in East Asian Summer Monsoon intensity. Records from Gonghai, Dali Lake, and Chagan Nor indicate that mid-Holocene (8–4 ka BP) water levels in North China were significantly higher than those of the late Holocene. However, distinct regressions (lake-level lowering) occurred around 8.2 ka BP, 7.2 ka BP, 5.5 ka BP and 4.2 ka BP (Fig. 5f–h). Comparisons with other climatic proxies suggest that these declines in lake levels were synchronous with weakened monsoon conditions (Goldsmith et al., 2017; Li et al., 2020b). Beyond these climate proxies, geochemical elemental records serve as crucial indicators for environmental evolution. Drought index from Baiyangdian Lake and Ningjinpo palaeolake reveal that during these four cooling events, aridity in North China also intensified markedly (Shen et al., 2018; Li et al., 2020a).

5.2. New discoveries on prehistoric agriculture in the QRB

Although the total number of charred crop seeds recovered from the QRB is limited, the diversity of the assemblage is notable. Identified include foxtail millet, broomcorn millet, rice, and soybean, and various charred fruit kernels, providing preliminary indicative evidence for the agricultural structure during the Middle Neolithic period in the QRB. Significantly, 13 rice grains were identified (Fig. 3c) (Supplementary Data S1). These may either represent local cultivation or introduction into the QRB through exchange networks rather than in situ production. Although the occurrence of rice at Zhujia is relatively rare, it is not an isolated phenomenon during this period (Fig. 6b). In Early Yangshao sites of the middle-lower Yellow River basin, small quantities of rice seeds have been found at Dingxian, Shangshaowang, and Diantoubao (Song et al., 2019) in the Sushui River basin; at Nanjiaokou (Qin and Fuller, 2009), Didongbei (Wei, 2014), and Gouwan (Wang et al., 2011b) in the Central Plains region; and Dongpan and Beiqian in the Haidai region (Jin et al., 2016). These findings indicate that rice cultivation during the Early Yangshao period was widespread across the middle and lower Yellow River basin.

Rice was initially domesticated in the lower Yangtze River region (Zhang et al., 2024). The northward dispersal of rice across Neolithic China unfolded in two primary phases, with the first wave initiating approximately 8 ka BP and the second occurring around 5 ka BP (Qin, 2012). During the climatic favorable period around 8 ka BP, rice first spread northward into the Central Plains and the Haidai region (He et al., 2017) (Fig. 6a). Although climatic conditions on the NCP during 7–6 ka BP were characterized by fluctuations, they remained relatively warm and humid overall (Fig. 5a–j). While such variability constrained the widespread cultivation of rice in the region, small-scale cultivation presumably persisted in microenvironments with favorable hydrothermal regimes, such as the QRB. Evidence from the Tanghu site in the Central Plains supports this hypothesis; the continuous presence of rice

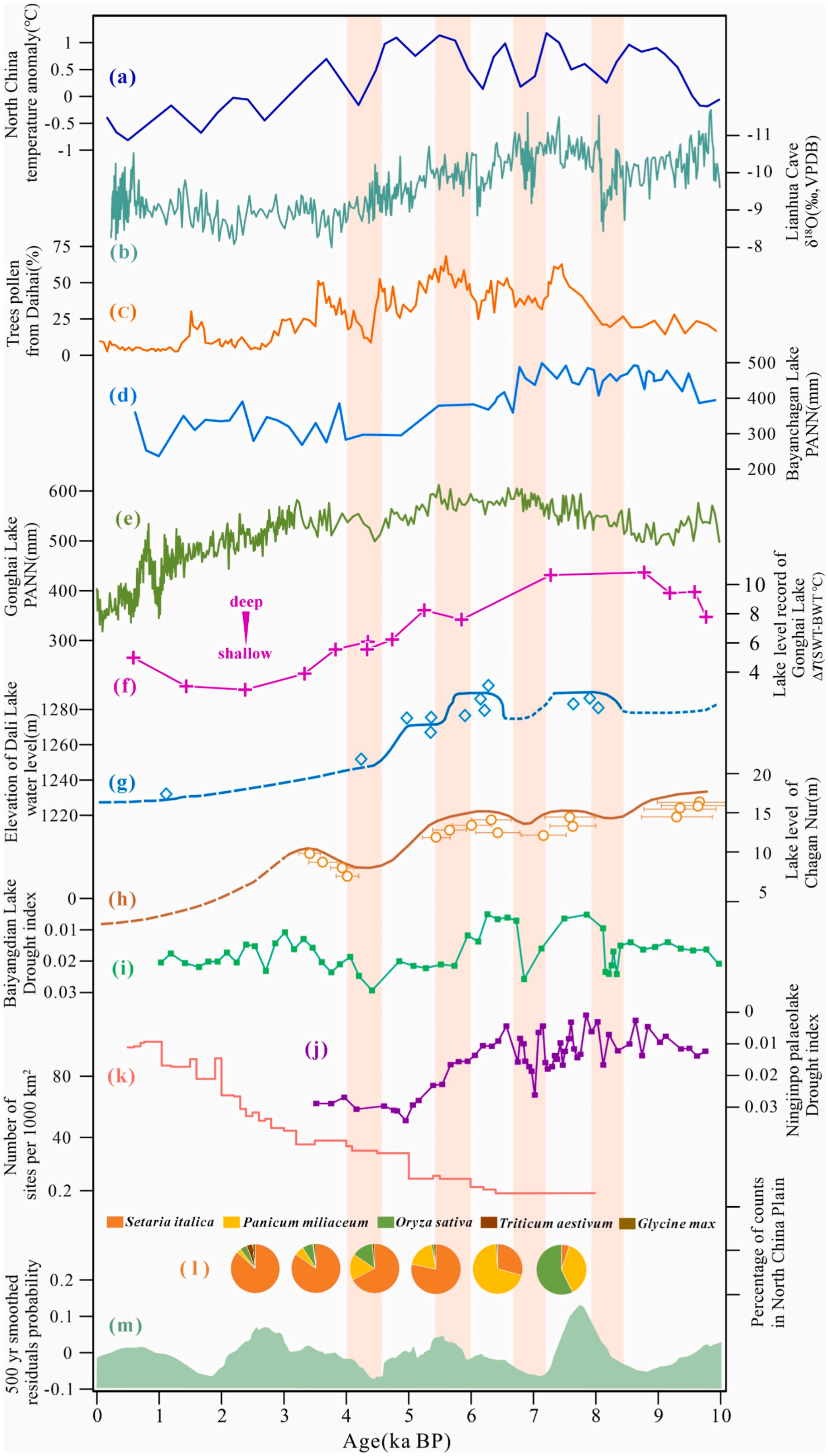

Fig. 5. Comparison of anthropogenic indicators and paleoenvironmental records in North China. (a) Holocene temperature record in North China (Hou and Fang, 2012); (b) $\delta^{18}O$ record from Lianhua Cave stalagmites (Dong et al., 2015); (c) Trees pollen record from Daihai Lake (Xiao et al., 2004); (d, e) Quantitative precipitation reconstruction based on pollen data from Bayanchagan Lake (Jiang et al., 2006) and Gonghai Lake (Chen et al., 2015); (f) GDGT-indicated lake-level records in Gonghai Lake (Cao et al., 2021); (g, h) Lake level fluctuations of Dali Lake (Goldsmith et al., 2017) and Chagan Nur (Li et al., 2020a); (i, j) Drought index from Baiyangdian (Shen et al., 2018) and Ningjinpo Palaeolake (Li et al., 2020b); (k) Density average estimates for the archaeological sites (number of sites per 1000 km^2) of northern China (Hosner et al., 2016); (l) The percentages of crop counts at 1000-year intervals in North China (this study); (m) Relative population growth and decline in China over the last 10000 years (Wang et al., 2014a). The pink bands indicate several major climatic drought events during the Neolithic period. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

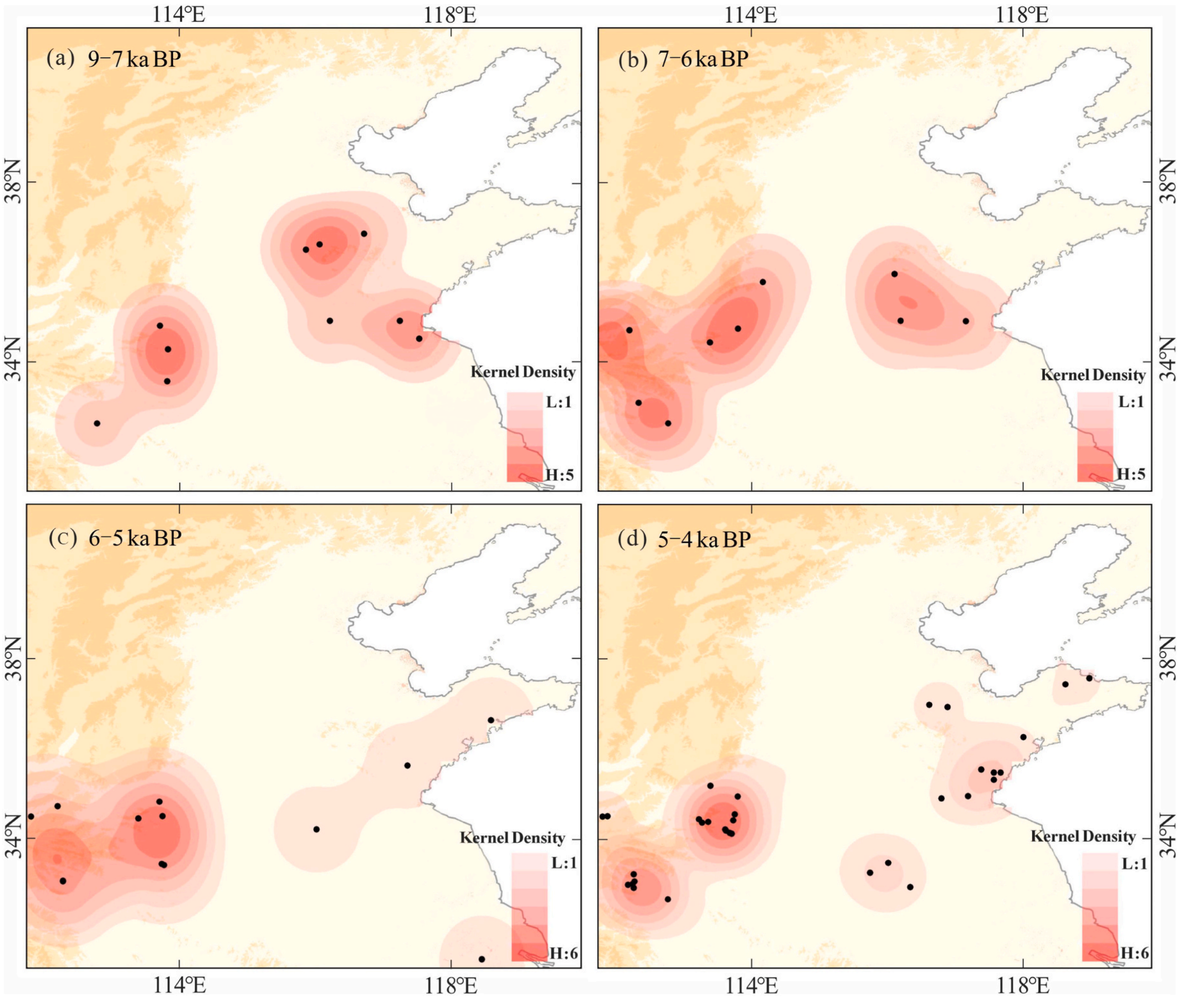

Fig. 6. Kernel density distribution of rice macrofossils in the North China Plain.

phytoliths throughout stratigraphic sequences dating to 7.8–4.5 ka BP attests to the persistence of rice cultivation during the Neolithic (Zhang et al., 2012). Therefore, synthesizing the regional climatic context with archaeological evidence of continuous cultivation, we speculate that the rice recovered from the Zhujia site likely represent local cultivation. However, this requires further verification.

Based on distinct ecological, morphological, and physiological characteristics, *japonica* rice is classified into temperate and tropical ecotypes. Modern molecular research indicates that temperate *japonica* rice evolved from tropical *japonica* rice, representing an adaptation to temperate climates during its northward dispersal. This adaptation process was significantly influenced by selection for cold tolerance, leading to morphological changes in rice (Liakat Ali et al., 2011). In terms of grain shape, typical tropical *japonica* varieties are slender, whereas temperate *japonica* varieties are characteristically short and rounded. Archaeological evidence corroborates this; rice grains recovered from sites dating to approximately 8 ka BP are predominantly slender, exhibiting widths generally less than 2 mm (He et al., 2017). Morphometric analysis of rice grains from the Zhujia site reveals an elongated morphology, with a mean length of 4.58 mm and a mean width of 2.02 mm (Supplementary Table S2). This shape closely resembles that of tropical *japonica*, likely reflecting the initial wave of northward rice dispersal. However, during the interval of 6–5 ka BP, the weakening of the East Asian Summer Monsoon and intensified aridification precipitated a southward retraction of the northern limit of rice distribution to regions south of 35°N (Jia et al., 2021b). Consequently, rice remains become markedly scarce in the QRB and the central–northern NCP during this phase (Fig. 6b and c). This contraction is attributed to abrupt climatic cooling, to which the tropical *japonica* ecotype was maladapted, leading to its virtual disappearance from the region. By the Longshan period, the number of sites with rice increased markedly. Furthermore, the proportion of rice at numerous sites such as Shilipubei (Guo et al., 2019a), Zhaojiazhuang (Jin et al., 2011), Quanjiu (Wei, 2014), and other sites showed increased proportions of rice seeds compared to the 6–5 ka BP period (Fig. 6d). This resurgence is likely attributable to the emergence of cold-tolerant temperate *japonica* rice around 5 ka BP, facilitating a second wave of northward dispersal into the Central Plains and Haidai regions (He et al., 2017). Nevertheless, constrained by the legacy of climatic deterioration during 6–5.5 ka BP (Marcott et al., 2013), rice remained a supplementary component of agricultural systems in the NCP, where dryland farming continued to dominate subsistence strategies (Wu et al., 2017b; Tao et al., 2022; Li et al., 2024a).

Another noteworthy aspect of the plant macrofossils from the QRB is the recovery of wheat grains at the Wangzhuang site, dated to approximately 3.5 ka BP (Fig. 3d). Previous research establishes that wheat originated in West Asia around 10 ka BP, progressively dispersed eastward, reaching the Xinjiang region of China at approximately 5.2 ka BP and subsequently spreading further east to the NCP by around 4.5 ka BP (Jin, 2007; Zhao, 2015; Zhou et al., 2020). The discovery of wheat in the QRB provides new archaeobotanical evidence supporting the eastward dispersal of wheat agriculture, indicating that sporadic wheat cultivation had begun on the NCP during this period.

5.3. Trends in the evolution of agricultural structure on the NCP since the Neolithic Period

The inception of agricultural activities on the NCP occurred during the transition from the Late Paleolithic to the Early Neolithic, approximately 11 ka BP. Early evidence of millet utilization has been documented at key sites such as Nanzhuangtou (11.5–11 ka BP), Donghulin (11–9.5 ka BP), and Cishan (10.3–8.7 ka BP) (Lu et al., 2009; Yang et al., 2012). However, definitive indicators of domestication during this period remain relatively scarce, with only limited traces found at a handful of sites. This suggests that agriculture was likely in a nascent phase, and cultivated crops served as a supplementary resource rather than the primary component of prehistoric human diets (Bestel et al., 2014; Zhao, 2014).

The Peiligang period (9–7 ka BP) was a critical period in the development of prehistoric culture in northern China. Dryland farming—primarily centered on foxtail millet and broomcorn millet—expanded rapidly during this time (Wang et al., 2017). Concurrently, rice farming, which originated in the lower reaches of the Yangtze River, gradually spread northward to the Huaihe River basin and even further north (Fig. 6a), resulting in a mixed farming system combining dryland and rice agriculture (Zhang et al., 2012; Wang et al., 2023). Among these, broomcorn millet predominated in the agricultural structure of the Peiligang period, followed by foxtail millet. Rice generally comprised a marginal fraction of the overall assemblage, it only constituted a higher proportion at sites such as Baligang, Jiahu, Xihe, Yuezhuang, and Zhuzhai (Jin et al., 2014; Deng et al., 2015; Crawford et al., 2016; Wang et al., 2018; Bestel et al., 2018).

During the Yangshao period (7–5 ka BP), prehistoric culture in North China advanced rapidly, the population grew dramatically, large settlements emerged (Liu and Chen, 2017), and agricultural development significantly improved. Intensive agriculture expanded quickly, and dryland farming gradually became the dominant economic activity in the arid and semi-arid regions of northern China (Yang et al., 2022). Around 6 ka BP, the dryland farming system in North China underwent its most significant transformation since the Neolithic period (He et al., 2022b). Foxtail millet began to surpass broomcorn millet in agricultural importance and eventually became dominated, while broomcorn millet was primarily cultivated in mountainous regions with relatively poor water and heat conditions (Yuan et al., 2020; He et al., 2022b). Concurrently, the occurrence of rice in archaeological sites declined sharply, and its primary distribution area continued to shift southward. Between 7 and 6 ka BP, the northernmost distribution of rice in North China was roughly at 36°N, but by 6–5 ka BP, it had retreated to around 35°N (Fig. 6b–c), establishing an agricultural production pattern characterized by “North millet, South rice” (Jia et al., 2021b).

During the Longshan period (5–4 ka BP), the process of social complexification accelerated, and a diverse yet unified historical landscape began to take shape. Agricultural production became the dominant economic activity among sedentary populations (Yuan et al., 2020). This period also marked a pivotal stage in the development and transformation of early agriculture. Mixed farming systems became more widespread and advanced across the NCP, with increasingly diversified crop structures (Yuan et al., 2020; Gao et al., 2022). During this phase, the scale of rice cultivation expanded, with evidence found at multiple sites in the Central Plains and the Haidai region, the northernmost distribution remaining around 35°N (Fig. 6d). Additionally, wheat from West Asia was introduced into eastern China, with scattered occurrences in archaeological sites across the NCP. Alongside the aforementioned crops, soybeans—an important component of prehistoric agriculture—exhibited a marked increase in ubiquity at Longshan period sites (Yang et al., 2024). These trends suggest that the level of agricultural economic development during the Longshan period marked a significant improvement compared to the Yangshao period, with a marked increase in the diversification of agricultural activities.

5.4. Synchrony between the evolution of Neolithic agricultural societies and drought events in the North China Plain

5.4.1. The 8.2 ka event and the evolution of agricultural societies

The 8.2 ka event represents one of the most pronounced and abrupt cold–dry climatic oscillations during the Holocene (Alley and Agustsdottir, 2005). Multiple paleoclimatic proxies indicate that during this interval, the mid-to-high latitudes of the Northern Hemisphere experienced cooler and drier conditions, while aridification intensified at lower latitudes (Wang, 2011a). This climatic anomaly significantly impacted human activities across diverse global regions (Flohr et al., 2016; Roffet-Salque et al., 2018). However, around the 8.2 ka BP, the number of sites declined markedly, although a limited number of sites—such as Cishan, Jiahu, Zhangmatun, and Shunshanji—persisted in resource-rich areas (Zhao, 2020). These “pioneering sites” are characterized by larger-scale population amalgamation, sedentary lifeways, intensive site utilization, and abundant material remains, indicating that early communities adopted strategies of settlement concentration in resource-rich zones and resource intensification to cope with climatic deterioration (Liu and Chen, 2017; Zhao, 2020).

The 8.2 ka event also precipitated notable shifts in agricultural practices in the NCP. Phytolith evidence from the Shunshanji and Hanjing sites in the Huaihe River basin reveals a two-phase evolution in rice cultivation management surrounding this event. During the initial phase (8.5–8.2 ka BP), rice was cultivated primarily in the lowlands and irrigated mainly by rainwater. In the subsequent phase (8.2–7.5 ka BP), cultivation changed to use highly managed regularly flooded and drained wetlands. This transition is likely directly associated with reduced precipitation around the 8.2 ka event (Luo et al., 2021). After 8.2 ka event, the strengthening of the East Asian summer monsoon facilitated increased precipitation in North China, fostering the development and dispersal of agriculture. Agricultural practices gradually became more scaled and systematized, transitioning from initial slash-and-burn agriculture toward foot-plough agriculture (Fig. 7a) (Crawford et al., 2016; Bestel et al., 2018). Compared with hunter-gatherer subsistence strategies, agriculture could sustain larger populations (Chen, 2020). Meanwhile, early Neolithic animal domestication provided important dietary supplements for early communities (Liu and Chen, 2017; Zhang et al., 2022). Consequently, demographic growth surged, reaching a peak around 7.7 ka BP (Wang et al., 2014a) (Fig. 5 l and 5m).

5.4.2. The 7.2 ka event and the evolution of agricultural societies

The 7.2 ka event represents another global-scale climatic perturbation documented in multiple paleoclimatic records worldwide, characterized primarily by weakening of the Asian summer monsoon and strengthening of the South American summer monsoon (Hou et al., 2023). Paleoclimatic signals associated with this event correlate closely with major societal upheavals observed archaeologically across many regions, including widespread site abandonment, population migration, and cultural transformations (Sánchez et al., 2012; Aubán et al., 2016). In North China, the 7.2 ka event had differential impacts on several prehistoric cultures. Specifically, the Laoguantai Culture (8–7 ka BP) in the Guanzhong Plain declined around this time (Lu and Zhang, 2008); the Dadiwan Culture on the Loess Plateau experienced an approximately 500-year occupational hiatus (Yang et al., 2025); and the Peiligang Culture gradually disintegrated around 7 ka BP (Liu et al., 2019).

In terms of agriculture, the 7.2 ka event induced a trend toward simplification of agricultural structures, with the most conspicuous change being the disappearance (or marked decline) of rice agriculture (Figs. 4 and 5i). Tropical *japonica* rice had dispersed northward into the Central Plains and Haidai regions during the climatically favorable interval around 8 ka BP (Liakat Ali et al., 2011). However, the abrupt climatic deterioration around 7.2 ka BP rendered these temperate regions unsuitable for the tropical subspecies. This led to a gradual transition from the mixed farming systems characteristic of the Peiligang

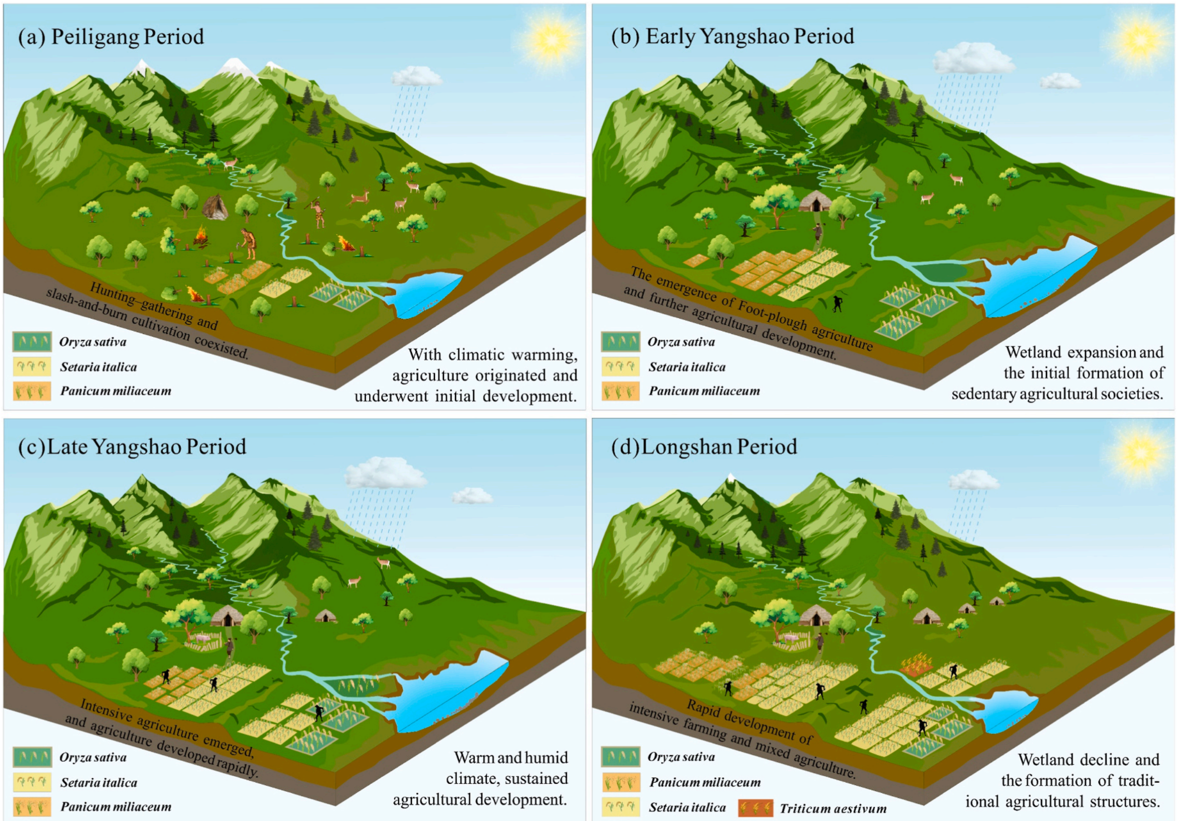

Fig. 7. Idealized representation of synchronous evolution between the ecological environment and agricultural development in the North China Plain during the Neolithic period.

period to predominantly dryland agriculture after ~7 ka BP (Fig. 4). Within dryland farming systems, broomcorn millet exhibits superior tolerance to harsh environmental conditions compared to foxtail millet, possessing greater resistance to drought and saline–alkaline soils, as well as a shorter growing season (Lin et al., 2002). Consequently, during cold and arid climatic phases, prehistoric populations preferentially selected broomcorn millet. Comparative studies indicate that the yields per unit area of foxtail millet and broomcorn millet are only about half that of rice (Wu, 2016). The decline of rice-based agriculture therefore resulted in reduced food availability relative to the preceding period, contributing to population decreases (Wang et al., 2014a). Statistical analysis reveals that between 8 and 7 ka BP, the mean proportion of rice in North China agricultural assemblages was 57.34 %; this figure plummeted to 1.15 % following the 7.2 ka event (Fig. 5l). Tracking this trend, population levels in NCP reached a peak around 7.7 ka BP before declining significantly around 7 ka BP (Fig. 5m). These patterns indicate that the 7.2 ka event had profound impacts on the agriculture and demography of the NCP. In response, early communities likely sought to maintain stable food supplies primarily through optimization of agricultural structures and increased agricultural investment (Fig. 7a and b).

5.4.3. *The 5.5 ka event and the evolution of agricultural societies*

The interval of 6–5 ka BP constitutes a pivotal phase in the development of prehistoric societies. With the gradual consolidation of agricultural economies, diversified subsistence strategies provided stable food supplies, thereby facilitating the formation of permanent settlements and the increase in settlement scale. These developments significantly underpinned population growth (Wang et al., 2014a). Consequently, during the Middle Neolithic, processes of social complexity emerged almost simultaneously in both the Yellow River and Yangtze River basins of China (Wang, 2014b). Concurrently, paleoclimatic records worldwide document a pronounced cooling event around 5.5 ka BP (Steig et al., 1998; Haug et al., 2001). In China, this event was primarily characterized by abrupt temperature drops and a weakening of the East Asian summer monsoon (Wu et al., 2018). During this interval, dryland agriculture in northern China underwent a structural transformation, marked by a fundamental shift in the relative proportions of foxtail millet and broomcorn millet (He et al., 2022b). The drivers of this transition are closely linked to the interplay of climatic change, cultural expansion, and rapid demographic growth (Zhao, 2014).

Specifically, climatic cooling constrained the carrying capacity of resources in North China, while population levels continued to rise. This resource-demography imbalance compelled early communities to seek additional food sources to sustain subsistence and social development. Although broomcorn millet is more resilient, foxtail millet possesses a significantly higher yield potential per unit area. Therefore, to address the urgent caloric demands of a growing population under conditions of resource stress, communities preferentially expanded foxtail millet cultivation (Fig. 7c and d) (He et al., 2022b). To maintain stable food supplies, early farmers implemented a suite of field management strategies in addition to optimizing agricultural structures. Evidence indicates that since the Late Neolithic, early farmers not only continuously expanded cultivated land areas but also widely adopted fertilization practices within dryland farming systems (Ouyang and Shang, 2025). This sustainable, intensified agricultural system enhanced the land's carrying capacity, thereby propelling the trajectory of social complexity in northern China (Fig. 7b and c).

5.4.4. *The 4.2 ka event and the evolution of agricultural societies*

The 4.2 ka event was a widespread climatic cooling and drying episode (Railsback et al., 2018) that precipitated profound societal shifts across multiple regions worldwide. For example, the Old Kingdom of ancient Egypt in the Nile Valley, the Akkadian Empire in Mesopotamia, and the Harappan Civilization in the Indus Valley all declined around 4.2 ka BP (Stanley et al., 2003; Dixit et al., 2014; Carolin et al., 2019). In China, the weakening of the East Asian monsoon, coupled with strong El Niño activity, produced a climate pattern characterized by general cooling and a distinct “northern drought–southern flooding” dipole in eastern China (Wu and Liu, 2004; Zhang et al., 2018a).

Due to the biological characteristics of different crops, the impact of climate change varied across agricultural systems. Although the 4.2 ka event intensified aridification trends in northern China, temperature and precipitation levels remained within the viable growth thresholds for millet agriculture. Indeed, moderate aridification led to the contraction of lakes and wetlands, which, paradoxically, opened new arable land for the expansion of millet cultivation (He et al., 2022a; Chen and Li, 2025). Consequently, during and after the 4.2 ka event, the Central Plains—where millet agriculture predominated during the Longshan period—exhibited continued prosperity. In sharp contrast, the Haidai region practiced a mixed farming economy heavily reliant on rice. Owing to rice's heightened sensitivity to temperature and hydrological changes, the intensified aridity during the 4.2 ka event caused a severe contraction of its ecological niche. This resulted in the rapid collapse of rice-based agriculture in the Haidai region (An et al., 2021).

In summary, while the 4.2 ka event restructured agricultural patterns in the NCP, overall agricultural activity demonstrated remarkable resilience rather than disruption. This resilience is likely underpinned by advancements in production technologies, such as irrigation and fertilization (Wang et al., 2022). Furthermore, with the intensification of social complexity during the Longshan period, societies characterized by specialized labor, social stratification, and higher levels of organization were more effective in mitigating natural risks—not only due to enhanced labor efficiency, but also through mechanisms of resource redistribution (Chen, 2020). Consequently, increasing social complexity also contributed to the sustained development of agriculture in North China (Fig. 7c and d).

6. Conclusion

Based on plant macrofossils recovered from the Zhujia, Wangzhuang, and Dalaidian sites in the Qihe River basin, this study analyzes the fundamental characteristics of regional agriculture during 6.5–3.5 ka BP and the influence of climatic change on shifts in agricultural structure, providing preliminary indicative evidence for agricultural development patterns during the Middle Neolithic in the Qihe River basin. Building upon this foundation, archaeobotanical data from 54 sites across the North China Plain were synthesized to examine the characteristics of Neolithic agricultural structures before and after four major drought events centered at approximately 8.2, 7.2, 5.5, and 4.2 ka BP. The results demonstrate that repeated abrupt drought events during the Neolithic exerted pronounced impacts on the development of agricultural societies on the North China Plain. Early populations were compelled to modify their original subsistence strategies and to maintain stable food supplies through a suite of measures, including resource integration, optimization of agricultural structures, and increased investment in field management. Notably, the magnitude of climatic impacts on human activities varied across different temporal nodes of the Neolithic and progressively diminished as early populations enhanced their capacities to adapt to and transform natural environments. Overall, transformations in agricultural structures represent a comprehensive expression of human agency under the combined influences of climatic change, population growth, and increasing social complexity.

Author contributions

Yanpeng Li, Xinying Zhou and Hai Xu designed the study. Keliang Zhao, Guanhan Chen, Yaping Zhang, Jiacheng Ma participated in archaeological survey and sample collection. Yanpeng Li and Shengrui Li wrote the first manuscript. Yong Ge, Yan Zheng, Keliang Zhao, Junchi Liu and Xiaoqiang Li revised the manuscript and offered constructive suggestions. Yanpeng Li and Shengrui Li contributed equally to this work and should be considered co-first authors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2026.109807.

Data availability

All data and/or code is contained within the submission.

References

Alley, R.B., Agustsdottir, A.M., 2005. The 8k event: cause and consequences of a major Holocene abrupt climate change. Quat. Sci. Rev. 24, 1123–1149. https://doi.org/10.1016/j.quascirev.2004.12.004.

An, C., Feng, Z., 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. https://doi.org/10.1002/jqs.849.

An, J., Kirleis, W., Jin, G., 2021. Understanding the collapse of the Longshan Culture (4400-3800 BP) and the 4.2 ka event in the Haidai Region of China – from an agricultural perspective. Environ. Archaeol. 29, 214–228. https://doi.org/10.1080/14614103.2021.2003583.

Aubán, J.B., Puchol, O.G., Barton, M., McClure, S., Pardo Gordó, S., 2016. Radiocarbon dates, climatic events, and social dynamics during the Early Neolithic in Mediterranean Iberia. Quat. Int. 403, 201–210. https://doi.org/10.1016/j.quaint.2015.09.020.

Bestel, S., Bao, Y., Zhong, H., Chen, X., Liu, L., 2018. Wild plant use and multi-cropping at the early Neolithic Zhuzhai site in the middle Yellow River region, China. Holocene 28, 195–207. https://doi.org/10.1177/0959683617721328.

Bestel, S., Crawford, G.W., Liu, L., Shi, J., Song, Y., Chen, X., 2014. The evolution of millet domestication, Middle Yellow River Region, North China: evidence from charred seeds at the late Upper Paleolithic Shizitan locality 9 site. Holocene 24, 261–265. https://doi.org/10.1177/0959683613518595.

Cao, J., Rao, Z., Shi, F., Lian, E., Jia, G., 2021. Lake-level records support a mid-Holocene maximum precipitation in northern China. Sci. China Earth Sci. 64, 2161–2171. 10.1007/s11430-020-9833-3.

Carolin, S.A., Walker, R.T., Day, C.C., Ersek, V., Sloan, R.A., Dee, M.W., Talebian, M., Henderson, G.M., 2019. Precise timing of abrupt increase in dust activity in the Middle East coincident with 4.2 ka social change. Proc. Natl. Acad. Sci. USA 116, 67–72. https://doi.org/10.1073/pnas.1808103115.

Chen, C., Yuan, D., Li, J., Wang, X., Cheng, H., Ning, Y., Edwards, R.L., Wu, Y., 2021. The 4.2 ka event in East Asian monsoon region, precisely reconstructed by multi-proxies of stalagmite. Clim. Past Discuss 1–42. https://doi.org/10.5194/cp-2021-20.

Chen, F., Xu, Q., Chen, J., Birks, H.J.B., Liu, J., Zhang, S., Jin, L., An, C., Telford, R.J., Cao, X., Wang, Z., Zhang, X., Selvaraj, K., Lu, H., Li, Y., Zheng, Z., Wang, H., Zhou, A., Dong, G., Zhang, J., Huang, X., Bloemendal, J., Rao, Z., 2015. East Asian summer monsoon precipitation variability since the last deglaciation. Sci. Rep. 5, 11186. https://doi.org/10.1038/srep11186.

Chen, L., Li, K., 2025. Mid-Holocene hydroclimatic changes drove Neolithic agricultural development in the Luoyang Basin of the Central Plains, China. Catena 258, 109241. https://doi.org/10.1016/j.catena.2025.109241.

Chen, S., 2020. Prehistoric Modernization: from Hunting and Gathering to the Origins of Agriculture. SDX Joint Publishing Company, Beijing (in Chinese).

Crawford, G.W., Chen, X., Luan, F., Wang, J., 2016. People and plant interaction at the Houli Culture Yuezhuang site in Shandong Province, China. Holocene 26, 1594–1604. https://doi.org/10.1177/0959683616650269.

Deng, Z., Qin, L., Gao, Y., Weisskopf, A.R., Zhang, C., Fuller, D.Q., 2015. From early domesticated rice of the Middle Yangtze Basin to Millet, rice and wheat agriculture: archaeobotanical macro-remains from Baligang, Nanyang Basin, central China (6700–500 BC). PLoS One 10, e0139885. https://doi.org/10.1371/journal.pone.0139885.

Dixit, Y., Hodell, D.A., Petrie, C.A., 2014. Abrupt weakening of the summer monsoon in northwest India ~4100 yr ago. Geology 42, 339–342. https://doi.org/10.1130/G35236.1.

Dong, G., Li, R., Lu, M., Zhang, D., James, N., 2020. Evolution of human–environmental interactions in China from the Late Paleolithic to the Bronze Age. Prog. Phys. Geogr. 44, 233–250. https://doi.org/10.1177/0309133319876802.

Dong, J., Shen, C., Kong, X., Wang, H., Jiang, X., 2015. Reconciliation of hydroclimate sequences from the Chinese Loess Plateau and low-latitude East Asian Summer Monsoon regions over the past 14,500years. Palaeogeogr. Palaeoclimatol., Palaeoecol. 435, 127–135. https://doi.org/10.1016/j.palaeo.2015.06.013.

Duan, P., Li, H., Ma, Z., Zhao, J., Dong, X., Sinha, A., Hu, P., Zhang, H., Ning, Y., Zhu, G., Cheng, H., Duan, P., Li, H., Ma, Z., Zhao, J., Dong, X., Sinha, A., Hu, P., Zhang, H., Ning, Y., Zhu, G., Cheng, H., 2024. A series of climate oscillations around 8.2ka revealed through multi-proxy speleothem records from North China. Clim. Past 20, 1401–1414. https://doi.org/10.5194/cp-20-1401-2024.

Flohr, P., Fleitmann, D., Matthews, R., Matthews, W., Black, S., 2016. Evidence of resilience to past climate change in Southwest Asia: early farming communities and the 9.2 and 8.2 ka events. Quat. Sci. Rev. 136, 23–39. https://doi.org/10.1016/j.quascirev.2015.06.022.

Gao, W., Hu, H., Hou, W., Zhang, P., Gong, P., Jia, W., Liu, X., Li, K., 2022. The spatiotemporal patterns of human settlement during the longshan and erlitou periods in relation to extreme floods and subsistence strategy in the upper and middle Qin River reaches, central China. Land 11, 1088. https://doi.org/10.3390/land11071088.

Goldsmith, Y., Broecker, W.S., Xu, H., Polissar, P.J., Demenocal, P.B., Porat, N., Lan, J., Cheng, P., Zhou, W., An, Z., 2017. Northward extent of East Asian monsoon covaries with intensity on orbital and millennial timescales. Proc. Natl. Acad. Sci. USA 114, 1817–1821. https://doi.org/10.1073/pnas.1616708114.

Guo, R., Gao, M., Sun, M., Wang, L., Wang, S., Jin, G., 2019. The carbonized plant remains of pre-qin period from Shilipubei site, Heze City, Shandong Province. Agric. Hist. China 38, 15–26 (in Chinese).

Guo, R., Jin, G., 2019. Study on the wheat agriculture in the pre-Qin period of Haidai Region. Quat. Sci. 39, 144–160. https://doi.org/10.11928/j.issn.1001-7410.2019.01.14 (in Chinese).

Haug, G.H., Hughen, K.A., Sigman, D.M., Peterson, L.C., Röhl, U., 2001. Southward migration of the intertropical convergence Zone through the Holocene. Science 293, 1304–1308. https://doi.org/10.1126/science.1059725.

He, K., Lu, H., Jin, G., Wang, C., Zhang, H., Zhang, J., Xu, D., Shen, C., Wu, N., Guo, Z., 2022a. Antipodal pattern of millet and rice demography in response to 4.2 ka climate event in China. Quat. Sci. Rev. 295, 107786. https://doi.org/10.1016/j.quascirev.2022.107786.

He, K., Lu, H., Zhang, J., Wang, C., 2022b. Holocene spatiotemporal millet agricultural patterns in northern China: a dataset of archaeobotanical macroremains. Earth Syst. Sci. Data 14, 4777–4791. https://doi.org/10.5194/essd-14-4777-2022.

He, K., Lu, H., Zhang, J., Wang, C., Huan, X., 2017. Prehistoric evolution of the dualistic structure mixed rice and millet farming in China. Holocene 27, 1885–1898. https://doi.org/10.1177/0959683617708455.

Henan Provincial Administration of Cultural Heritage (HPACH), 2008. Henan Cultural Relics. Wenxin Press, Zhengzhou (in Chinese).

Hollander, D., Howe, T., 2020. A Companion to Ancient Agriculture. John Wiley & Sons.

Hosner, D., Wagner, M., Tarasov, P.E., Chen, X., Leipe, C., 2016. Spatiotemporal distribution patterns of archaeological sites in China during the Neolithic and Bronze Age: an overview. Holocene 26, 1576–1593. https://doi.org/10.1177/0959683616641743.

Hou, G., Fang, X., 2012. Integrated reconstruction and characteristics analysis of Holocene temperature sequences in China. Acta Geogr. Sin. 14, 243–252 (in Chinese).

Hou, M., Wu, W., Cohen, D.J., Zeng, Z., Huang, H., Zheng, H., Ge, Q., 2023. Detection of a mid-Holocene climate event at 7.2 ka BP based on an analysis of globally-distributed multi-proxy records. Palaeogeogr. Palaeoclimatol. Palaeoecol. 618, 111525. https://doi.org/10.1016/j.palaeo.2023.111525.

Hou, M., Wu, W.X., 2021. A review of 6000–5000 cal BP climatic anomalies in China. Quat. Int. 571, 58–72. https://doi.org/10.1016/j.quaint.2020.12.004.

Jia, X., Li, H., Lee, H.F., Liu, Z., Lu, Y., Hu, Z., Sun, X., Zhao, Z., 2021. Agricultural adaptations to topography and climate changes in Central China during the mid- to late-Holocene. Holocene 31, 1705–1715. https://doi.org/10.1177/09596836211033201.

Jiang, W., Guo, Z., Sun, X., Wu, H., Chu, G., Yuan, B., Hatté, C., Guiot, J., 2006. Reconstruction of climate and vegetation changes of Lake Bayanchagan (Inner Mongolia): holocene variability of the East Asian monsoon. Quat. Res. 65, 411–420. https://doi.org/10.1016/j.yqres.2005.10.007.

Jin, G., 2007. Archaeological discoveries and research on early wheat in China. Agric. Archaeol. 11–20 (in Chinese).

Jin, G., Wagner, M., Tarasov, P.E., Wang, F., 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. https://doi.org/10.1177/0959683616641746.

Jin, G., Wang, H., Yan, D., Liu, C., Lan, Y., Tong, P., 2011. Study on the Longshan cultural charred botany in Zhaojiazhuang site. Technol. Archaeol 37–73 (in Chinese).

Jin, G., Wu, W., Zhang, K., Wang, Z., Wu, X., 2014. 8000-Year old rice remains from the north edge of the Shandong Highlands, East China. J. Archaeol. Sci. 51, 34–42. https://doi.org/10.1016/j.jas.2013.01.007.

Li, C., Li, B., Li, Y., Chen, B., Xu, Q., Zhang, W., Liu, W., Ding, G., 2020a. Variation of summer monsoon intensity in the North China Plain and its response to abrupt climatic events during the early-middle Holocene. Quat. Int. 550, 66–73. https://doi.org/10.1016/j.quaint.2020.03.033.

Li, G., Wang, Z., Zhao, W., Jin, M., Wang, X., Tao, S., Chen, C., Cao, X., Zhang, Y., Yang, H., Madsen, D., 2020b. Quantitative precipitation reconstructions from Chagan Nur revealed lag response of East Asian summer monsoon precipitation to summer insolation during the Holocene in arid northern China. Quat. Sci. Rev. 239, 106365. https://doi.org/10.1016/j.quascirev.2020.106365.

Li, X., 2013. New progress in the Holocene climate and agriculture research in China. Sci. China Earth Sci. 56, 2027–2036. https://doi.org/10.1007/s11430-013-4758-3.

Li, Y., Gu, Y., Jiang, M., Fang, S., Fu, Z., Guan, S., Liu, R., Zhu, Z., Liu, H., 2025. Neolithic human adaptations to the environmental changes in the Jianghan Plain, middle Yangtze Valley. Quat. Sci. Rev. 355, 109271. https://doi.org/10.1016/j.quascirev.2025.109271.

Li, Y., Zhou, X., Sun, N., Zhao, K., Chen, G., Zhang, Y., Ma, J., Liu, J., Li, X., 2024a. Evolution of agricultural structure and its adaptation to the environment in North China during the Middle Holocene Warm Period. Quat. Sci. 44, 1433–1449. https://doi.org/10.11928/j.issn.1001-7410.2024.05.28 (in Chinese).

Li, Y., Zhou, X., Zhao, K., Liu, J., Chen, G., Zhang, Y., Ma, J., Sun, N., Li, X., 2024b. Cultivation and morphology of jujube (*Ziziphus Jujuba* Mill.) in the Qi River Basin of Northern China during the Neolithic Period. Sci. Rep. 14, 2305. https://doi.org/10.1038/s41598-024-52260-8.

Liakat Ali, M., McClung, A.M., Jia, M.H., Kimball, J.A., McCouch, S.R., Eizenga, G.C., 2011. A rice diversity Panel evaluated for genetic and agro-morphological diversity between subpopulations and its geographic distribution. Crop Sci. 51, 2021–2035. https://doi.org/10.2135/cropsci2010.11.0641.

Lin, R., Chai, Y., Liao, Q., 2002. Minor Cereals in China. China Agricultural Science and Technology Press, Beijing (in Chinese).

Liu, L., Chen, X., 2017. Chinese Archaeology: from the Late Paleolithic to the Early Bronze Age. SDX Joint Publishing Company, Beijing (in Chinese).

Liu, L., Chen, X., Wright, H., Xu, H., Li, Y., Chen, G., Zhao, H., Kim, H., Lee, G.-A., 2019. Rise and fall of complex societies in the Yiluo region, North China: the spatial and temporal changes. Quat. Int. 521, 4–15. https://doi.org/10.1016/j.quaint.2019.05.025.

Liu, X., Liu, J., Chen, S., Chen, J., Zhang, X., Yan, J., Chen, F., 2020. New insights on Chinese cave δ18O records and their paleoclimatic significance. Earth Sci. Rev. 207, 103216. https://doi.org/10.1016/j.earscirev.2020.103216.

Lu, H., 2017. New methods and progress in research on the origins and evolution of prehistoric agriculture in China. Sci. China Earth Sci. 60, 2141–2159. https://doi.org/10.1007/s11430-017-9145-2.

Lu, H., Zhang, J., 2008. Neolithic cultural evolution and Holocene climate change in the Guanzhong basin, Shaanxi, China. Quat. Sci. 28, 1050–1060 (in Chinese).

Lu, H., Zhang, J., Liu, K., Wu, N., Li, Y., Zhou, K., Ye, M., Zhang, T., Zhang, H., Yang, X., Shen, L., Xu, D., Li, Q., 2009. Earliest domestication of common millet (*Panicum miliaceum*) in East Asia extended to 10,000 years ago. Proc. Natl. Acad. Sci. USA 106, 7367–7372. https://doi.org/10.1073/pnas.0900158106.

Luo, W., Yang, Y., Zhuang, L., Gan, H., Gu, C., Huang, C., Lin, L., Zhang, J., 2021. Phytolith evidence of water management for rice growing and processing between 8,500 and 7,500 cal years bp in the middle Huai river valley, China. Veg. Hist. Archaeobotany 30, 243–254. https://doi.org/10.1007/s00334-020-00782-2.

Marcott, S.A., Shakun, J.D., Clark, P.U., Mix, A.C., 2013. A reconstruction of regional and global temperature for the past 11,300 years. Science 339, 1198–1201. https://doi.org/10.1126/science.1228026.

Milla, R., Osborne, C.P., 2021. Crop origins explain variation in global agricultural relevance. Nat. Plants 7, 598–607. https://doi.org/10.1038/s41477-021-00905-1.

Ouyang, H., Shang, X., 2025. Enhancing sustainability in early millet agriculture: manuring practices in the Yellow River Valley. Palaeogeogr. Palaeoclimatol. Palaeoecol. 679, 113283. https://doi.org/10.1016/j.palaeo.2025.113283.

Qin, L., 2012. Archaeobotanical research on the origins of agriculture in China: progress and prospects. Archaeological Research in China 2012, 260–315 (in Chinese).

Qin, L., Fuller, D., 2009. The 2007 Nanjiaokou site excavated Early to Mid Yangshao plant remains. Nanjiaokou Site in. Science Press, Sanmenxia Beijing, pp. 427–435.

Railsback, L.B., Liang, F., Brook, G.A., Voarintsoa, N.R.G., Sletten, H.R., Marais, E., Hardt, B., Cheng, H., Edwards, R.L., 2018. The timing, two-pulsed nature, and variable climatic expression of the 4.2 ka event: a review and new high-resolution stalagmite data from Namibia. Quat. Sci. Rev. 186, 78–90. https://doi.org/10.1016/j.quascirev.2018.02.015.

Reimer, P.J., Austin, W.E.N., Bard, E., Bayliss, A., Blackwell, P.G., Ramsey, C.B., Butzin, M., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kromer, B., Manning, S.W., Muscheler, R., Palmer, J.G., Pearson, C., Plicht, J. van der, Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Turney, C.S.M., Wacker, L., Adolphi, F., Büntgen, U., Capano, M., Fahrni, S.M., Fogtmann-Schulz, A., Friedrich, R., Köhler, P., Kudsk, S., Miyake, F., Olsen, J., Reinig, F., Sakamoto, M., Sookdeo, A., Talamo, S., 2020. The IntCal20 Northern hemisphere radiocarbon Age calibration curve (0–55 cal kBP). Radiocarbon 62, 725–757. https://doi.org/10.1017/RDC.2020.41.

Roffet-Salque, M., Marciniak, A., Valdes, P.J., Pawłowska, K., Pyzel, J., Czerniak, L., Krüger, M., Roberts, C.N., Pitter, S., Evershed, R.P., 2018. Evidence for the impact of

the 8.2-kyBP climate event on Near Eastern early farmers. Proc. Natl. Acad. Sci. USA 115, 8705–8709. https://doi.org/10.1073/pnas.1803607115.
Sánchez, M.C., Espejo, F.J.J., Vallejo, M.D.S., Gibaja Bao, J.F., Carvalho, A.F., Martinez-Ruiz, F., Gamiz, M.R., Flores, J.-A., Paytan, A., López Sáez, J.A., Peña-Chocarro, L., Carrión, J.S., Muñiz, A.M., Izquierdo, E.R., Riquelme Cantal, J.A., Dean, R.M., Salgueiro, E., Martínez Sánchez, R.M., De la Rubia de Gracia, J.J., Lozano Francisco, M.C., Vera Peláez, J.L., Rodríguez, L.L., Bicho, N.F., 2012. The Mesolithic–Neolithic transition in southern Iberia. Quat. Res. 77, 221–234. https://doi.org/10.1016/j.yqres.2011.12.003.
Shen, G., Ding, G., Yang, X., Zhang, R., Li, Y., Li, B., 2018. Holocene climate and environmental change in the Baiyangdian area. Quat. Sci. 38, 756–768. https://doi.org/10.11928/j.issn.1001-7410.2018.03.20 (in Chinese).
Song, J., Wang, L., Fuller, D.Q., 2019. A regional case in the development of agriculture and crop processing in northern China from the Neolithic to Bronze Age: archaeobotanical evidence from the Sushui River survey, Shanxi province. Archaeol. Anthropol. Sci. 11, 667–682. doi:10.1007/s12520-017-0551-0.
Stanley, J., Krom, M.D., Cliff, R.A., Woodward, J.C., 2003. Short contribution: nile flow failure at the end of the Old Kingdom, Egypt: strontium isotopic and petrologic evidence. Geoarchaeology 18, 395–402. https://doi.org/10.1002/gea.10065.
Steig, E.J., Brook, E.J., White, J.W.C., Sucher, C.M., Bender, M.L., Lehman, S.J., Morse, D.L., Waddington, E.D., Clow, G.D., 1998. Synchronous climate changes in Antarctica and the North Atlantic. Science 282, 92–95. https://doi.org/10.1126/science.282.5386.92.
Stevens, C.J., Zhuang, Y., Fuller, D.Q., 2024. Millets, dogs, pigs and permanent settlement: productivity transitions in Neolithic northern China. Evolut. Hum. Sci. 6, e44. https://doi.org/10.1017/ehs.2024.31.
Sun, Y., Zhang, S., Xu, Q., Walker, M., Johnsen, S., Rasmussen, S.O., Popp, T., Steffensen, J., Gibbard, P., Hoek, W., Lowe, J., Andrews, J., Björck, S., Cwynar, L.C., Hughen, K., Kershaw, P., Kromer, B., Litt, T., Lowe, D.J., Nakagawa, T., Newnham, R., Schwander, J., 2009. Formal definition and dating of the GSSP (Global Stratotype Section and Point) for the base of the Holocene using the Greenland NGRIP ice core, and selected auxiliary records. J. Quat. Sci. 24, 3–17. https://doi.org/10.1002/jqs.1227.
Surovell, T.A., Finley, J.B., Smith, G.M., Brantingham, P.J., Kelly, R., 2009. Correcting temporal frequency distributions for taphonomic bias. J. Archaeol. Sci. 36, 1715–1724. https://doi.org/10.1016/j.jas.2009.03.029.
Tao, D., Liu, X., Xiao, Y., Chen, Z., 2022. Human subsistence in the late Neolithic age revealed by the remains of charred plants in Lutai site, Henan province. Acta Anthropol. Sin. 41, 73–84. https://doi.org/10.16359/j.1000-3193/AAS.2021.0001 (in Chinese).
Wang, C., Lu, H., Gu, W., Wu, N., Zhang, J., Zuo, X., Li, F., Wang, D., Dong, Y., Wang, S., Liu, Y., Bao, Y., Hu, Y., 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. https://doi.org/10.1016/j.scib.2017.10.003.
Wang, C., Lu, H., Gu, W., Zuo, X., Zhang, J., Liu, Y., Bao, Y., Hu, Y., 2018. Temporal changes of mixed millet and rice agriculture in Neolithic-Bronze Age Central Plain, China: archaeobotanical evidence from the Zhuzhai site. Holocene 28, 738–754. https://doi.org/10.1177/0959683617744269.
Wang, C., Lu, H., Zhang, J., Gu, Z., 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. https://doi.org/10.1016/j.quascirev.2014.05.015.
Wang, J., He, Y., Tang, Y., Liu, L., Li, Y., Chen, X., Gu, W., 2023. An interplay of dryland and wetland: Millet and rice cultivation at the Peiligang site (8000–7600 BP) in the middle Yellow River Valley, China. Agronomy 13, 2130. https://doi.org/10.3390/agronomy13082130.
Wang, J., Zhang, Y., Wen, J., Sun, J., 2015. Temporal and spatial changing features of climate in North China Plain. Geoscience 29, 299–306 (in Chinese).
The Institute of Archaeology, Chinese Academy of Social Sciences (IA CASS), 2003. Archaeology of China: Xia and Shang Dynasties. China Social Sciences Press, Beijing (in Chinese).
Wang, S., 2011a. The Holocene Climate Change. China Meteorological Press, Beijing (in Chinese).
Wang, W., 2014b. Chinese Dictionary of Archaeology. Shanghai Lexicographical Publishing House, Shanghai (in Chinese).
Wang, X., Zhao, Z., Zhong, H., Chen, X., Hu, Y., 2022. Manuring and land exploitation in the Central Plains of late Longshan (2200–1900 BCE) China: implications of stable isotopes of archaeobotanical remains. J. Archaeol. Sci. 148, 105691. https://doi.org/10.1016/j.jas.2022.105691.
Wang, Y., Zhang, P., Jin, G., Jin, S., 2011b. Results and analysis of plant flotation from the 2007 excavation at the Gouwan site, Xichuan, Henan. Sichuan Cultural Relics 2011, 80–92 (in Chinese).
Wei, X., 2014. The discoveries and preliminary researches of plant remains inthe Region of the Western Henan and the Southwestern Shanxi in the Neolithic Age. East Asia Archaeol 2014, 343–364 (in Chinese).
Wu, C., Xu, Q., Liu, J., 2017. New Perspectives on the Geomorphology of North China. Science Press, Beijing (in Chinese).
Wu, H., 2016. Study on Grain Yield per Mu in Successive Dynasties of China. China Agriculture Press, Beijing (in Chinese).
Wu, W., Liu, T., 2004. Possible role of the "Holocene Event 3" on the collapse of Neolithic Cultures around the Central Plain of China. Clim. Past 61, 1805–1817. https://doi.org/10.1016/S1040-6182(03)00125-3.
Wu, W., Zheng, H., Hou, M., Ge, Q., 2018. The 5.5 cal ka BP climate event, population growth, circumscription and the emergence of the earliest complex societies in China. Sci. China Earth Sci. 61, 134–148. https://doi.org/10.1007/s11430-017-9157-1.
Wu, X., Guo, M., Wang, R., Guo, R., Jin, G., 2017. Analysis of plant remains from Dalaidian site in Longshan period. Orient. Archaeol. 184–201 (in Chinese).
Xiao, J., Xu, Q., Nakamura, T., Yang, X., Liang, W., Inouchi, Y., 2004. Holocene vegetation variation in the Daihai Lake region of north-central China: a direct indication of the Asian monsoon climatic history. Quat. Sci. Rev. 23, 1669–1679. https://doi.org/10.1016/j.quascirev.2004.01.005.
Xu, Q., Xiao, J., Li, Y., Tian, F., Nakagawa, T., 2010. Pollen-Based quantitative reconstruction of Holocene climate changes in the Daihai Lake Area, Inner Mongolia, China. J. Clim. 23, 2856–2868. https://doi.org/10.1175/2009JCLI3155.1.
Yang, J., Zhang, D., Yang, X., Wang, W., Perry, L., Fuller, D.Q., Li, H., Wang, J., Ren, L., Xia, H., Shen, X., Wang, H., Yang, Y., Yao, J., Gao, Y., Chen, F., 2022. Sustainable intensification of millet–pig agriculture in Neolithic North China. Nat. Sustain. 5, 780–786. https://doi.org/10.1038/s41893-022-00905-9.
Yang, M., Yang, Y., Gu, W., Wei, Q., Li, M., Ding, L., Zhang, J., 2024. The agricultural basis for the continuous development of the Central Plains civilization: a systematic radiocarbon dating and archaeobotanical study at the Qingtai site, central China. Holocene. https://doi.org/10.1177/09596836241297666.
Yang, X., Wan, Z., Perry, L., Lu, H., Wang, Q., Zhao, C., Li, J., Xie, F., Yu, J., Cui, T., Wang, T., Li, M., Ge, Q., 2012. Early millet use in northern China. Proc. Natl. Acad. Sci. USA 109, 3726–3730. https://doi.org/10.1073/pnas.1115430109.
Yang, Y., Liu, X., Li, Y., Tan, L., Wang, X., Ma, L., Ren, L., Cheng, P., Chui, Y., Zhao, H., Sun, Y., 2025. The 7.2 ka cold event and its societal impact: climate-induced hiatus in the Dadiwan Culture of the Chinese Loess Plateau. Catena 260, 109448. https://doi.org/10.1016/j.catena.2025.109448.
Yang, Y., Yang, M., Sun, B., Li, W., Cheng, Z., Yao, L., Lan, W., Zhou, X., Zhang, J., 2023. Mixed farming of rice and millets became the primary subsistence strategy 6400 years ago in the western Huanghuai Plain of Central China: new macrofossil evidence from Shigu. Archaeol. Anthropol. Sci. 15, 122. https://doi.org/10.1007/s12520-023-01821-5.
Yuan, J., Campbell, R., Castellano, L., Chen, X., 2020. Subsistence and persistence: agriculture in the Central Plains of China through the Neolithic to Bronze Age transition. Antiquity 94, 900–915. https://doi.org/10.15184/aqy.2020.80.
Zhang, D.D., Brecke, P., Lee, H.F., He, Y., Zhang, J., 2007. Global climate change, war, and population decline in recent human history. Proc. Natl. Acad. Sci. USA 104, 19214–19219. https://doi.org/10.1073/pnas.0703073104.
Zhang, H., Cheng, H., Cai, Y., Spötl, C., Kathayat, G., Sinha, A., Edwards, R.L., Tan, L., 2018a. Hydroclimatic variations in southeastern China during the 4.2 ka event reflected by stalagmite records. Clim. Past 14, 1805–1817. https://doi.org/10.5194/cp-14-1805-2018.
Zhang, J., Jiang, L., Yu, L., Huan, X., Zhou, L., Wang, C., Jin, J., Zuo, X., Wu, N., Zhao, Z., Sun, H., Yu, Z., Zhang, G., Zhu, J., Wu, Z., Dong, Y., Fan, B., Shen, C., Lu, H., 2024. Rice's trajectory from wild to domesticated in East Asia. Science 384, 901–906. https://doi.org/10.1126/science.ade4487.
Zhang, J., Lu, H., Gu, W., Wu, N., Zhou, K., Hu, Y., Xin, Y., Wang, C., 2012. Early mixed farming of Millet and rice 7800 years ago in the middle Yellow River Region, China. PLoS One 7, e52146. https://doi.org/10.1371/journal.pone.0052146.
Zhang, J., Zhu, W., Zhao, F., Zhu, L., Li, M., Zhu, M., Zhang, X., 2018b. Spatial variations of terrain and their impacts on landscape patterns in the transition zone from mountains to plains—A case study of Qihe River Basin in the Taihang Mountains. Sci. China Earth Sci. 61, 450–461. https://doi.org/10.1007/s11430-016-9158-2.
Zhang, M., Liu, Y., Li, Z., Lü, P., Gardner, J.D., Ye, M., Wang, J., Yang, M., Shao, J., Wang, W., Dai, Q., Cao, P., Yang, R., Liu, F., Feng, X., Zhang, L., Li, E., Shi, Y., Chen, Z., Zhu, S., Zhai, W., Deng, T., Duan, Z., Bennett, E.A., Hu, S., Fu, Q., 2022. Ancient DNA reveals the maternal genetic history of East Asian domestic pigs. J. Genet. Genomics 49, 537–546. https://doi.org/10.1016/j.jgg.2021.11.014.
Zhao, C., 2020. The climate fluctuation of the 8.2 ka BP cooling event and the transition into Neolithic lifeways in north China. Quaternary 3, 23. https://doi.org/10.3390/quat3030023.
Zhao, Z., 2014. The process of origin of agriculture in China: archaeological evidence from flotation results. Quat. Sci. 34, 73–84. https://doi.org/10.3969/j.issn.1001-7410.2014.10 (in Chinese).
Zhao, Z., 2015. Research on the introduction of wheat to China: evidence from archaeobotany. Cult. Relics South. China 44–52 (in Chinese).
Zhou, X., Yu, J., Spengler, R.N., Shen, H., Zhao, K., Ge, J., Bao, Y., Liu, J., Yang, Q., Chen, G., 2020. 5,200-year-old cereal grains from the eastern Altai Mountains redate the trans-Eurasian crop exchange. Nat. Plants 6, 78–87. https://doi.org/10.1038/s41477-019-0581-y.
Zhuang, Y., Fuller, D.Q., 2024. Landscape of loess, millets, and boar—the environmental contexts of early cultivars in Northern China. Curr. Anthropol. 65, S3–S31. https://doi.org/10.1086/731785.