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► To cite this version:

Elizabeth Berger, Katherine Brunson, Brett Kaufman, Gyoung-Ah Lee, Xinyi Liu, et al.. Human adaptation to Holocene environments: Perspectives and promise from China. *Journal of Anthropological Archaeology*, 2021, 63, pp.1-16. 10.1016/j.jaa.2021.101326 . hal-03413723

HAL Id: hal-03413723

<https://hal.science/hal-03413723v1>

Submitted on 4 Jun 2024

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Publication Date

2021-09-01

DOI

10.1016/j.jaa.2021.101326

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Peer reviewed



Contents lists available at ScienceDirect

Journal of Anthropological Archaeology

journal homepage: www.elsevier.com/locate/jaa

Review

Human adaptation to Holocene environments: Perspectives and promise from China



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ARTICLE INFO

Keywords:

Holocene

Anthropocene

China

Archaeology

Human-environment interaction

Climate change

ABSTRACT

This paper reviews recent archaeological research on human-environment interaction in the Holocene, taking continental China as its geographic focus. As China is large, geographically diverse, and exceptionally archaeologically and historically well-documented, research here provides critical insight into the functioning of social-natural systems. Based on a broad review of the field as well as recent advances and discoveries, the authors reflect on research themes including climate change and adaptive systems theory, spatial and temporal scale, anthropogenic environmental change, risk management and resilience, and integration of subdisciplines. These converge on three overarching conclusions. First, datasets relevant to climate change and ancient human-environment interaction must be as local and specific as possible, as the timing of environmental change differs locally, and the human response is highly dependent on local social and technological conditions. Second, the field still needs more robust theoretical frameworks for analyzing complex social-natural systems, and especially for integrating data on multiple scales. Third, for this work to contribute meaningfully to contemporary climate change research, effective communication of research findings to the public and to scientists in other disciplines should be incorporated into publication plans.

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<https://doi.org/10.1016/j.jaa.2021.101326>

Received 23 February 2021; Received in revised form 4 June 2021;

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1. Introduction

As global climate changes rapidly, research into past human-environment interaction has attracted great interest, and the potential contributions of archaeologists to contemporary climate change research are now widely recognized (d'Alpoim Guedes et al., 2016; Fisher and Feinman, 2005; Lane, 2015; Rick and Sandweiss, 2020; Rockman and Hritz, 2020; Stephens et al., 2019). The public and policymakers have a particular interest in the instructive value of studies on paleoclimatic shifts and the purported collapse of past civilizations (e.g., Coombes and Barber, 2005; Robbins Schug et al., 2019; Wang et al., 2016), including how human behavior transformed landscapes and either helped or hindered adaptation to climate change. This paper will address the state of research on these themes in continental China, a vast and geographically diverse area with important contributions to make to the global archaeology of climate change.

We believe a regionally specific approach is fruitful because of both its geographic focus and its methodological breadth. Such an approach can address questions of local interest, such as the rise of urbanism, the origins of metallurgy, and the spread of specific domesticates, as well as those of global interest, such as the limits of human adaptive potential, the interaction of social and biophysical environments, and the role of technology in social complexity. The authors also intend to illustrate how the archaeological subdisciplines articulate with each other, and how cross-disciplinary work is essential to building a fuller picture of past human-environment interaction.¹

1.1. Geographic and temporal context

Though far from a comprehensive review of the entirety of Chinese archaeology, we hope this paper will serve as a resource for students and scholars working in other parts of the world who are interested in global connections and comparative research. To that end, Fig. 1 and Table 1 provide an overview of regions, geographic features, time periods, and archaeological cultures mentioned in the text.

The vast majority of archaeological research in China has concentrated on the middle and lower reaches of the two largest rivers in China, the Yellow and the Yangzi (Yangtze) Rivers. These watersheds contain most of China's arable land, and as a result, the greatest population density during the Holocene, the fastest contemporary urbanization and economic development leading to archaeological exploration, and consequently the majority of China's published archaeological sites.

Surrounding these are areas that became integrated into various dynastic spheres of influence and governance over the past two thousand years. In the south, Lingnan was one of the last refuges for hunter-gatherers in the Late Holocene, and later the entrepôt to the South China Sea (Allard, 1997; Chi and Hung, 2008; Hung and Zhang, 2019). The low-density communities of the southeast coast practiced terrestrial and marine hunting, fishing, and foraging, eventually supplemented by rice and pig husbandry (Chi and Hung, 2008; Jiao, 2013). To the southwest, the Yungui (Yunnan-Guizhou) Plateau is a mountainous region with deep valleys that supported intensive rice cultivation in human-made paddy soils (Yao, 2016; Yao et al., 2015). In Northeast China (Dongbei), cold temperatures and low rainfall have limited the agricultural productivity in many areas (Nelson, 2002). To the west are the "Inland Frontiers" of Inner Mongolia, the Hexi Corridor, the Tarim Basin, and the Dzungaria, historically contested by agro-pastoralist kingdoms and China's empires (Di Cosmo, 1994). Settlement of the arid, high-altitude Qinghai-Tibet Plateau was made possible by a range of behavioral adaptations, including hunting and foraging, vertically transhumant pastoralism, husbandry of millet and eventually wheat and barley, and

¹ To reflect the collaborative nature of this paper, after the corresponding author, authors are listed as: section lead authors in alphabetical order, followed by contributing authors in alphabetical order.

exchange with lower-altitude communities (Hein, 2018).

1.2. Definitions and themes of this review

Much of the research presented here relies on an ecological framework, including certain shared concepts, such as resilience and risk management. Resilience, as defined by ecologists, refers to the amount of disturbance a system can endure and still remain in its original state (Holling and Gunderson, 2002). Particularly, resilience theory's emphasis on "reorganization" rather than "collapse" can help archaeologists better conceptualize historic and prehistoric social change. Risk, in this case, is variability in outcome, along a probabilistic distribution (Stephens, 1990). Risk management strategies (e.g. diversifying crops) increase system resilience (Marston, 2011), but are highly context-dependent, specific to the local socioecological system, available technology and domesticates, and environmental conditions (Chen et al., 2020).

In addition to archaeological applications, these concepts can be used to re-interpret China's two-millennia-old tradition of official histories, and several recent meta-analyses take advantage of the growing corpus of paleoenvironmental data alongside historical data to examine adaptive trends in Chinese history (Fang et al., 2019; Lee et al., 2017; Wei et al., 2015; Zhang et al., 2006; Zhang et al., 2007). Resilience is a particularly useful construct for dissecting the dynastic cycle, by reframing it as an anthropological research question and identifying the social factors involved in the dissolution and reconstitution of various dynasties (Liu and Feng, 2012; Wu and Liu, 2004). For instance, recent studies at the site of Sanyangzhuang have attempted to connect village life to larger trends at the end of the Western Han dynasty (206 BCE–9 CE) as a means to understand the strengths and weaknesses of dynastic governance, and how reorganization of political systems influenced changes at a local material level (Kidder et al., 2015; Kidder et al., 2012; Zhuang et al., 2016).

These ecological concepts can also inform our interpretation of archaeological data, especially relating to human responses to climate change. In 2018, the International Commission on Stratigraphy codified the current geological age as the "Meghalayan," a subdivision of the Holocene epoch defined by paleoclimate changes related to widespread aridification at approximately 2200 BCE, often designated the 4.2 ka BP event (Cohen et al., 2018). However, the significance for human civilization of the megadrought at 4200 years ago is debated (Middleton, 2018): it has been implicated in the collapse or transformation of numerous societies around the world (e.g., Anderson et al., 2011), including Neolithic cultures in and around Central China (Wu and Liu, 2004), though many have argued against a climatological explanation for these transformations (Dong et al., 2013; Drennan et al., 2020; Jaffe et al., 2020; Jaffe and Hein, 2020; Shelach, 2009). The lack of scientific dating of many sites in China is also a principal methodological concern in drawing causal connections, or even correlations, between social and climatological events (Jaffe et al., 2020; Liu et al., 2020c).

Meanwhile, another concept, the "Anthropocene," has been more broadly employed since being introduced by climate scholars (Bauer and Bhan, 2018; Bauer and Ellis, 2018; Crutzen and Stoermer, 2000; Smith and Zeder, 2013). Various opinions have been put forward concerning when this proposed epoch began:

- 1) the Industrial Revolution, defined by harm to the environment from fossil fuel combustion (Nriagu, 1996), habitat depletion and resource overexploitation (Kidder and Zhuang, 2015; Rosen et al., 2015), and epidemiological transitions (Omran, 1971; Omran, 1983);
- 2) the beginning of the nuclear age, a more recent and specific geological event (Waters et al., 2016; Zalasiewicz et al., 2015);
- 3) coincident with European colonization of indigenous lands, especially in the Americas, a framing which questions the universality of a Euro-centric narrative, points to colonialism as the root of today's environmental problems, and mobilizes the Anthropocene concept



Fig. 1. Major geographic regions and features of continental China, including those mentioned in the text. (Made with Natural Earth. Free vector and raster map data @ naturalearthdata.com.)

Table 1

Time periods and archaeological cultures mentioned in the text. Archaeologically derived/prehistoric dates are cited, and may differ slightly between authors.

Time period	Archaeological culture/period (region)	Chronological dates
Neolithic	Yangshao period (Yellow River Valley)	ca. 5000–3000 BCE ¹
	Liangzhu culture (Yangzi River Delta)	ca. 3300–2200 BCE ²
	Longshan period (Yellow River Valley)	ca. 2600–1900 BCE ³
Bronze Age	Erlitou culture	ca. 1900–1550 BCE ⁴
	Erligang culture/early Shang dynasty	ca. 1600–1300 BCE ⁴
	Yinxu/late Shang dynasty	ca. 1300–1050 BCE ⁴
	Western Zhou dynasty	1046–771 BCE
Iron Age (from 5th c.)	Eastern Zhou dynasty/Spring and Autumn period	771–476 BCE
	Eastern Zhou dynasty/Warring States period	475–221 BCE
Dynastic period	Qin empire	221–206 BCE
	Western Han dynasty	206 BCE–9 CE
	Eastern Han dynasty	25–220 CE
	Tang dynasty	618–907 CE
	Song dynasty	960–1279 CE
	Jin (Jurchen) dynasty	1115–1234 CE
Yuan dynasty	1271–1368 CE	

¹ Jaffe and Flad (2018).

² Jaffe et al. (2020).

³ Luan and Wagner (2009).

⁴ Shelach and Jaffe (2014).

for anti-colonial aims (Davis and Todd, 2017; Lewis and Maslin, 2015); and

- the start of longer-term anthropogenic geological processes (Fuller et al., 2011b), e.g., atmospheric lead and copper pollution deposits detectable beginning in the Bronze Age (Hong et al., 1994, 1996), changes in land use and niche construction with the domestication of plants and animals (Boivin et al., 2016; Smith and Zeder, 2013; Stephens et al., 2019), or the transformation of the hydrology, geology, and ecology of watersheds such as that of the Yellow River (Zhuang and Kidder, 2014).

Despite the lack of agreement on a definition, the use of Anthropocene to represent human impacts on the environment has achieved broad appeal. Although, as reflected in the third definition, some have questioned whether the Anthropocene adequately recognizes unequal responsibility for human-induced environmental changes (Bauer and Bhan, 2018; Morrison, 2018), or critiqued the debate as “dithering” (Hornborg, 2017; see Kosiba, 2019: 450 for further discussion), as Johnson and Earle (2000: 24) state, “the more we learn of history, the more we come to see the environment as an artifact of human activity.”

2. Study of the geophysical environment

2.1. Geoarchaeology

Millennia of economic and sociopolitical processes have made China one of the places on Earth whose environment has been most thoroughly transformed by human action. This history is recorded in paleoenvironmental archives, which reveal phenomena such as anthropogenic soils, increased rates of erosion, ancient pollution, variations in the extent and severity of fire, plant and animal translocation and extirpation, modification of waterways and the water table, and the emergence

of anthropogenic landforms.

Anthropogenic soils are prevalent throughout China and have a long history of development and use (Gong et al., 1999; Storozum et al., 2018). In the south, in Lingnan and the Jianghuai plain, where rice agriculture is common and sedimentation rates are much lower, ancient rice paddies have been in use for thousands of years (Cao et al., 2006; Kölbl et al., 2014; Yasuda et al., 2004). The successive use of these rice paddies has created anthropogenic soils that are remarkably resilient to changes in climate and environment, and also exhibit significantly different characteristics from the surrounding natural soil. To the west, in the arid areas of China, there are some examples of human-altered desert soils, though more work needs to be done here (Li et al., 2019). In northern China, most of the anthropogenic soils should be found in arable zones. However, in the North China Plain the vast majority of the former agricultural landscape has been buried by massive Yellow River floods over the past 3000 years (Shi et al., 2010), only occasionally exposed at locations like Sanyangzhuang (Storozum et al., 2018).

China's Yellow River is one of the most anthropogenic fluvial systems in the world. Beginning at the latest in the Han dynasty, erosion rates began to increase and give the river its characteristic yellow color, and the river course began its periodic shifts (Yuan, 2021). In particular, geological coring on the North China Plain and excavations in the valleys of the Loess Plateau reveal that sedimentation rates have increased dramatically since the development of iron technologies and the migration of people into the Loess Plateau to conduct agriculture (Milliman et al., 1987; Ren, 2015; Ren and Zhu, 1994). This increase in the amount of the sediment load of the Yellow River significantly altered the sediment flux of the river, creating a "hanging river" phenomenon, whereby the main course of the Yellow River is elevated precariously over the North China Plain. When the Yellow River breaches its banks, as it has done dozens of times throughout the past 3000 years, the river floods catastrophically (Chen et al., 2012).

China was also home to one of the most technologically advanced metallurgical industries in antiquity. At one point, the Tang dynasty (618–907 CE) likely accounted for over half the world's metal smelting (Hong et al., 1996). This consequently left behind many traces of heavy metal pollution that are now being found in lacustrine records throughout China (Jin et al., 2013; Yan et al., 2010). For instance, in Yunnan, around 600 years ago during the Mongol Yuan dynasty (1271–1368 CE), heavy metal pollution exceeded even modern pollution multiple times over (Hillman et al., 2015). Geoarchaeological investigations at the city of Kaifeng have also revealed that heavy metal pollution from nearby industries dating to the Song dynasty (960–1279 CE) left behind highly toxic anthropogenic sediments that gradually became integrated into the urban soils (Storozum et al., 2020b). (See next section.)

2.2. Archaeometry

"Technology" (broadly defined) constitutes a suite of practices that have fundamentally transformed the environment throughout human history. Some environmental signs of human activity, such as lead and copper deposits in ice cores, are unintended byproducts of material production processes. Such processes depend on great quantities of fuel, produce tons of consumable goods that become trash, and generate waste byproducts that leave harmful residues. Archaeology can contribute to an understanding of the late Holocene Meghalayan, or Anthropocene, by modeling these impacts, and can contribute to modern environmental remediation through survey and ground-truthing of pollutive production sites with elevated heavy metal concentrations. Furthermore, China is an ideal place to study such impacts, as it is not only an expansive land mass with historically large populations, but was also a pioneer in several energy-dependent ancient technological innovations, including the casting of iron (Han and Chen, 2013). It is therefore useful to approach the cultural history of China through an ecological-technological lens. Changes in technology as reconstructed

from environmental evidence may also reflect the interaction of human agency, environmental conditions, and various forms of social organization (Womack et al., 2021).

As an example, research into the development of state-level society in Bronze Age China is becoming increasingly reliant on archaeometric analyses of ancient technologies, particularly archaeometallurgy. Metallurgical production in antiquity had two major environmental impacts: 1) deforestation for fuel and 2) pollution from smelting and melting activities resulting in toxicity of water (Li et al., 2017a; Li et al., 2011; Lin et al., 2016), sediment (Zhang et al., 2017), and atmosphere (Hong et al., 1994, 1996). According to the Chinese government, one sixth to one fifth of China's arable land today is contaminated by heavy metals (China MEP, 2013; Hillman et al., 2015; Wong, 2014), some of which is legacy pollution from metallurgical activities since the Bronze Age.

In addition, archaeologists have focused on identifying the extraction, production, and use of raw materials to reconstruct sociopolitical and paleoecological processes. For instance, during the Erligang (1600–1300 BCE) expansion, local smiths across the Central Plains casted a variety of culturally-specific shapes from imported ingots, using copper ores possibly from the Qinling Mountains (Chen et al., 2019: 134), or from other sources such as Panlongcheng and the Yangzi River Valley, though the emerging picture of the exchange network of raw materials and finished vessels is increasingly complex (Liu et al., 2019c). Meanwhile, as outlined by Mei Jianjun and colleagues (Chen et al., 2016a; Linduff and Mei, 2009; Mei et al., 2015), a renewed focus on regional typologies and alloying styles for bronzes, as well as accompanying infrastructure such as crucibles and molds (Chastain, 2019; Chen et al., 2009; Liu et al., 2013), holds further promise for high-resolution reconstructions of the socioeconomic organization and mineral resource trade networks of the economy during the Shang dynasty (1600–1050 BCE).

Industrial production of metal also requires massive amounts of fuel, though fuel for specific metallurgical processes varied greatly (e.g. timber charcoal vs. dung charcoal vs. coal). In the 12–13th centuries CE (during the Jin dynasty in Hebei Province), for instance, combustion of metallurgical coal and coke for silver smelting was likely first adopted after rampant deforestation greatly reduced the available timber charcoal (Liu et al., 2019d). Promising recent work attempts to discern fuel sources by identifying carburized timber cell structure for charcoal, or minor elemental constituents such as potassium and sulfur in the slag byproduct associated with coal (Li et al., 2018). Field methods employing volumetric excavations to record fuel:slag ratios could also assist in the reconstruction of paleoecology (Kaufman et al., 2021).

An additional area of research on technology that is relevant to human-environment interaction is the study of the production of building materials. Previous settlement studies in China have addressed socioeconomic change, subsistence, craft specialization, site features, and statehood (e.g., Chifeng, 2003; Falkenhausen, 2018; Li and Liang, 2018; Liu, 1996; Liu et al., 2004; Liu and Chen, 2012; Underhill et al., 2008; Wu and Liu, 2004; Beijing Daxue et al., 2015; Guojia Wenwuju, 2007; Guojia Wenwuju, 2018; Horsley et al., 2009), but there is much work to be done on the long-term environmental impact of settlement construction and urban landscapes in China.

While pyrotechnology for making ceramic cookware dates to as early as 20,000 years ago (Wu et al., 2012), manufactured building materials such as plaster, brick, and tile only appeared much later. The use of fire to treat house floors and walls existed by 3000 BCE or even earlier (Henan, 2002; Zhonguo and Shaanxi, 1962; Beijing Daxue et al., 2015; Henan et al., 2015), evidenced by burnt wattle and daub. The earliest known manufactured building material was found at Dadiwan, where kiln-processed silicates (ginger stone and Aga soil) were used to produce a hard mortar for the flooring of the F-901 "palace" (ca. 3500–3000 BCE) (Li et al., 2013b). Another early example is the use of lime powder for house floors and walls used during the Longshan period (2600–1900 BCE), manufactured in kilns (Qian et al., 2009; Xibei and Shaanxi,

2005), as well as ceramic pipes (Sebillaud, 2016). Later, flat tiles are found in the early urban center of the Zhengzhou Shang city in Henan (Li et al., 2007).

Eventually, manufactured building materials became associated with the growth and expansion of political power. The earliest possible evidence for ceramic roof tiles in China comes from Bronze Age sites including Taosi in Shanxi (2300–1900 BCE) (He, 2018) and Qiaocun in Gansu (c. 1900 BCE) (Gou and Wang, 2010), with indisputable use of fired ceramic roof tiles at the site complex of Zhouyuan, the birthplace of the Western Zhou dynasty (1046–771 BCE) (Shaanxi, 1979). Many hollow bricks were found in the nearby Western Zhou settlement of Zhougongmiao (Xu, 2006). A standardized building tradition is evident at the State of Qin's capital of Yongcheng (400–300 BCE) (Guo, 2016), and throughout the Qin Empire (221–206 BCE), including at the massive palace site at Xianyang (Qindu, 1976; Tang and Loewe, 2015). Demand for building materials was also associated with large migrations of households into the capital (Shaanxi kaogu et al., 2013; Sima, 1997), brick tomb construction (Luoyang, 1959; Nickel, 2015; Shaanxi and Shihuangling, 1988), and the need for canals, roads, and granaries to sustain urban populations (Nylan and Loewe, 2015). As today, construction was “one of the leaders in deterioration of [the] environment by depleting resources” (Devi et al., 2017: 156).

2.3. Landscape, spatial, and settlement analysis

Because the diachronic investigation of human-environment relations requires a large quantity of spatial data, China's impressive amount of available archaeological material makes it a key contributor to research on this topic. Important foci include changes in land use and food production, population growth, construction of anthropogenic landscapes, and associated social changes. For example, on the topic of food production, spatial analysis that addresses the transition to farming in Northeast China belies the neo-evolutionist model of linear social development (see Jia, 2008: 11). Rather, the variety of subsistence “mixes” coexisting in Northeast China from the early Neolithic (10,000 BCE) (Wang and Sebillaud, 2019) to the Bronze Age (around 1000 BCE) shows complex and evolving economic strategies, which are not captured by the dichotomies of sedentism vs. nomadism, or foraging vs. farming. Some scholarship has focused on the ways that environmental change may have caused, encouraged, or constrained cultivation, animal management, and agriculture (e.g., d'Alpoim Guedes et al., 2016). More work might attend to the effects of agricultural technology on landscapes, following the literature on niche-construction (Boivin et al., 2016; Fuller and Qin, 2010; Laland and O'Brien, 2010; Odling-Smee et al., 2003; Rowley-Conwy and Layton, 2011; Smith, 2011; Zeder, 2012a). (See Paleoethnobotany below for a more detailed discussion of these transformations.)

Many topographic features of the Chinese landscape are anthropogenic, having been created by both intentional and unintentional human action, often related to subsistence technologies. These processes demonstrate the role that political and social organization have in the human impacts on the landscape. Such ancient anthropogenic transformations included considerable physical reconfiguration of the landscape. For example, the “Horqin desert” in Northeast China, although it has changing boundaries, commonly refers to the transitional area between Inner Mongolia and the Northeast China Plain, totaling an area of 500,000 km² (Yi et al., 2013; Zhao et al., 2013). A vast lake until the middle Neolithic, through desiccation the region gradually became marshes and hollows, and eventually formed an expansive steppe zone, a rich pastureland that has been in use for centuries. The forest was converted to agricultural land over the course of the last millennium to support a fast-growing sedentary population, and has now become flat “sandy land,” a patchwork of fields and salty desert, with evaporating lakes in constant aeolian erosion and drought (Sebillaud et al., 2019, 2021). Similarly, study of the Hani mire in southeast Jilin Province has revealed the periodicity of natural and anthropogenic fires destroying

the forest, and its subsequent regeneration (Li et al., 2013a). The Jiang-Huai and Jiangnan Plains, much wetter landscapes, were bisected by anthropogenic canals since at least the Song dynasty (Needham and Lu, 1971).

The nature and speed of local anthropogenic landscape changes are often complex and localized, so as the macro-processes become clearer, a more small-scale analysis is needed of anthropogenic transformation of local ecologies. Such local changes include the creation of agricultural fields such as rice paddies (Hu et al., 2013; Qin et al., 2006; Rosen et al., 2017; Zheng et al., 2009; Zong et al., 2007), the creation of artificial hydrology such as irrigation networks (Li et al., 2017b; Liu et al., 2017a; Storozum et al., 2018) and fish ponds (Nakajima et al., 2019), and earth-moving to create terraces, ditches, and walls (Xie, 2018; Xie et al., 2015; Xie et al., 2017). For instance, at Kaifeng, the interior city is at a lower elevation than the surrounding plain, because the walls around the city prevented sediment build-up in the city limits (Storozum et al., 2020a); similar landforms can be found throughout the North China Plain.

As the above examples show, recent scholarship has thoroughly critiqued dichotomies of culture and nature, and instead focused on the ways in which things, people, animals, and the environment are interconnected in networks of interdependency (Knappett, 2013; Kosiba, 2019). The construction of settlements and new landscape features are particularly important aspects of the place-making that occurred throughout the Holocene, as populations increasingly invested in agriculture and lived in urban places. As Cerulo (2009) points out, non-human actors, including new raw materials, new domesticates, and new forms of settlements, become agents of social interaction. Understanding these processes is at the heart of understanding the relationship between technological change and changes to the landscape that relate to human activities.

The interaction of environmental and social conditions has not traditionally been a focus of Chinese archaeology, because of its historiographic orientation (Falkenhausen, 1993), though historical geographers such as Hou Renzhi of Peking University have made great contributions in this area. Now, many researchers are studying broad trends in climate change and settlement distribution using China's *Atlas of Cultural Relics* series (*Wenwu Dituji* 文物地图集), a multi-volume compendium of archaeological data across China. The volumes are an ambitious and critical repository, but they have limitations for studies of human-environment interaction. The sites in the *Atlas* volumes are mostly not scientifically dated, and are known from unsystematic surveys, making it difficult or impossible to determine their temporal relationship with any particular climatic event, or with one another (Jaffe et al., 2020).

Systematic archaeological survey is a critical source of data, to build on those in the *Atlas* volumes. Surveys reveal how global-, regional-, and local-scale patterns in the settlement record reflect complementary and concomitant rhythms in ancient political organization and subsistence modes (Braudel, 1996; Liu et al., 2020c), especially over long time scales (Guilaine, 2000). In Northeast China, systematic surveys of over 200 km² have revealed differences in settlement patterns, over both time and space, in the Chifeng mountainous region (Chifeng International Collaborative Archeological Research Project, 2003; Linduff et al., 2004; Teng, 2009), the Upper Daling River Valley (Drennan et al., 2014; Liaoning, 2010; Peterson et al., 2014), the mixed grassland and hills of Zhangwu (Williams, 2014, 2017a, 2017b), and the flatlands around the Yueliangpao and Xinhuangpao lakes at the northern border of the Horqin Desert (Liu et al., 2017c; Wang et al., 2015; Sebillaud et al., 2021). The long-running Yiluo regional survey project, covering over 1000 km², has found a complex trajectory of fluctuating population size, shifting political centers, and ever-increasing site hierarchy after the beginnings of sedentism in that region (Liu et al., 2019a). A long-term survey of coastal southeastern Shandong Province, which has covered over 3000 km² so far, has also revealed complex changes in settlement pattern and population across millennia (Feinman et al., 2019). These projects explicitly document that while landscape and environment are

key factors affecting settlement, human socioeconomic systems as well as extra-regional networks also have an enduring role.

Therefore, multiscale analysis is needed to understand the dynamic processes that govern the constant reorganization of human settlements. Models of human-environment systems in human-scale landscapes, such as river valleys, reveal different patterns than data on a regional scale. For instance, in an analysis of the spatial organization of settlements in the middle and lower courses of the Yellow River Valley during the transition from the Late Neolithic to the Early Bronze Age (c. 2500–1050 BCE), spatial statistics derived from over 6000 sites revealed that before 2000–1900 BCE, during the Longshan period, occupation of arable land was relatively homogeneous. Afterwards, many sites were abandoned and most new settlements were located on higher ground. The Yiluo Basin held a high concentration of sites of various sizes, likely a single settlement system, and the Erlitou site, at the core of this system, fostered an ever-growing population and fulfilled more and more social and political functions. Finally, after around 1600 BCE, a settlement pattern that used most of the available land was gradually restored during the Shang period (c. 1600–1050 BCE), with political centers shifting roughly every 200 years and new architectural features protecting the large cities from floods and wars (Sebillaud, 2014). For a spatially small-scale *longue durée* study of a site in Shaanxi, see Ye and Hein (2020), and for a detailed spatial study of a Bronze Age city in Shandong, see Li and Liang (2018).

A key motivating factor in settlement distribution is risk management, which might have been at the heart of the formation of the earliest political organizations. A comparison of the Western Liao Valley and the Central Plains shows two very different risk management strategies in the Neolithic, likely due to household-level decision making: the first tended towards dispersed households with access to multiple types of land, while the latter tended towards aggregation and cooperation in larger settlements (Drennan et al., 2020). Meanwhile, in Southeast China, the massive fortifications and water control systems built by the Liangzhu polity (Liu et al., 2017a) show that a priority of the politically powerful was to respond to the rise of sea-level. Moreover, in Zhejiang, where Liangzhu is located, there is a close relationship between human activity and environmental change: spatial analysis shows that the distribution of settlements was closely related to Holocene sea-level fluctuations, especially on Hangzhou Bay (Wu et al., 2014).

Information on human-environment and human-landscape interaction is essential to a better understanding of spatial data such as ancient people's site location choices, access to resources, implementation of exchange networks, etc. For instance, there is no way to correctly interpret the settlement patterns of northwest Jilin Province's proto-historic period without understanding the changes in the Nen River (or Nonni in Manchu) (Sebillaud, 2022; Zhu et al., 2013), to interpret the Longshan to Erlitou periods changes without a focus on the Yellow River floods (Cai, 1998; Wang, 1993, 1999), or to interpret land use in Neolithic Zhejiang without a good grasp of sea-level change (He et al., 2018). Landscape and spatial studies will tremendously influence how we understand human adaptation to past environmental change in China.

3. Study of the biosphere

3.1. Paleoethnobotany

Paleoethnobotanical research in China has contributed to knowledge of resilient responses to climate change, risk management through landscape management, changing food customs, and the spread of crops. This work is furthered by stable isotope analysis, in part thanks to the isotopic contrast between key cultivars: broomcorn and foxtail millet are C₄ plants whose $\delta^{13}\text{C}$ values differ from the wild C₃ plants that dominate the natural vegetation in most parts of North China (Rao et al., 2010), while rice, the dominant crop of the south, is a C₃ plant (d'Alpoim Guedes, 2011). Other C₃ cultivars domesticated or adopted later in the

region including wheat, barley, buckwheat, and soybeans, together with multiple fruits, tubers, and nuts (An et al., 2015; Barton and An, 2014; Crawford, 2018; Crawford, 2017; Dong et al., 2017a; Jiang et al., 2019; Lee et al., 2011; Liu et al., 2015; Liu et al., 2014b; Liu et al., 2016; Long et al., 2018; Zhou et al., 2016).

Recent studies document increasing social-ecological resilience in the midst of climate changes through broadening plant food resources in China since the Last Glacial Maximum (LGM) period. Wild annual grains, including Job's tears and tribes of wheat and millet, were already collected as a starchy food source by Upper Paleolithic populations along the Qingshui River, a tributary of the Yellow River, by 28,000–24,000 cal BP (Bestel et al., 2014; Liu et al., 2018a; Liu et al., 2019b). Broad-spectrum resource use is well documented worldwide (Zeder, 2012a) in the Pleistocene-Holocene transition, and the use of starch from underground organs, nuts, and wild annuals was maintained in China even after millet farming was well established (Liu et al., 2014a; Wang et al., 2019).

Archaeological research has painted a sophisticated picture of the agricultural transitions of East Asia during the Holocene (recent syntheses include Lander et al., 2020; Leipe et al., 2019; Liu, 2016; Liu et al., 2015; Silva et al., 2015; Stevens and Fuller, 2017; Weisskopf et al., 2015). The adoption of domesticated plant species across China occurred through multiple mechanisms, and settlement changes and agricultural intensifications interacted throughout the Holocene climate fluctuations; this farming transition has been reviewed comprehensively elsewhere (Crawford, 2018; Crawford, 1992, 2006; Crawford, 2017; Crawford et al., 2016; Liu et al., 2015; Wang et al., 2019; Zhao, 2011). With the return of the colder and drier regime after the Holocene Climate Optimum, increasing hierarchy in settlements and social systems was probably supported by agricultural intensification in the Yellow River region (Crawford et al., 2005; Lee et al., 2007; Liu, 2015; Liu et al., 2019a). Experimental study of carbonization indicates the interdependence of agricultural producers and consumers across the settlement hierarchy in the Yiluo Basin during the Neolithic and later (Walsh et al., 2016). Rice cultivation also deeply modified the vegetation cover during the Neolithic in the Yangzi River region, but broad-leaf forest was restored rapidly following the collapse of Liangzhu civilization (Li et al., 2010).

Between 5000 and 1500 cal. BCE, the Eurasian and African landmass underpinned a continental-scale process of "globalization" of food and foodways (e.g., Jones et al., 2011; Lee, 2016; Liu et al., 2019e; Liu and Jones, 2014). Some species domesticated within China spread into contiguous ecological zones beyond their natural habitat, for instance, rice (Bettinger et al., 2010; Gross and Zhao, 2014) and millet. Millet likely originated in several places (Bettinger et al., 2007; Bettinger et al., 2010), including a fertile arc around the Central Plains of North China (Liu et al., 2012). Even more dramatic was the transplantation of some plants and animals into regions distant from their natural habitats, such as West Asian animals and plants introduced into East Asia, including sheep, goat, cattle, horses, barley, and wheat, among other technologies (recent publications include Barton and An, 2014; d'Alpoim Guedes, 2015; d'Alpoim Guedes et al., 2015; Dong et al., 2017a; Jaang et al., 2018; Jaffe and Flad, 2018; Jones et al., 2011; Lister et al., 2018; Liu et al., 2019e; Liu et al., 2014b; Long et al., 2018; Spengler et al., 2014; Stevens et al., 2016).

Both broomcorn and foxtail millet were first cultivated by ca. 7000–5000 BCE in the foothills running northeast-to-southwest along the eastern and southern parts of the Loess Plateau (Barton et al., 2009; Crawford, 2018; Lee et al., 2007; Liu et al., 2009; Tang et al., 2020; Zhao, 2011). Then, during the third millennium BCE, millet appeared in regions far west of where it first originated, e.g. southeast Kazakhstan (Frachetti et al., 2010; Hermes et al., 2019). It then expanded further westwards along a narrow foothill ecological zone (800–2000 m.a.s.l.) (Miller et al., 2016), in conditions similar to the landscape where millets were first cultivated (Frachetti, 2012; Liu et al., 2009; Ren et al., 2016). In the second millennium BCE, broomcorn millet appeared in

Kazakhstan, Kyrgyzstan, Afghanistan, Turkmenistan, and Turkey (Miller et al., 2016; Motuzaitė Matuzevičiūtė et al., 2017; Spengler et al., 2014), as well as Yemen and Sudan (Boivin and Fuller, 2009; Fuller et al., 2011a). Millets are known from Europe (see Liu et al., 2018b for a review), the oldest uncontested direct date for which is c. 1600 cal. BCE in Hungary, during the Bronze Age (Motuzaitė Matuzevičiūtė et al., 2013), and supported by both archaeobotanical and isotopic evidence (Lightfoot et al., 2013; Varalli et al., 2016). A series of much older, indirect dates of Neolithic millet remains (Jones, 2004) have been called into question (Hunt et al., 2008; Motuzaitė Matuzevičiūtė et al., 2013). To the east, broomcorn millet is reported from Korea in the late fifth millennium BCE, and the Russian Far East in the fourth millennium BCE; foxtail millet in Taiwan and Thailand in the late third millennium BCE; and both millets at late Harappan sites in India from at least c. 2000 BCE (Kuzmin, 2013; Kwak and Lee, 2020; Li et al., 2020a; Pokharia et al., 2014; Stevens et al., 2016; Tsang, 2012).

By 2500 BCE, the southwest Asian cereals, specifically wheat and barley taxa, were also present along the Inner Asian Mountain Corridor, including the Altai (Frachetti, 2012; Spengler et al., 2014; Zhou et al., 2020), the Indus, and the upper Ganges (Liu et al., 2016; Liu et al., 2017b; Stevens et al., 2016). The chronology and routes of the subsequent introduction of wheat and barley into ancient China and broader East Asia have been much debated (Barton and An, 2014; Betts et al., 2014; Chen et al., 2020; Flad et al., 2010; Lee, 2016; Long et al., 2018; Zhao, 2009). However, substantial movements of wheat and barley took place during the third and second millennia BCE, spreading along the Inner Asian Mountain Corridor, then to northwest China (e.g., Liu et al., 2016; Ren et al., 2020; Spengler 2015). Some have argued the initial expansions of wheat and barley into China might be distinct in time and space, including a possible maritime route (Zhao, 2009) and a route over the southern Tibetan Plateau (Lister et al., 2018; Liu et al., 2017b).

Recent discussion has moved beyond routes and chronologies to consider the context in which agricultural innovation occurred. The timing of the eastern dispersal of wheat and barley reflects a range of choices that different communities made, sometimes driven by ecological expediency in novel environments. For example, when wheat and barley arrived in central China, they brought with them a degree of genetic diversity in flowering time responses, allowing farmers to exploit previously untenable farming seasons (Liu et al., 2017b). Such adaptive traits may have been developed first in the Tibetan Plateau in response to high-altitude environments, a possibility which has received much insightful discussion recently (d'Alpoim Guedes, 2015; d'Alpoim Guedes et al., 2014).

Culinary systems also influenced the adoption of novel crops. Early communities in East and West Asia were characterized by different food processing technologies: boiling and steaming of grain in the East, and grinding grain and baking flour in the West (Fuller and Rowlands, 2011). These culinary preferences had consequences for the selection of grain type and gluten/starch quality. Broomcorn millet, for example, underwent selection for waxy or glutinous starch in central-eastern China (Hunt et al., 2013), and wheat may have undergone selection for traits adapted to the boiling-and-steaming tradition (Liu et al., 2016). Contra to the rapid reception of wheat and barley in human diets in the continental interior, the very gradual adoption of these staples in central-eastern China (Li et al., 2020b; Liu et al., 2014b) was perhaps connected with their incompatibility with local culinary practices, which prioritized compact grains and starch quality (Liu and Reid, 2020).

Fermentation, another culinary tradition, is evidenced in rice remains at the Jiahu site in Henan Province as early as 9000 cal. BP (McGovern et al., 2004). Fermentation analysis has revealed the use of rice in beverages in the Neolithic (Liu et al., 2019b), and the north-westward expansion of rice to the Wei River region may have been related to its importance in alcohol production as early as 8000 years ago (Liu et al., 2019a). However, fermentation started long before fully domesticated rice was available. Various wild and domesticated plants,

including broomcorn millet, wheat tribe wild grasses, Job's tears, rice, beans, snake gourd root, ginger, yam, lily and more, were fermented with various regional techniques, as documented in starch granules, phytoliths, and fungi residues extracted from early Neolithic vessels found in the Yellow and Yangzi River basins (Liu et al., 2020a; Liu et al., 2020b). The same taxa of wild grains, tubers, and nuts, as well as crops, were found further northwest in China (Wang et al., 2019), indicating a wide spread of these plant resources as food and possibly fermented drinks.

Recent developments in the understanding of Eastern farming systems have expanded notions of the origin of agricultural civilization. The dispersal of millets, for example, provides a clear case, possibly the oldest, of how East Asian agriculture had an influence on global systems. This encourages us to reflect on the assumptions we have held in a Western context, including those concerning what agriculture is and can be (Liu et al., 2018b).

3.2. Zooarchaeology

China's zooarchaeological record contributes to archaeological research on climate change and human-environment interaction in Holocene China in two main areas: by documenting human impacts on East Asia's native wild fauna, and by clarifying animal domestication processes. The continued development and application of scientific techniques in zooarchaeology is also a critical part of environmental archaeology in China (Lin, 2014).

Zooarchaeological research in China has revealed regional differences in the availability and use of wild and domestic fauna during the Neolithic and Bronze Age. For example, although domesticated taxa made up increasingly large proportions of faunal assemblages in the Yellow River Valley region, hunting and fishing of wild animals remained important in the Yangzi River Valley region (Jing et al., 2008; Yuan, 2015). On the Tibetan Plateau, foragers hunted a wide variety of animals including deer, gazelle, marmots, and large cats (either leopards or tigers), but supplemented their diet with domestic plant resources such as millet acquired through exchange with farmers living at lower elevations (Ren et al., 2019; Zhang et al., 2019). Shell midden sites are common in Shandong Province and along the coast where locally available marine resources made up a significant part of the diet (Zhongguo, 2007). In regions such as Yunnan that have a high degree of ecological diversity, animal exploitation also shows a high degree of variability as people adapted their subsistence strategies to local environmental conditions (Ren et al., 2017).

Deer were particularly important to people in early China both for meat and for their bones and antlers, which were used to make various artifacts. Their remains have been identified at over 90% of Neolithic and Bronze Age archaeological sites in the Yellow River Valley (Lander and Brunson, 2018b). Sika deer (*Cervus nippon*) have been identified at over 60% of all archaeological sites in the Yellow River Valley, often in considerable quantities. This suggests they were well adapted to living in anthropogenic environments around villages, and people may even have modified local ecosystems to create deer habitat. A similar scenario is also likely for certain kinds of birds (e.g. pheasants) typically considered "wild" but whose abundance, diversity, and diet may be strongly influenced by human action and landscape modification (Barton et al., 2020).

Much foundational work has been done on the adaptive responses of late Pleistocene/early Holocene hunter gatherers (Barton et al., 2007; Bettinger et al., 2010; Elston et al., 1997; Madsen et al., 1996; Yue et al., 2019; Zhao, 2020), but agriculture eventually became the dominant ecological system across much of Asia. A major consequence of this success over the last 5000 years, and the accompanying anthropogenic landscape alteration, was a dramatic reduction in biodiversity in China (Lander, 2020). Clearing of fields, lumbering, irrigation, population growth, and increased hunting led to the eradication of scores of previously common taxa, including charismatic megafauna, such as

elephants, rhinoceroses, and alligators (Cao, 2018; Elvin, 2004; Lander and Brunson, 2018a; Lander and Brunson, 2018b). Domesticated animals often replaced their wild relatives, since they shared the same diets and habitats, and as niches were improved for domesticated species, niches conducive to reproduction of other taxa were lost. Various animals such as rats, cats, bats, and sparrows moved into human settlements and became inseparable parts of those ecosystems (Vigne et al., 2016).

Zooarchaeological assemblages are the only way to document the distributions of wild taxa in periods before textual records, and remain the most reliable one for most of the historical period. Many questions remain, though, about how people responded to declining numbers of once-common animals. In other parts of the world, researchers have documented zooarchaeological evidence for resource depression caused by human over-hunting or habitat modification, such as size reduction of prey species, shifting from high rank prey to low rank prey, and hunting a wider array of species (Broughton, 1994; Erlandson and Rick, 2009; Grayson, 2001; Nagaoka, 2002). There is great potential to look for similar evidence in China's zooarchaeological record—such as by looking at deer body size reduction through time—in order to clarify the nature and environmental impacts of human hunting strategies.

Another important area for development in zooarchaeological research in China is in the field of applied zooarchaeology (Rick and Lockwood, 2013; Wolverton and Lyman, 2012; Wolverton et al., 2016). Modern conservation biologists are often limited to observations about changing animal distributions over the last few decades. Zooarchaeologists can use animal bones to track changes in animal distributions over thousands of years. There is great potential to bring zooarchaeological data from China into discussions about the long-term ecological impacts of human activities (Cao, 2018; Turvey et al., 2017; Turvey et al., 2013).

However, it is important to remember that the zooarchaeological record does not reflect the entire suite of wild species that were ever present in a region. Fauna identified at archaeological sites have passed through a cultural filter (Daly, 1969; Reed, 1963), and are subject to taphonomic changes that may lead to underrepresentation of small animals, especially non-mammals. Traditionally, methods like fine mesh screening or flotation have been comparatively uncommon in archaeological excavations in China, so most zooarchaeological assemblages consist predominantly of larger animal bones collected by hand.

One promising technique that could supplement traditional zooarchaeological methods for documenting changes in faunal distributions through time is metagenomic analyses of ancient environmental DNA extracted from soils and sediment cores. Environmental DNA techniques identify the range of plant and animal species that were present, making it possible to reconstruct local ecosystems at various points in time (Bálint et al., 2018; Thomsen and Willerslev, 2015). This could also be useful for refining the chronology and routes of introduction for key domesticated species, even when macroscopic remains are not preserved.

A second way that zooarchaeology contributes to research on human-environment interaction is by documenting domestication and the introduction of foreign domesticates. Several animals were domesticated in China, including dogs, pigs, chickens, ducks, yaks, carp, and silk worms. Pigs are the best-studied of these animals, and provide a good example of the ways that animal domestication in ancient East Asia involved a combination of ecological and social factors. The wild progenitors of pigs, wild boar, are well adapted to anthropogenic niches, and likely followed a commensal pathway toward domestication (Zeder, 2012b, c). Pigs were domesticated in China gradually, perhaps initially as pets (Luo, 2012; Yuan, 2020). Pigs held a variety of roles in Neolithic and Bronze Age societies for subsistence as well as ritual practice (Luo, 2012), and pig manure was an important source of fertilizer in agricultural fields (Lander et al., 2020).

Pig domestication has also been studied isotopically in order to reveal when pigs began eating human agricultural waste (Barton et al., 2009; Cucchi et al., 2016). However, continued refinement of isotopic

methods is still needed, e.g., to identify the isotopic signatures of native plants found in various regions of China. In particular, we cannot assume that millets were the only C₄ plants that animals ate. Paleogenomic research on pigs and other Chinese domesticates is also ongoing and has great potential to clarify the locations and timing of animal domestication, the relationships between wild and domesticated populations, and genes that were subject to selection during domestication.

Numerous domesticated animals including sheep, goats, cattle, horses, donkeys, water buffalo, and camels were introduced to China during the middle to late Holocene. The onset of the Meghalayan may have been a catalyst for promoting the adoption of new species, especially cattle, sheep, goats, and horses, as the climate of North China became more arid and people turned to pastoral activities to take advantage of new environmental niches (Brunson et al., 2016a; Brunson et al., 2020), though horseback riding was not introduced to China until the late first millennium BCE (Li et al., 2020c). The arrival of these new taxa and the expansion of agricultural and pastoral activities coincides with the decline of native species (Lander and Brunson, 2018b).

Research on the timing and routes of introduction for non-indigenous domesticated animals depends on further refining zooarchaeological methods for accurate species identification. There is already work being done to determine reliable morphological criteria for distinguishing between the bones of similar-looking species such as sheep, goats, and various wild bovids present in North China (Wang, 2017). Morphometric techniques for caprine identification (e.g., Salvagno and Albarrella, 2017) may prove useful as well. Biomolecular methods such as collagen fingerprinting and ancient DNA also have great potential to clarify the introduction of West Asian domesticates (e.g., Cai et al., 2020; Dodson et al., 2014).

A final challenge to research on the introduction of domesticated animals into China is the lack of direct radiocarbon dates from the animal bones themselves (Brunson et al., 2020). Whenever possible, direct radiocarbon dates from animal bones should be used to document the emergence of new domesticates rather than dating by association. We also need better methods for data sharing and publication of raw data, which can facilitate synthetic, regional zooarchaeological analyses (Atici et al., 2013).

3.3. Bioarchaeology/human osteoarchaeology

All the processes outlined above impact not only the social-ecological systems of which humans are a part, but also the physical bodies of individual humans. Where we see the evidence of ancient environments on human bodies, those environments should be understood as both social and biophysical. For instance, nutritional inadequacy can result from causes as diverse as drought (the biophysical environment) or unequal distribution of food (social environment). Bioarchaeology is therefore well positioned to identify biocultural processes of adaptation and interaction with the environment.

Within bioarchaeology, subsistence activity and diet are perhaps the most well-studied mechanisms of adaptation. Subsistence activities are best reconstructed using material culture and faunal and floral remains, though degenerative changes to the body that result from daily activities are also detectable in the skeleton (Eng, 2016; Zhang et al., 2016). While dietary reconstruction can be approximated with oral health, as with animal remains, more specific insights can be gained from stable isotope analysis. Chinese bioarchaeology has a long history of stable isotope applications (Berger and Pechenkina, 2018; Hu, 2018) that offer information on diet and mobility over the life course, and this area of research is witnessing a great deal of recent growth. By 2018, there were over 90 articles published in English and Chinese reporting stable isotope compositions measured from human bone collagen, apatite, and/or tooth enamel from more than 120 sites across China (see Liu and Reid, 2020 for a review).

Human stable isotope signatures must be interpreted in the context of local plant and animal values and wider archaeological data on diet

and subsistence, making the development of detailed local and regional databases an important goal (Makarewicz and Sealy, 2015). Human $\delta^{13}\text{C}$ values begin to indicate significant millet consumption at some sites in the Early Neolithic, suggesting initial domestication (Atahan et al., 2011b; Hu et al., 2008; Liu et al., 2012). This continued from the Yangshao period (5000 to 3000 BCE) onward for sites in the Yellow River drainage (e.g., Atahan et al., 2014; Barton et al., 2009; Chen et al., 2016b; Pechenkina et al., 2005; Zhang et al., 2011). The $\delta^{13}\text{C}$ values of some domesticated species—pigs, dogs, and later cattle—also frequently indicate millet consumption, showing that foddering or stubble grazing of selected animals was a key component of subsistence strategies (e.g., Atahan et al., 2011a; Barton et al., 2009; Chen et al., 2016c; Dai et al., 2016; Hou et al., 2013; Ma et al., 2016b; Pechenkina et al., 2005; Yang et al., 2019).

Even after the appearance of C_3 cultivars in the archaeological record, stable isotope analyses show that their early nutritional importance varied regionally. Human and animal bone $\delta^{13}\text{C}$ values indicating significant reliance on C_3 cultivars appear in the Hexi Corridor around 1900 BCE, and the upper Yellow River around 1600 BCE (Liu et al., 2014b; Long et al., 2018; Ma et al., 2016a; Ma et al., 2014; Yang et al., 2019). By contrast, on the Central Plains this shift does not start until the Eastern Zhou (771–221 BCE) and Han (206 BCE–220 CE) eras, and is characterized by high within- and between-site $\delta^{13}\text{C}$ variability (e.g., Atahan et al., 2014; Dong et al., 2017b; Hou et al., 2012; Pechenkina, 2018; Zhou and Garvie-Lok, 2015; Zhou et al., 2017). The $\delta^{13}\text{C}$ patterning at some sites suggests more C_3 consumption by the poor than by the rich, and more by women than by men (Dong et al., 2017b; Pechenkina, 2018; Zhou et al., 2017; Zhou et al., 2019), suggesting, for instance, a “bottom-up” pattern for the shift to dietary reliance on C_3 crops in the Hexi Corridor (Liu and Jones, 2014). However, the cultural, economic, and environmental reasons behind the shift are still debated (e.g., Barton and An, 2014; Cheung et al., 2019; Hou et al., 2012; Lister et al., 2018; Long et al., 2018; Pechenkina, 2018). This is a key area where fine-grained stable isotope studies of human and faunal remains will continue to yield important insights into changing subsistence adaptations.

Beyond these large-scale ancient subsistence transitions, climate change events are generally assumed to have a major impact on human health through a variety of mechanisms, including warfare and resource shortages (Wang et al., 2016; Zhang et al., 2006). The introduction of new animal species may also have introduced novel zoonotic diseases, whose transmission and evolution could be reconstructed through human paleopathology, zooarchaeology, and phylogenetic analysis of pathogen DNA (Berger and Pechenkina, 2018; Puckett et al., 2020), though this work has only just begun (for a review of aDNA research in China, see Sheng et al., 2016). However, as with cases discussed above, combining different scales of analysis presents the risk of oversimplifying complex interactions within systems (Coombes and Barber, 2005; Harrod and Martin, 2014; Jaffe et al., 2020; Martin and Osterholtz, 2016). For instance, bioarchaeological research comparing the health of populations who lived in the second and first millennia BCE in the Hexi Corridor (Berger and Wang, 2017) found improvement in community health, despite climatic fluctuation. This is likely due to the diverse and flexible subsistence system reconstructed for this time (e.g., Jaffe and Hein, 2020; Yang et al., 2019). Meanwhile, contemporaneous populations on the edge of the Qinghai Plateau give more ambiguous results (Berger and Wang, 2017; Han, 1990; Wang and Zhu, 2004). For instance, long bone measurements suggest males had better growth outcomes after 2000 BCE, but the opposite trend is seen among females (Eng and Zhang, 2021). Finally, the site of Mogou (1750–1100 BCE) in eastern Gansu Province has produced skeletons that show a much higher burden of infectious and metabolic diseases, as well as a high incidence of fatal violence among males (Dittmar et al., 2019; Dittmar et al., 2021). Therefore, multiple contradictory trends in growth, trauma, and nutrition can be observed within the same time period just within one part of Northwest China, indicating the gap between local and regional

trends.

Beyond diet, indicators of general physiological stress can be used to assess mechanisms of risk aversion, resilience, and adaptation through careful integration of bioarchaeological evidence with archaeological and environmental context. For example, analysis of non-elites from Shang society has shown high levels of multiple indicators of both childhood and adult stress, likely caused by the correlates of urbanization and exacerbated by social and sex-based inequity (Zhang et al., 2016). By contrast, all occupants of Bronze Age Houtaomuga in north-east China older than 4 years of age exhibited enamel defects in the teeth, indicating disruptions in growth. However, the lesions can only form if an individual survives physiological stress, so despite encountering high stress levels, the population must also have had mechanisms of risk management. For instance, the addition of millet to the diet may have mitigated extreme stress in the face of deteriorating environmental conditions (Merrett et al., 2016).

Moving beyond North China, the Inner Asian steppe zone, which stretches across a broad geographic band with tremendous environmental and ecological diversity, provides more bioarchaeological evidence for risk management strategies. Pastoralism developed in the steppe during the Bronze Age and was further refined into mobile herding strategies in the early Iron Age. Mixed economic strategies further exploited the diverse available resources, from hunting and fishing near water sources, to agriculture in the northern areas of China and within the oases of the Tarim Basin. It may be expected that human remains from these different regions of the steppe reflect differences in diet and stressors, due to this diversity of lifeways. Indeed, recent stable isotope studies of human and animal remains (Hrivnyak and Eng, 2020; Machicek and Eng, 2017) have shown that in Northern Mongolia, human diets from the Bronze to the Iron Ages shifted from being consistent within each site but varying across sites, to being more diverse within each site but consistently so across the region. The occupation of the same locales but with more varied diets in the later period suggests behavioral changes, such as diversified subsistence strategies, or increased trade and exchange of resources likely accompanied by increased mobility. Meanwhile, in Xinjiang in far Northwest China, the diet shifted from primarily C_4 -based to primarily C_3 -based. This work has revealed significant diversity in ecological landscapes and biocultural adaptation within and between communities of the steppe zone.

Bioarchaeology can reconstruct both population-level changes and the impact of environmental and social change on individual lives, something that is hard to do in other areas of archaeology except perhaps mortuary analysis or household archaeology. Bioarchaeological datasets in China are rapidly growing, and have much to contribute in the areas of paleopathology, paleoepidemiology, paleogenetics, and paleodemography, in addition to dietary reconstruction and population history, which have been the field's main foci to date (Berger and Pechenkina, 2018, 2020; Pechenkina, 2012). Bioarchaeology in China is also well-integrated with archaeology, with bioarchaeologists taking part in field excavations, and their analyses are increasingly featured as integral parts of site reports rather than appearing as appendices (e.g., Ningxia and Pengyang, 2016; Shaanxi et al., 2018).

4. Conclusions and future goals

Three overarching conclusions emerge from the preceding synthesis. The contributors agree that datasets and research questions relating to ancient human-environment interaction should ideally be specific, multiscalar, and cross-disciplinary:

Specificity First, datasets must be as local and specific as possible in both chronological and spatial terms, since both environmental changes and human responses are highly local and contingent. Examples given above include the need for detailed spatial knowledge about changes to specific landscape features over time (e.g. river

courses), the reconstruction of food systems at individual sites in order to detect trade vs. food production, and differing diet and health transitions during the Bronze Age across Northwest China and the Inner Asian steppe zone.

Multiscalarly Second, the field needs a robust theoretical framework for integrating data on multiple scales of complex social-natural systems, because the relationships between processes at different spatial and temporal scales must be shown rather than taken for granted. Examples discussed above include human-scale anthropogenic landforms interacting with regional-scale geomorphic processes, food production in individual villages interacting with dynastic governance and land management policies, regional vs. local forces driving technological innovation, and the adoption of new food crops at specific sites vs. the pan-continental process of their transmission.

Cross-disciplinarity Third, for our work to meaningfully contribute to urgent contemporary climate change research, effective communication of research findings to the public and to scientists in other disciplines should be routinely incorporated into research and publication plans. Archaeology can provide policy-related data, such as the composition of faunal communities over time, the origins of modern diseases, and the resilience of past communities. In addition, as is made clear by the same research topics arising in multiple sections of this paper, the work of various archaeological sub-disciplines must be interpreted in light of each other.

Related to this last point, archaeology everywhere in the world has long had an omnivorous appetite for scientific methods borrowed from the natural and physical sciences. Archaeological science is well-funded and developing at a rapid pace in China, augmenting traditional archaeological field research, and archaeologists and other interested scientists are working to develop research projects that not only contribute to the task of reinforcing national identity, but also meaningfully contributing to policy by providing a longer and more objective perspective on environmental and social issues.

Finally, an important goal for a future-oriented archaeology in China, as everywhere, is breaking down institutional divisions. Projects must be able to incorporate data from across provinces administered by separate cultural heritage bureaus. Field work and archaeological science must work together at every stage, from designing a research question and conducting an excavation, to sampling artifacts, performing scientific analyses, and studying previously excavated legacy collections. International collaborations can also be very productive for developing scientifically robust, multidisciplinary approaches, and often have a large body of output. It would also be helpful to focus on improving the cross-linguistic accessibility of publications in both Chinese and other languages, by translating published papers, publishing bilingual reports, and at the least including bilingual abstracts. Finally, perhaps the most monumental task is to move towards open data standards (Jaffe et al., 2020). There are vast quantities of raw geological, archaeological, and historical data in China that could be published for potential collaborators, thereby ensuring that they will be reused and incorporated into future work (current efforts include Brunson et al., 2016b; Niu and Li, 2018; Womack and Hein, 2018).

China's high population density and interconnected physical geography present unique opportunities for insight into the human past and future. Historical sources in China are exceedingly rich and abundant, allowing the possibility of greater collaboration between historians and archaeologists. Moreover, China is one of the only large nations in the world that has developed a fairly standardized archaeological practice, uniform publishing language, and robust infrastructure supporting archaeological and geological surveys and excavations, producing datasets that span the Holocene and Pleistocene history of a vast landmass. The challenges should therefore not deter recognition of this work, as China is an essential piece of the anthropological puzzle of human behavior and environmental interactions.

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.

Acknowledgements

This paper resulted from insights gained during a two-day conference held at the Lieberthal-Rogel Center for Chinese Studies (LRCCS) at the University of Michigan in February of 2019, titled "Environments and Adaptation in Ancient China: Recent Advances and Global Context," co-organized by Dr. Elizabeth Berger and Dr. Pär Cassel.² We are indebted to the fifteen archaeologists from around the US and Canada who convened to present original research, and to discuss recent trends and future directions, many of whom contributed to this paper. We are also grateful to the eight UM-affiliated discussants, and the sponsoring units at UM, including the LRCCS, the Museum of Anthropological Archaeology, the Department of Anthropology, the Department of History, the Office of Research, the College of Literature, Science, and the Arts, the Institute for the Humanities, and the Rackham Graduate School. Finally, our thanks go to Dr. Lothar von Falkenhausen and Dr. Pär Cassel for comments on earlier drafts of this paper.

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² The conference program can be viewed here: <https://ii.umich.edu/lrccs/news-events/events/conferences/environments-and-adaptation-in-ancient-china-recent-advances-an.html>.

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