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Link between black carbon, fires, climate change, and human activity during the Holocene period shown in the loess-paleosol sequence from Henan, China

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Abstract

Henan was the site of development for several ancient cultures during the Holocene. In this study, black carbon (BC) in the Holocene sediment is compared with known climatic changes and cultural events to provide information concerning the link between fire, climatic changes, and human activity in Xiangcheng. Prior to 8000 cal yr BP, the occurrence of fires was low under cold and dry climatic conditions. The BC content in 8000–1000 cal yr BP indicates a gradual increase in fire, with two peak values at 7500 cal yr BP and 3500 cal yr BP. The first peak correlates to the development of the Peiligang culture, and the second peak correlates to the development of wet and warm climate conditions along with the appearance of the Xia–Shang dynasties. Increases in fire activity could therefore be attributed to climate change and the development of human civilization in the region. Another sharp increase in fires around 1000 cal yr BP was consistent with a sharp increase in population during the Tang dynasty.

Keywords: Black carbon; Holocene; Climate change; Human activity; Paleofires

INTRODUCTION

Black carbon (BC), which is ubiquitous in the atmosphere, soil, and aquatic (lacustrine and marine) sediments (Masiello and Druffel, 1998; Wang et al., 2005; Ahmed et al., 2009; Poot et al., 2009), is a residue produced by incomplete combustion of fossil fuels and biomass materials (Lim and Cachier, 1996; Bird and Cali, 1998; Gelinas et al., 2001; Muri et al., 2002; Elmquist et al., 2004; Poot et al., 2009) and represents a continuum from charcoal and char to soot particles without any agreed-on clear-cut boundaries (Schmidt and Noack, 2000). The release of BC has had a significant impact on climate because it is a strong absorber of solar radiation (Jacobson, 2001; Randerson et al., 2006; Ramanathan and Carmichael, 2008).

Because of its thermal stability and inertness (Preston and Schmidt, 2006), BC can be preserved in soils and sediments for thousands to millions of years (Kuhlbusch et al., 1995; Simpson et al., 2004; Sun et al., 2008). BC can provide important information for the study of paleoclimatic changes and human activity (Lim and Cachier, 1996; Zhang et al., 1997; Bird and Cali, 1998; Masiello and Druffel, 1998, 2004; Gelinas et al., 2001; Muri et al., 2002; Dickens et al., 2004; Fried et al., 2004; Kim et al., 2004; Ohlson et al., 2009; Poot et al., 2009). BC can serve as a proxy record for changes in the frequency and extent of paleofires (Clark, 1988; Yang et al., 2001; Huang et al., 2006; Whitlock et al., 2007; Ali et al., 2009). Fire occurrence is influenced by climate change, which also affects vegetation type and coverage (Wang et al., 2012; Tan et al., 2015). Some scientists have suggested that climate change is an important factor for wildfires, which might occur more frequently under drier climatic conditions (Clark, 1988; Verardo and Ruddiman, 1996; van der Kaars et al., 2000; Fried et al., 2004; Han et al., 2012; Tan et al., 2015; Zhang et al., 2015). Other research has suggested that fires might occur more readily when a humid climate changes to a dry climate (Bird and Cali, 1998; Yang et al., 2001; Zhou et al., 2007). On the other hand, limited vegetation productivity and fuel availability under dry and cold climatic conditions could reduce the spread of natural fires (Daniau et al., 2010; Han et al., 2012; Tan et al., 2015; Mu et al., 2016).

Archaeological evidence indicates many uses for fire, including cooking, warfare, and clearing pests and disease

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vectors in a variety of environments (Marlon et al., 2013). BC is mainly derived from two sources: natural wildfires (e.g., forest and grass fires caused by lightning: Griffin and Goldberg, 1983; Wolbach and Anders, 1989; Muri et al., 2002; Zhou et al., 2007; Ohlson et al., 2009) and anthropogenic biomass burning (e.g., deforestation for building homes, for cooking and heating, and for farming: Qin et al., 2001; Carcaillet et al., 2002; Ruddiman, 2003, 2007; Zheng et al., 2007).

In previous paleoenvironmental research, the links between fires and climate change, vegetation, and human activity have been estimated by analyzing the relationship between BC and other environmental proxies (e.g., total organic carbon [TOC], magnetic susceptibility, and/or pollen) in East Asia, especially in China (Long et al., 1998; Yang et al., 2001; Huang et al., 2006; Zhou et al., 2007; Han et al., 2012; Wang et al., 2012, 2013; Tan et al., 2015). However, such studies of the Holocene have mainly focused on the semiarid and arid regions (Yang et al., 2001; Wang et al., 2005, 2012, 2013; Zhou et al., 2007; Tan et al., 2015). In contrast, there are few studies involving fire history reconstructions in the semihumid areas of China.

The Huaihe River basin is located in the Jianghuai region, a semihumid zone of East China in the transitional region between southern and northern China. The climate is strongly influenced by the Meiyu (the East Asian rainy season, commonly called "plum rain"), which is caused by precipitation along a stationary front that persists for nearly 2 months during the late spring and early summer (Xu and Tian, 2005; Mao et al., 2006, 2008). As one of the cradles of Chinese civilization, the Huaihe River basin saw rapid social development during the Holocene. Evidence of regional human activity is prolific in the archaeological record, and a secure culture sequence has been established for the Lijiagou, Peiligang, Yangshao, and Longshan cultures. Records show that agriculture and a strong tradition of pottery developed in the region during the Holocene (An, 1989; Lu and Wu, 1999; Yang and Sun, 2002; Wei, 2012; Xu et al., 2013).

Qin et al. (2015) found that the characteristics of Holocene climate change in the Huaihe area were different from those in arid and semiarid areas, arguing that the latter were influenced by an intensified India summer monsoon (ISM), whereas the Meiyu in the Jianghuai region was dominated by westward movement of the western Pacific subtropical high during a weakened ISM.

This study aims to reconstruct the paleofire history and interactions between climate, human activities, and fires during the Holocene in the semihumid areas of China, by using a multiproxy approach. Here we use thermal/optical reflectance method (TOR method) to measure BC concentrations and obtain Holocene variations of BC from the loess-paleosol profile of Xiangcheng, Henan Province, in the northwestern Huaihe River basin. In this area, developed human activities and climate change, which were different from those in arid and semiarid areas, might have significant influences on paleofire variations. These BC records were therefore compared with climatic changes, population fluctuations, and settlement activity to discuss the influence of variations on paleofires.

STUDY AREA

Selection of study section

The Huaihe River basin can be divided into two sections, north and south, in which the sediment compositions differ. Along the northern slope of the Dabie Mountains in the southern section of the Huaihe River basin, Holocene loess sediments are incomplete because of abundant rainfall and erosion. The lacustrine deposits in northern section of the basin are also incomplete and significantly altered because the Yellow River has changed course, flooded, and overtaken the Huaihe River repeatedly throughout history.

Extensive and complete loess sediments can be found only in the northwestern section of the Huaihe River basin. This area is at a higher elevation, not affected by the flooding of the Yellow River, and the average precipitation levels are lower, resulting in loess sediments with the best preservation.

Xiangcheng County, in the northwestern Huaihe River basin, lies in a warm temperate continental monsoon zone. In the summer, the dominant wind is southeasterly, bringing humid air from the Pacific Ocean. In the winter, the prevailing wind is northwesterly, which results in a cold and dry climate. At this location, the mean annual temperature is about 14.7°C and the mean annual precipitation is 579 mm.

The study section is located south of Wangluo in Xiangcheng County, Henan Province (33°57′N, 113°28.8′E). This region is approximately 20 km northwest of the Dayu Mountains and adjacent to the Ruhe, Blue, and Yinghe Rivers, with an elevation of 96 m above sea level (Fig. 1).

Description of study section

The total thickness of the Xiangcheng loess/paleosol sequence is approximately 2.5 m. A detailed description of the stratigraphy was recorded based on field observations of variations in color and texture, and samples were taken at 2-cm intervals (Table 1). The section has the following characteristics: (1) a typical soil aggregate structure without horizontal bedding, (2) evidence of snails, (3) strong eluviation of calcium carbonate that has resulted in a significant quantity of calcium carbonate concretions, and (4) lack of evidence of influence by the Yellow River and mountain flooding. Based on these characteristics, the sediment can be identified as loess-paleosol sediment that differs from the loess sediment of the Chinese Loess Plateau, where the Holocene paleosol is reddish brown rather than gray black.

METHOD

BC measurement

TOR method

TOR analysis is based on the preferential oxidation of organic carbon (OC) and BC compounds at different

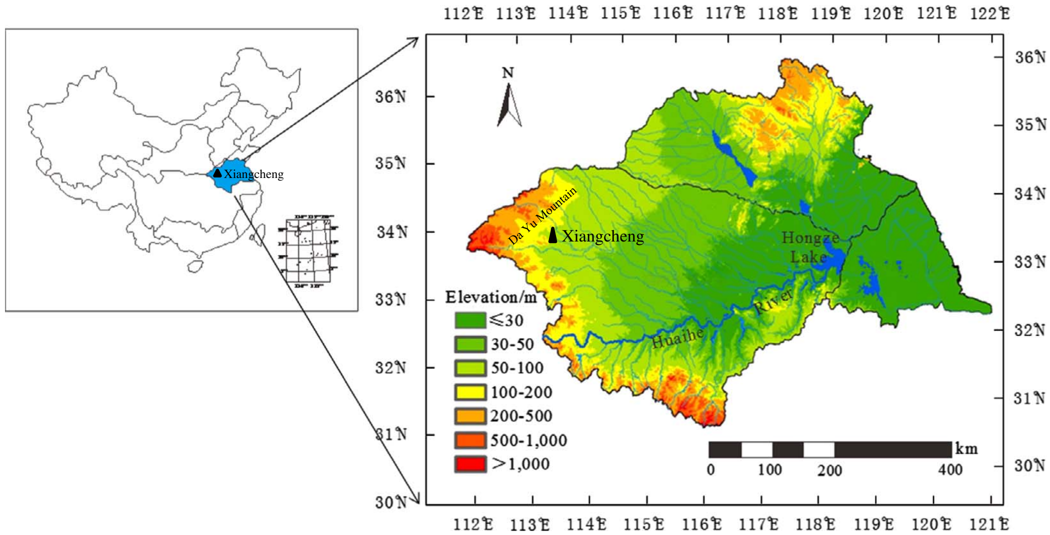

Figure 1. (color online) Location of Xiangcheng section.

temperatures and in different atmospheres. Interagency monitoring of protected visual environments is one protocol that is most commonly used in this carbon analysis (Chow et al., 1993, 2004; Han et al., 2007a, 2007b, 2008, 2009a, 2009b; Cao et al. 2008; Wang et al., 2012). The instrument used in this study was a DRI Model 2001 Thermal/Optical Carbon Analyzer.

The TOR method has been widely used for BC quantification in sediments and soils (Han et al., 2007b). Carbonate and silicate were extracted by adding hydrochloric acid and hydrofluoric acid. The details of the pretreatment procedures used are described by Mu et al. (2014).

The carbon is made to evolve through programmed, progressive heating to produce eight carbon fractions: four OCs (OC1, OC2, OC3, and OC4 at 120°C, 250°C, 450°C, and 550°C in pure He), one pyrolyzed OC (PyC, produced in the nonoxidizing heating process), and three BC fractions (BC1, BC2, and BC3 at 580°C, 700°C, and 800°C in 2% O_2/98% He). The pyrolysis darkens the filter deposit and can be corrected by monitoring the laser reflectance as the sample is being analyzed and noting when the optical response has returned to its original intensity. OC is defined as OC1 + OC2 + OC3 + OC4 + PyC, and BC as BC1 + BC2 + BC3 – PyC (Chow et al., 2004; Han et al., 2007a, 2007b, 2008, 2009a, 2009b).

Table 1. Description of loess/paleosol sequence at Xiangcheng site.

Depth (cm)	Stratigraphic subdivision	Pedological description
0–17	Farming layer	Silt, small pebbles, light brown
17–35	Loess	Silt, pale yellow
35–110	Paleosol	Reddish brown, silt, organic rich
110–130	Loess	Pale yellow, silt, $CaCO_3$ concretion
130–172	Loess	Pale yellow, silt
172–180	Loess	Silt, organic rich
180–190	Loess	Silt, pale yellow, $CaCO_3$ concretion rich
190–210	Loess	Silt, pale yellow

Chronology

Eight radiocarbon samples from this loess/paleosol section were dated using an accelerator mass spectrometry system at Beta Analytic Inc., Miami, Florida, USA (Table 2).

The Pretoria Calibration Procedure program was chosen for these calendar calibrations. This program uses dendrochronological data for the creation of calibration curves and splines in order to eliminate the majority of statistical scatter within the data points. The spline calibration allows for adjustment of the average curve by a quantified closeness-of-fit parameter for the measured data. The calibration database used was IntCal13. To compare the various sources of paleoenvironmental information, a precise time scale was required (Fig. 2).

As Table 2 and Figure 2 show, the measured age at the depth of 24 cm is reversed, which might be related to the farming activities at the top of the section. The measured age at the depth of 200 cm, which is nearly the same as at 160 cm, apparently deviates from the entire age–depth trend. This bias would make the fitting line deviate from most of the age-control points. Therefore, in this study, we excluded these two measured ages where the age–depth model was estimated.

The sedimentation rate for the loess-paleosol section changes significantly (Fig. 2). In particular, the sedimentation rate of paleosol between 4000 and 2000 cal yr BP was higher than that of loess. This variation was determined by the changes of source distance and wind strength of dust source areas (An et al., 1991; Ding et al., 2001). In the study of Qin et al. (2015), during the interval between 4000 and 2000 cal yr BP, the intensity of wind strength was high while the source distance began to decrease. The high wind strength and decreasing source distance were critical for the increasing sedimentation rate.

Table 2. Accelerator mass spectrometry (AMS) radiocarbon dates of samples.

Sample number	Depth (cm)	Dating material	AMS ^{14}C yr BP	Calibrated ^{14}C age (2σ) (cal yr BP)
XC-2013-12	24	Organic matter	2240 ± 3	2350–2310/2220–2210
XC-2013-20	40	Organic matter	1880 ± 30	1885–1730
XC-2013-35	70	Organic matter	2430 ± 30	2700–2635/2615–2590
XC-2013-45	90	Organic matter	3220 ± 30	3640–3470
XC-2013-55	110	Organic matter	3970 ± 30	4520–4465/4450–4410
XC-2013-80	160	Organic matter	5670 ± 40	6535–6395/6365–6355
XC-2013-103	200	Organic matter	5770 ± 40	6665–6470
XC-2013-110	220	Organic matter	9860 ± 50	11,607–11,523/11,503–11,238

RESULTS AND INTERPRETATION

Holocene variations of BC in Xiangcheng

Large variations in the levels of BC are reflected throughout the Holocene, as shown in Figure 3b. Prior to ca. 8000 cal yr BP, the BC values were low and began to have a modest, punctuated increase between 8000 and 1000 cal yr BP, sharply increasing to high levels after 1000 cal yr BP. At around 7300 and 3500 cal yr BP, two maxima are observed, with a more modest jump around 4000 cal yr BP. Particularly at ~7300 cal yr BP, BC increased rapidly to its peak value and then declined.

Relationship between BC and climatic parameters (temperature and precipitation)

Fire behavior and fuel flammability are influenced by weather conditions such as precipitation, humidity, lightning, and air temperature (Pyne et al., 1996). In a dry cold climate, the frequency of fire ignition increases (Wang et al., 2005; Zhang et al., 2015), which is called the "triggering effect." In a moist climate, increasing vegetation density provides abundant fuel for fire; this is known as the "fuel supply effect." Both climate and biomass play a significant role in fire occurrence, though the linkages are complex on any time scale. For example, on century and millennial time scales, changes in fire activity are linked to changes in atmospheric and ocean circulation that affect regional vegetation and fuel conditions (Whitlock and Bartlein, 2003).

Changes in temperature and precipitation have been found to be the most dominant influence on fires during the Holocene (Daniau et al., 2012; Zhang et al., 2015). High temperature in general is associated with increased occurrence of fires, and the relationship between temperature and fires is also mediated by precipitation, both of which determine the net primary productivity and the abundance of fire fuels (Dennison et al., 2008; Daniau et al., 2012; Zhang et al., 2015).

Qin et al. (2015) estimated the index of near-surface temperature (INST) in the spring and the effective moisture (EM) in the region. Their result can be used to analyze the relationship between BC and climate change. In Figure 4a, it

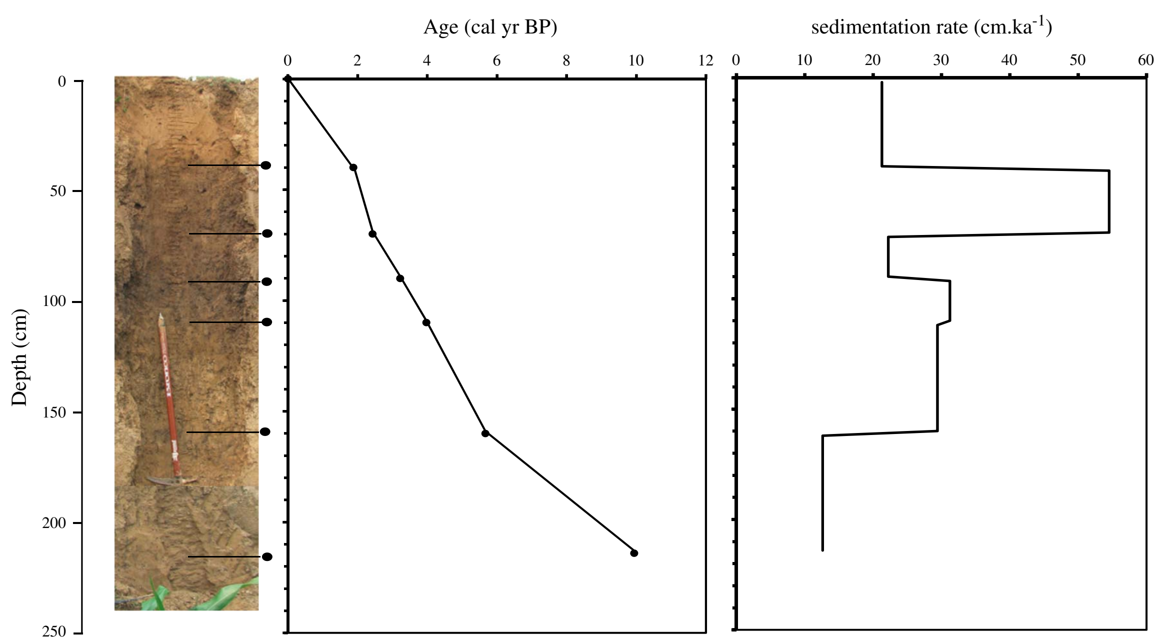

Figure 2. (color online) Pedostratigraphic subdivision, the age–depth curve, and sedimentation rate of the Xiangcheng profile.

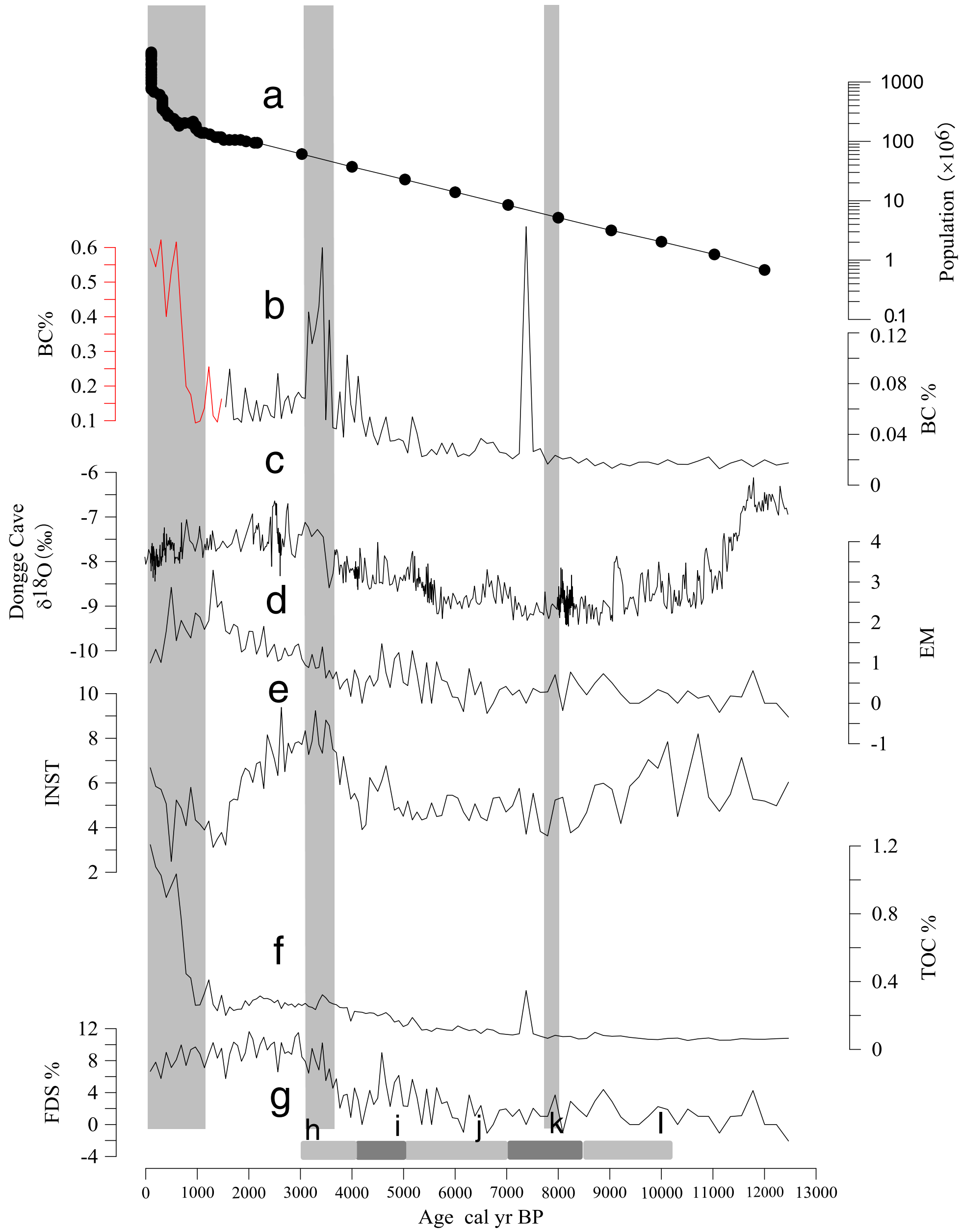

Figure 3. (color online) Comparison of paleoclimate proxies for the central plains of China during the Holocene. (a) Estimated changes in population in East Asia (Marlon et al., 2013). (b) Black carbon (BC) measured by thermal/optical reflectance method. (c) $\delta^{18}O$ data from Dongge Cave (Dykoski et al., 2005). (d–g) Effective moisture (EM) index, normalized index of near-surface temperature (INST), total organic carbon (TOC), and frequency-dependent magnetic susceptibility (FDS %) from Qin et al. (2015). (h) Xia–Shang dynasties. (i) Longshan culture. (j) Yangshao culture. (k) Peiligang culture. (l) Lijiagou culture. Horizontal gray bars bracket the stages characterizing the pattern of changes in fire occurrence and climate.

can be seen that the BC content is positively correlated with the INST, even though the regression slope and correlation coefficient ($r = 0.53$, $P < 0.001$) after 1500 cal yr BP are far larger than those prior to 1000 cal yr BP ($r = 0.49$, $P < 0.001$). This suggests that the increase in temperature is beneficial to BC production. BC content is also positively correlated with EM ($r = 0.47$, $P < 0.01$) (Fig. 4b), meaning that BC increased under wet climate conditions. However, BC values after about 1000 cal yr BP were much higher than that before 1000 cal yr BP, indicating the effect of later (after about 1000 cal yr BP) might mainly increase the intensity of human activity (Fig. 4b). Clearly, during a warm and wet climate, high content of TOC indicates relatively high vegetation coverage (Fig. 3f) (Gasse et al., 1991; Zhou et al., 1996; Zaady et al., 2001). Abundant fire fuel and developing human activity might influence the occurrence of fire in our study area.

In contrast, in semiarid and arid regions of China, some scientists have suggested that wildfires might occur more frequently under drier climatic conditions (Wang et al., 2005;

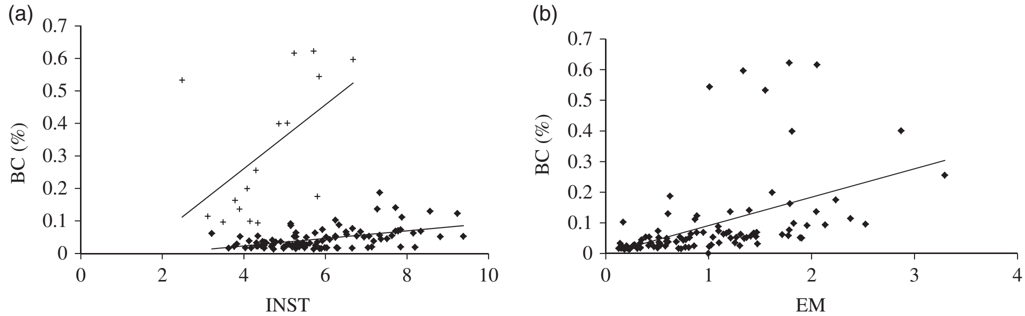

Figure 4. Correlations between BC content and potential covarying proxies. (a) Index of near-surface temperature (INST), crosses represent black carbon (BC) values after 1500 cal yr BP ($r = 0.53$, $P < 0.001$), and dots represent BC values prior to 1500 cal yr BP ($r = 0.49$, $P < 0.001$). (b) Effective moisture (EM) index (Qin et al., 2015) ($r = 0.47$, $P < 0.01$).

Han et al., 2012; Tan et al., 2015). For example, dry and cold conditions occurred during the early Holocene on the Loess Plateau, which enhanced regional wildfire activity (Tan et al., 2015); Han et al. (2012) thought that negative correlations observed between BC from Lake Daihai and monsoon intensity, and abrupt declines in temperature, were also linked with widespread declines in fire in Inner Mongolia.

Link between BC, fire, human activity, and climatic change during the Holocene

The pattern of BC shows variation in biomass burning during the Holocene. Humans are believed to be the principal source of fires in many regions of the world (Daniau et al., 2012). Previous studies have provided a great deal of speculation about the role of ancient humans in the increase of paleofires (Carcaillet et al., 2002; Ruddiman, 2003; Fowler and Konopik, 2007).

The variation in BC content indicates a low and stable trend of paleofire occurrence prior to 8000 cal yr BP (during the early Holocene). The temperature and precipitation were low, as shown in Figure 3d and e (Qin et al., 2015). Stalagmite records from Donge Cave (Fig. 3c), which reveal variability in the ISM through higher rainfall corresponding to more negative precipitation of the oxygen isotope $\delta^{18}O$ (Chen et al., 2014; Liu et al., 2014; Tan, 2014), indicate that the ISM intensity gradually increased during this period. However, the Meiyu in this area was weak when the ISM was strong (Qin et al., 2015). Under the cold and dry climatic conditions during this period, limited vegetation productivity and fuel abundance may have inhibited the spread of natural fires (Fig. 3f) (Han et al., 2012). Our results in the Jianghuai region are contrary to the suggestion of Zhang et al. (2015) that high fire activity occurred when the climate was cold and dry in southwest China.

The variation of fire occurrence in our study is asynchronous with the population growth curves before 8000 cal yr BP (Fig. 3a and b), implying weaker influence of human activity on biomass burning during this period. Previous studies have often assumed that human fire use had limited effects in Asia during the early Holocene because of low populations (Pinter et al., 2011).The intensity of fires related to human activity (e.g., slash-and-burn cultivation or cooking) would also have been relatively low because of the relatively minor human activity during this period in Xiangcheng. From 10,500 to 8600 cal yr BP, the Lijiagou culture developed, but hunting remained an important component of the culture (Wei, 2012).

After 8000 cal yr BP, the temperature and precipitation remained low. However, climate effects on biomass burning are more difficult to determine because of the agricultural development since the Neolithic age and the development of dynasties (Carcaillet et al., 2002). In our study, from 8000 to 1000 cal yr BP, the mean variation of fire occurrence is also synchronized with the population growth curve (Fig. 3a and b), implying a rapid increase in the effects of human activity with time. The populations in the Neolithic and metal ages deforested most of the continent, probably using the slash-and-burn cultivation system. Fires used for cooking might also comprise most of the paleofires during this period. This interval is characterized by three events: two spikes at ~7300 and ~3500 cal yr BP, and one at 7000–4100 cal yr BP.

Fire occurrence increased sharply at around 7500 cal yr BP, the period when the Peiligang culture developed. A wide array of archeological and cultural evidence has provided viable explanations of anthropogenic changes resulting from early agriculture in Eurasia, such as the beginning of forest clearance 8000 yr ago (Ruddiman, 2003). In addition, professional pottery workshops were built, increasing the amount of wood burning within settlements (An, 1989; Yang and Sun, 2002; Wei, 2012). As the population increased, the maintenance of fires for household purposes such as cooking would also have been more prevalent. However, because there is only one age-control point in the early Holocene, the one point peak may represent impact and influence from the Longshan culture period.

Fires began to increase gradually after the decline of the peak value at 7500 cal yr BP and then reached a new peak level at 3500 cal yr BP. Our study (magnetic susceptibility, INST, and EM in Fig. 3) shows that the climate clearly became warmer and wetter since ~7000 cal yr BP and sharply changed to dry and cold at ca. 4000 cal yr BP. There was a multifold increase in fire occurrence, corresponding to this climatic "deterioration" event at ca. 4000 cal yr BP, because there was more biomass fuel accumulation when a warm and humid climate sharply changed to a dry and cold climate (Bird and Cali, 1998; Yang et al., 2001; Zhou et al., 2007). After the "deterioration" event ca. 4000 cal yr BP, the climate returned to warm and humid, and the population continued to increase (Fig. 3a). During the period 4000–3000 cal yr BP (~3500 cal yr BP), the increase in fire occurrence corresponds to the establishment of the Xia–Shang dynasties. Tan et al. (2015) also thought the high peak in the abundance of BC (3500–2800 cal yr BP) coincided with activities associated with large-scale land reclamation for agriculture and gray pottery development during the Shang and predynasty Zhou periods in the Guanzhong basin.

In the period 7000–4100 cal yr BP, the Yangshao (7000–5000 cal yr BP) and Longshan (5000–4000 cal yr BP) cultures developed in Henan Province, and highly developed agriculture and pottery were prevalent (An, 1989; Yang and Sun, 2002; Wei, 2012). Therefore, fires used to deforest land, produce pottery, and support household activity should contribute significantly to BC levels. Although the fire occurrence was increasing during this period, it was still low, and BC content during this period experienced only a slight increase. So it is still questionable whether the low BC values were caused by human activities (e.g., cultural center and settlement migration from the study area to other places) or climate change (limited vegetation productivity and fuel under low temperature and moisture). More work is needed in future studies to explore this question.

Since 1000 cal yr BP, the climate has been predominantly warmer and wetter (Fig. 3d–g), and the occurrence of fires has increased. This increase might be synchronous with the variation in TOC and population growth during this period (Fig. 3a, b, and f). This consistency indicates that vegetation biomass (abundant fuel) and human activity played significant roles in fire use (e.g., deforestation, farming, and domestic fuel) (Carcaillet et al., 2002; Ruddiman, 2003, 2007; Han et al., 2012; Tan et al., 2015; Zhang et al., 2015). The Tang dynasty brought prosperity, and the Northern Song dynasty developed, providing ideal conditions for a rapid increase in population from around 1000 cal yr BP (Fig. 3a). During this period, social economies developed and human activity intensified. However, the upper part of the section (~1000 cal yr BP to present) is composed of soil influenced by farming activities, and so our age control is unconstrained. The fire increase during this period can also be explained by modern human activities. Therefore, discussion concerning this period might have considerable uncertainty, and further research on this topic is needed.

CONCLUSIONS

In our study, we link fire regimes in the Huaihe region of China during the Holocene to climate change and human activity by presenting a well-dated BC record from a loess-paleosol profile in Xiangcheng, Henan Province.

Fire occurrence was low under cold and dry climatic conditions prior to 8000 cal yr BP. Fires gradually increased between 8000 and 1000 cal yr BP , with two peak values at different periods. First, fire occurrence increased sharply at around 7500 cal yr BP under cold and dry climate conditions, which is also the period when the Peiligang culture developed. At ~3500 cal yr BP, more frequent occurrence of fires can be attributed to climate change and the further development of human civilization in the region. A sharp increase in fires since around 1000 cal yr BP is consistent with a significant increase in population, indicating that the Tang dynasty brought prosperity and population growth during this period. The fire increase during this period can also be explained by modern human activities.

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