

Charcoal records of fire history in the Holocene loess–soil sequences over the southern Loess Plateau of China

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Abstract

Charcoal preserved in accretionary loess–soil profiles within the southern part of the Loess Plateau has recorded fire history and landscape evolution connected with climatic variations and human activities. Local wildfires occurred frequently during the late last glacial period and the early Holocene before 8500 years BP when steppe vegetation expanded from the Inner Mongolian Plateau southerly over the Loess Plateau. During the Holocene climatic optimum between 8500 years BP and 3100 years BP, natural wildfires were largely reduced. Pedogenesis of the Luvisols and Isohumisols was intensified because of the increased monsoonal precipitation and soil moisture. Localized fires in connection with human activities occurred in different patterns at the study sites. Fire seems to have been applied to vegetation clearance for land reclamation for millet cultivation at many places during the Neolithic and early Bronze Age. Levels of biomass burning were very high during the late Holocene, when the climate became drier and historical land-use became more intensive. At some sites, the intensity of human disturbance by fire and cultivation increased continuously during the last 3100 years. At the other sites, local fires occurred most frequently between 3100 years BP and 1500 years BP during the major period of land reclamation for cereal cultivation. Human burning of the landscape has been reduced since then. © 2006 Elsevier B.V. All rights reserved.

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1. Introduction

Frequently occurring wildfires play an important role in the evolution of semi-arid temperate ecosystems, especially the steppe, shrub steppe and forest-steppe (Long et al., 1998). In studying the formation of modern cultivated landscapes in semi-arid zones, wildfires must not be ignored. During the last 50 years, there were

50,000 fires recorded over the Chinese grasslands, and about 200 million ha of grasslands were burnt (Zhang, 1998). Over the Inner Mongolian steppe where annual precipitation varies between ca. 300 and 500 mm, there were 4266 fires recorded between 1980 and 2000 (Guo et al., 2003). The southern part of the Chinese Loess Plateau is situated between the Inner Mongolia steppe and the temperate mixed forest, where the landscape is rather vulnerable to both climatic variability and human disturbance. The Quaternary loess–palaeosol stratigraphy over the plateau has been studied intensively and successfully for reconstruction of the history of monsoonal climatic change during the last 2.6 Ma

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(Kukla et al., 1988; Rutter et al., 1991; Porter and An, 1995; Kemp, 2001). The scarcity of fossil pollen and spores in the loess and palaeosols has limited the study of vegetation change and landscape evolution in the region. The transition from a natural landscape to a most intensively disturbed cultivated landscape over the plateau remains to be studied in depth.

Charcoal preserved in the accretionary soil and sediment profiles resulted from wildfires or human burning of the landscape. Charcoal analysis has been used successfully to study fire history and landscape evolution in Europe, Australia, Africa, South and North America and even Southeast Asian Islands (Scott et al., 2000; Wooler et al., 2000; Haberle and Ledru, 2001; Huber et al., 2004; Umbanhowar, 2004). Fire history in East Asia is barely known to date because of the lack of charcoal data from sedimentary sources. Our previous investigations on Holocene environmental change in the middle reaches of the Yellow River show that microscopic charcoal from atmospheric fallout deposited on loess ground can be well preserved with eolian dust in loess–palaeosol stratigraphy (Huang et al., 2002). Charcoal sequences retrieved from the accretionary loess–palaeosol stratigraphy can be used for studying past wildfire events and for reconstruction of

fire history, and further for understanding landscape evolution over the Chinese Loess Plateau. Climate proxies and records of human activities obtainable from such stratigraphy provide opportunities of determining the causes behind the temporal and spatial patterns of wildfire occurrence. An evaluation of the charcoal records of wildfires, climatic variations, and human land-use changes helps decouple human impact from natural processes in regional landscape evolution.

2. Regional setting

The southern part of the Loess Plateau was investigated for this study (Fig. 1). The elevation of the region varies from 320 m asl at the valley bottom to 1800 m asl at the top of the plateau. The landscape includes several levels of loess-blanketed river terraces, alluvial fans and neo-tectonically uplifted loess tablelands and deeply dissected loess hills. In the region, mean annual temperature is 8.0–12.8 °C, with mean monthly temperature –5 to –2 °C in January and 20–26 °C in July; mean annual precipitation is 500–600 mm, ca. 55% to 70% of which occurs between June and September; and mean annual evaporation is 1500–2000 mm at the present (Qian, 1991). Ustic

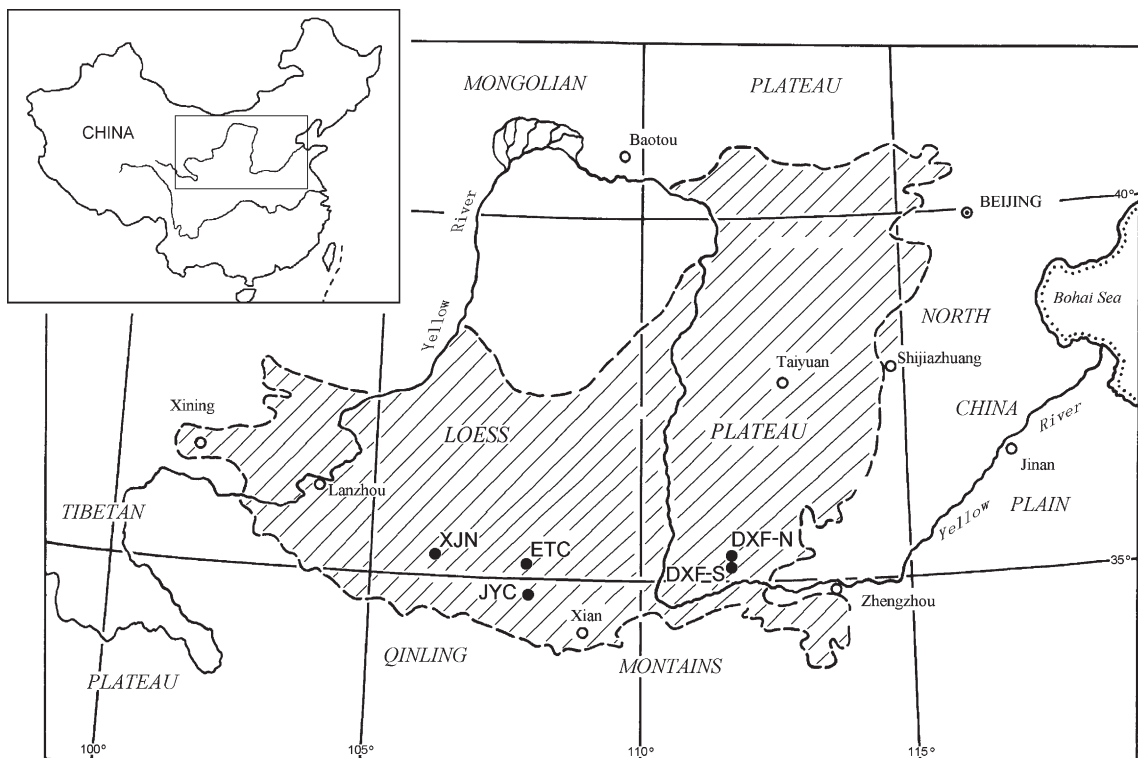


Fig. 1. Site map showing the Loess Plateau in the middle reaches of the Yellow River, China. The sites of the studied Holocene loess–soil profiles are marked: XJN–Xujianian, ETC–Ertangcun, JYC–Jiangyangcun, DXF-S–Dongxiafeng South, and DXF-N–Dongxiafeng North.

Luvisols (Cinnamon soils) and Ustic Isohumisols (Heilusols) were developed on the loessial lands at lower elevation (<1000m asl) and higher elevation (>1000m asl), respectively, during the mid-Holocene under mixed forest or forest steppe (Gong, 1999). Woodland clearance for arable farming started at ca. 8000 years BP from the early Neolithic. The region has an 8000-year history of rain-fed agricultural land-use (Chen, 2002). There are also historical records that nomadic tribes of the Bronze Age from the northern steppe invaded or occupied the region intermittently since 1100 B.C. (Shi, 2001). Cereal production has been very important, and fruit production (apples, pears, peaches and apricots) has increased during the last 20 years. After the domestic fuel of the villagers shifted entirely to coal in the 1990s, crop stalks have been burnt in the field after harvest. The ash and charcoal produced from the burning of the stalks are often redistributed by wind, and mixed with the ploughed layer of the loessial topsoil during cultivation.

3. Methods

Field investigations in the southern part of the Loess Plateau were carried out between 2001 and 2004. Five Holocene loess–soil profiles at four sites were chosen for study. At the each site, samples were taken every 2 cm down the profile after field observation and description. Samples for OSL dating were taken at the same time, and closely packed with lightproof materials. The pedo-stratigraphic subdivisions were made in the field by examination of the colour, texture and structure in the profiles. Detailed pedo-sedimentary descriptions were made on air-dried samples in the laboratory. A sample of 50 g sediment was processed for charcoal analysis. The preparation included: adding marking pollen grains (*Artemisia*); adding 18% HCl and boiling, washing and decanting; adding 2% Na₂CO₃ and boiling, washing and decanting; charcoal was extracted by using heavy liquid (1.8 g ml⁻¹) composed of HI, Zn, and KI (656 ml: 145 g: 644 g). Charcoal fragments in the prepared samples were then counted under the microscope, and charcoal concentration was calculated as grain g⁻¹. Magnetic susceptibility was measured with a Bartington MS2 magnetic susceptibility meter (0.47/4.7 kHz). Grain-size distribution was analyzed using the hydrometer method (Lewis, 1984). The particles >0.1 mm were analyzed using the wet-sieving method and examined under a binocular microscope for identification of fragment of pottery, burnt earth, macroscopic charcoal, and sand from the tiny carbonate concretions. Total iron (Fe) was analyzed using a WCF-X atomic absorption

spectrum analyzer. Total carbon (TC) and total organic carbon (TOC) were analyzed using a High TOC-II analyzer, and the percentages of carbonates (CaCO₃) were then calculated according to molecular weight. In the TL/OSL dating laboratory of Shaanxi Normal University, Blue light simulated OSL dating was carried out on a Risø-TL/OSL-DA15 Dating System using the fine-grain single-aliquot regenerative-dose protocol (Murray and Wintle, 2000).

4. Site, stratigraphy and chronology

Five Holocene loess–soil profiles at four sites, including Xujianian (XJN, 1620 m asl), Ertangcun (ETC, 1050 m asl), Jiangyangcun (JYC, 685 m asl), and Dongxiafeng South and North (DXF-S/N, 500 m asl), in the southern part of the Loess Plateau were investigated (Fig. 1). The Holocene loess–soil sequences are well preserved at the study sites (Fig. 2). The profiles are pedo-stratigraphically correlated to each other. They were identified to be accretionary profiles of eolian origin from their colour, texture and structure. The chronological framework for the pedo-stratigraphy in profiles was established on the basis of OSL dating, archaeological identification of the cultural remains, and stratigraphic correlations (Huang et al., 2003). The OSL dates are given in years BP and ¹⁴C dates are given in cal. years BP. The pedo-stratigraphic structure in the Ertangcun (ETC) profile on the top of the plateau is typical of the Loess Plateau. In the ETC profile, the boundary between the Malan Loess (L₁) of the last glaciation and the early Holocene transitional loess (L_e) was observed at a depth of 266 cm. An OSL date 10,850 ± 150 years BP was obtained at a depth range 292–290 cm. The mid-Holocene palaeosol (S₀), a typical Ustic Isohumisol (Heilusol), developed between 8500 years BP and 3100 years BP at many sites (>1000 m asl) over the Loess Plateau (Huang et al., 2004), was identified at a depth range of 240–150 cm. Remains of the Laoguantai Neolithic Culture (¹⁴C dated to 7800–7000 cal. years BP; Institute of Archaeology, CASS, 1991; Editorial Board, 1998), including fragments of orange–red pottery and macroscopic charcoal, were identified at a depth of 230–220 cm in the bottom part of the palaeosol S₀. The cultural remains of the Pre-dynastic Zhou (¹⁴C dated to 3350–3100 cal. years BP; Institute of Archaeology, CASS, 1991), including fragments of rope-patterned grey pottery, macroscopic charcoal and sand, were identified at a level of 180–160 cm in the top part of the palaeosol S₀. The palaeosol S₀ is underlain by the early Holocene transitional loess (L_e) accumulated before 8500 years BP and overlain by

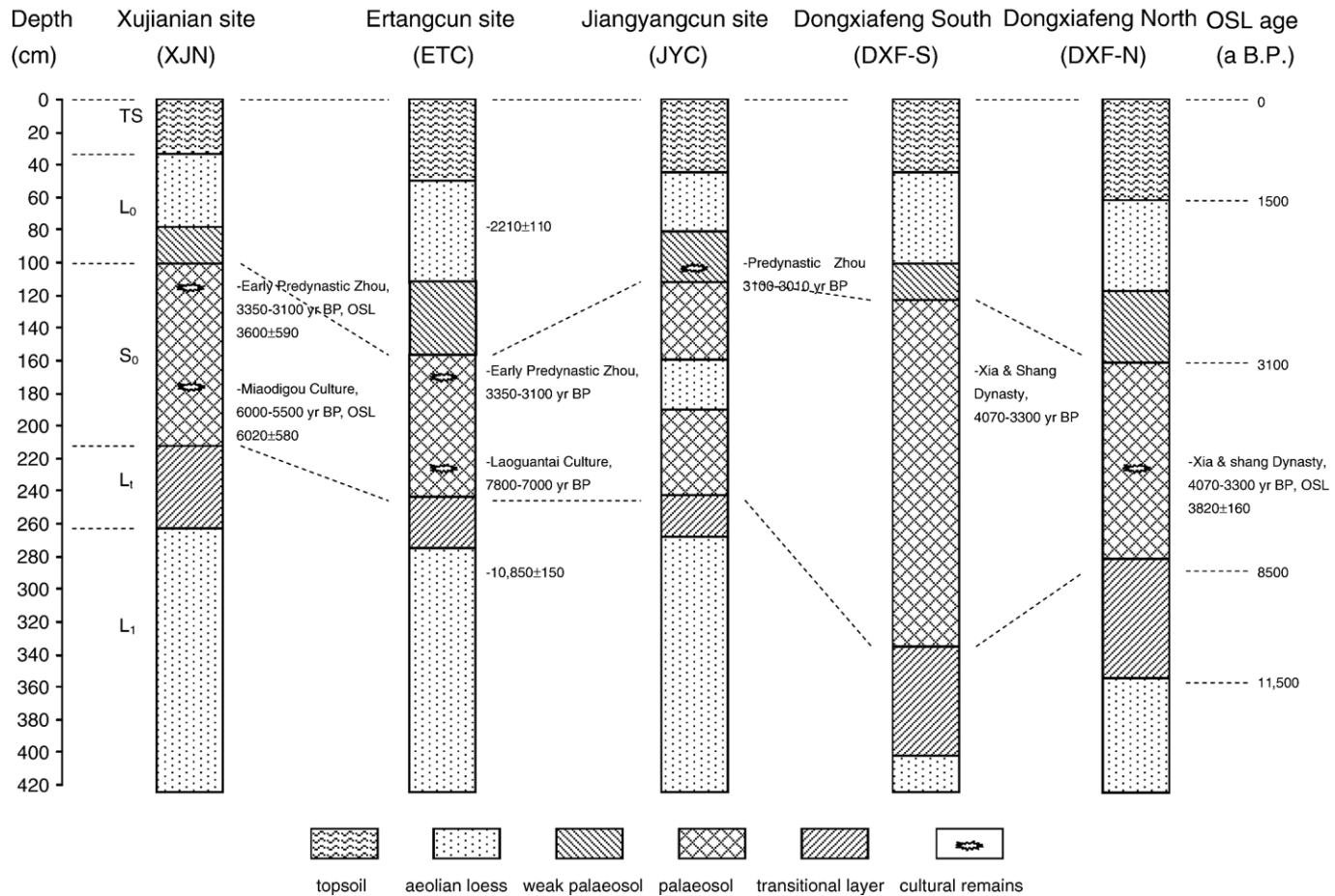


Fig. 2. Pedo-stratigraphic correlations of the five study Holocene loess–soil profiles in the southern part of the Loess Plateau, China. The chronological framework is based on OSL dating, archaeological identification of cultural remains, and pedo-stratigraphic correlations with other dated profiles.

the recent loess (L_0), and the loessial topsoil (TS) accumulated during the past 3100 years. An OSL date 2210 ± 110 years BP was obtained at a depth of 70–68 cm in the top part of the recent loess (Fig. 2). The age/depth curve in the ETC profile is shown in Fig. 3. The increased depositional rates in the top 150 cm of the profile may have been caused by rainwash adding to the accumulating dust because of intensified human land reclamation for arable farming since the Pre-dynastic Zhou.

In the Xujianian profile, the colored pottery of the Miaodigou Neolithic Culture (^{14}C dated to 6000–5500 cal. years BP; Institute of Archaeology, CASS, 1991) was retrieved at 180–170 cm and was OSL dated to 6020 ± 580 years BP. The rope-patterned grey pottery of the Siwa Nomadic Culture (^{14}C dated to 3350–2650 cal. years BP; Institute of Archaeology, CASS, 1991) was found at 120–100 cm and OSL dated to 3600 ± 590 years BP (Fig. 2). In the DXF-N profile at the Dongxiafeng site, the rope-patterned grey pottery of

the Xia Culture (^{14}C dated to 4070–3600 cal. years BP; Institute of Archaeology, CASS, 1991) was found at 240–230 cm and OSL dated to 3820 ± 160 years BP. In the JYC profile, cultural remains of the Pre-dynastic Zhou (3100–3010 cal. years BP) were identified at 110–80 cm. The formation of the Luvisols/Isohumisols (S_0) at the study sites is therefore considered to have occurred between 8500 and 3100 years BP.

5. Results and interpretations

In the Ertangcun (ETC), Jiangyangcun (JYC) and Xujianian (XJN) loess–soil profiles, total charcoal concentrations vary between 200 and 1200 grain g^{-1} with a few peaks exceeding 1200 grain g^{-1} (Figs. 4–6). Concentrations of small-sized charcoal ($<50\mu\text{m}$) vary between 200 and 1000 grain g^{-1} . This may indicate that regional fires occurred frequently during the late last glaciation and the Holocene. Concentrations of the large-sized charcoal ($>50\mu\text{m}$) vary between 30 and

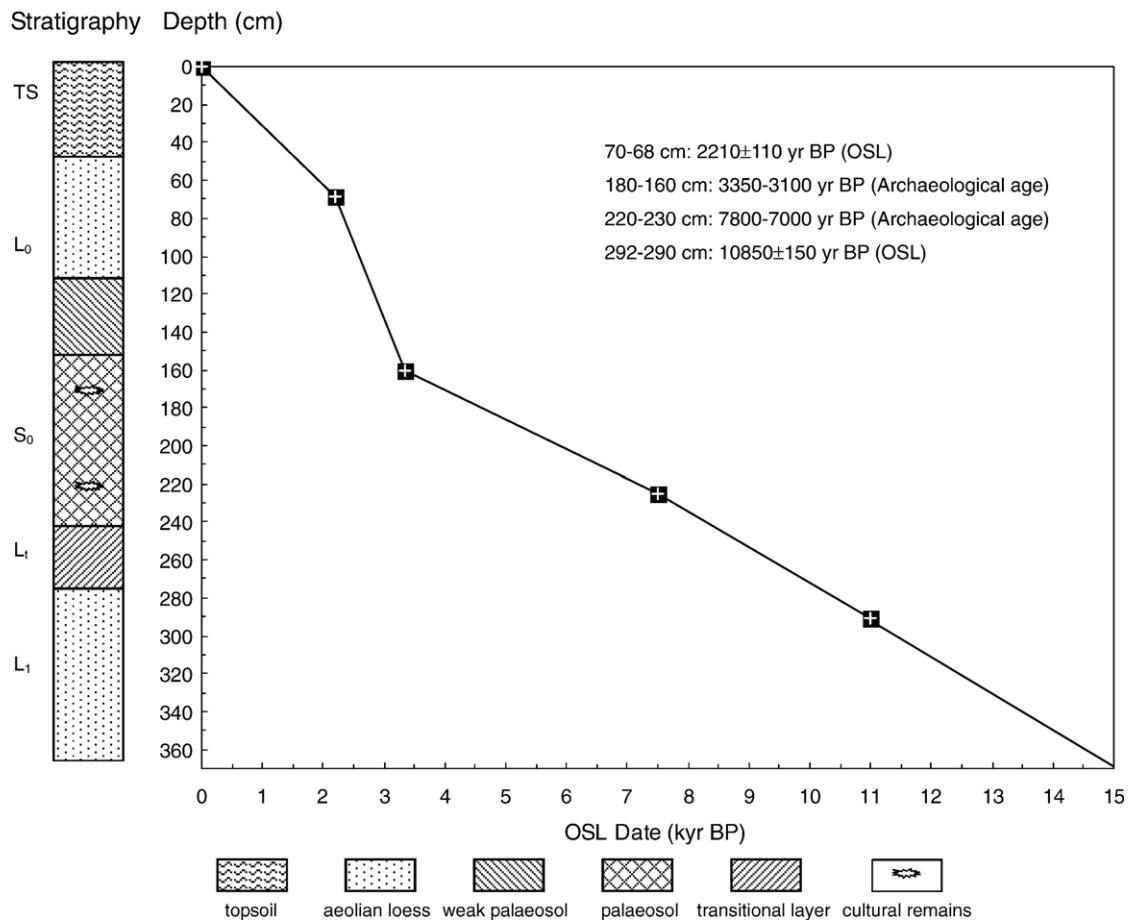


Fig. 3. Diagrams showing the stratigraphy and the age/depth curve in the Holocene loess–soil profile at the Ertangcun site (ETC) in the southern Loess Plateau of China.

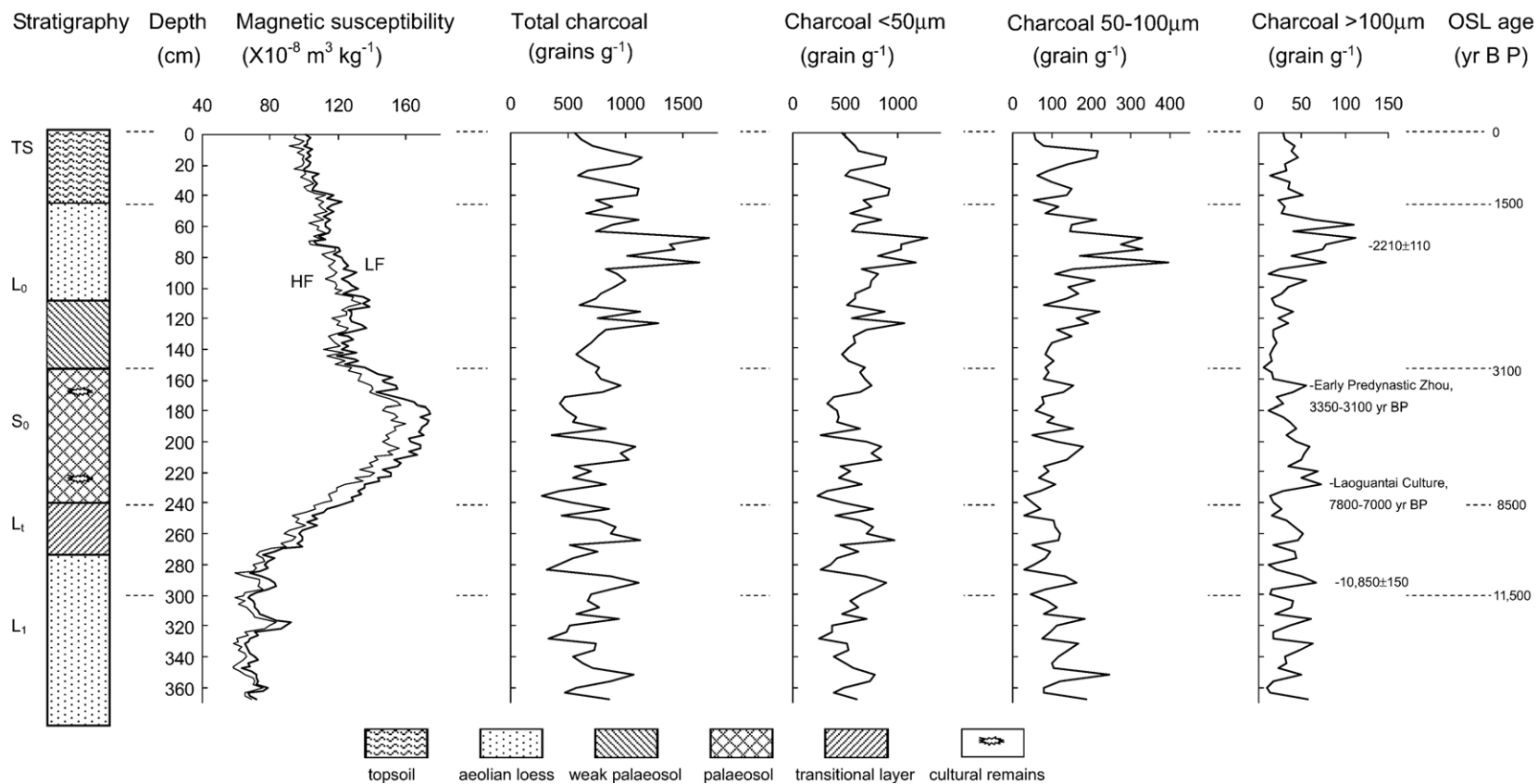


Fig. 4. Diagrams showing charcoal concentrations in the Holocene loess–soil profile at the Ertangcun site (ETC) in the southern Loess Plateau of China.

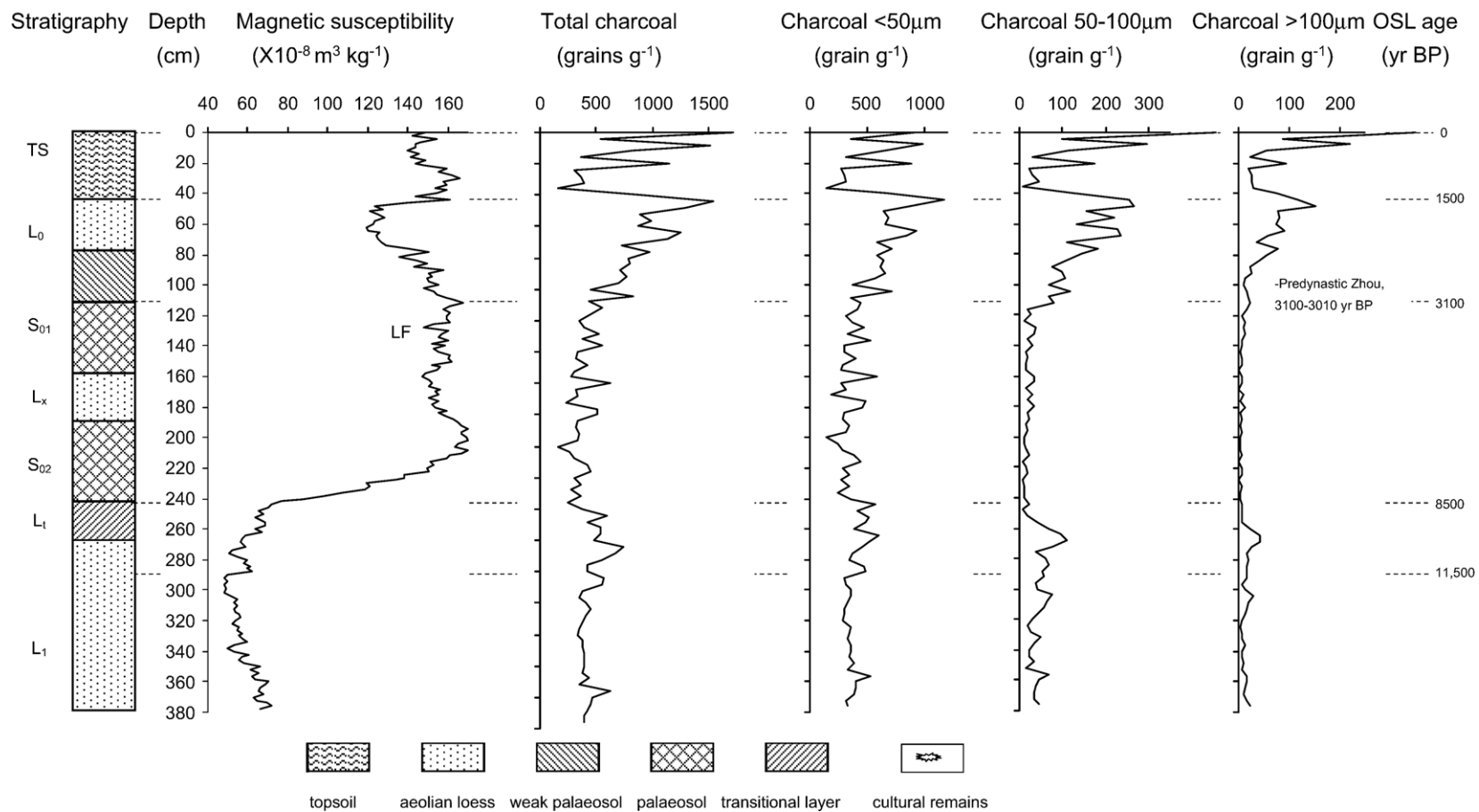


Fig. 5. Diagrams showing charcoal concentrations in the Holocene loess–soil profile at the Jiangyanguan site (JYC) in the southern Loess Plateau of China.

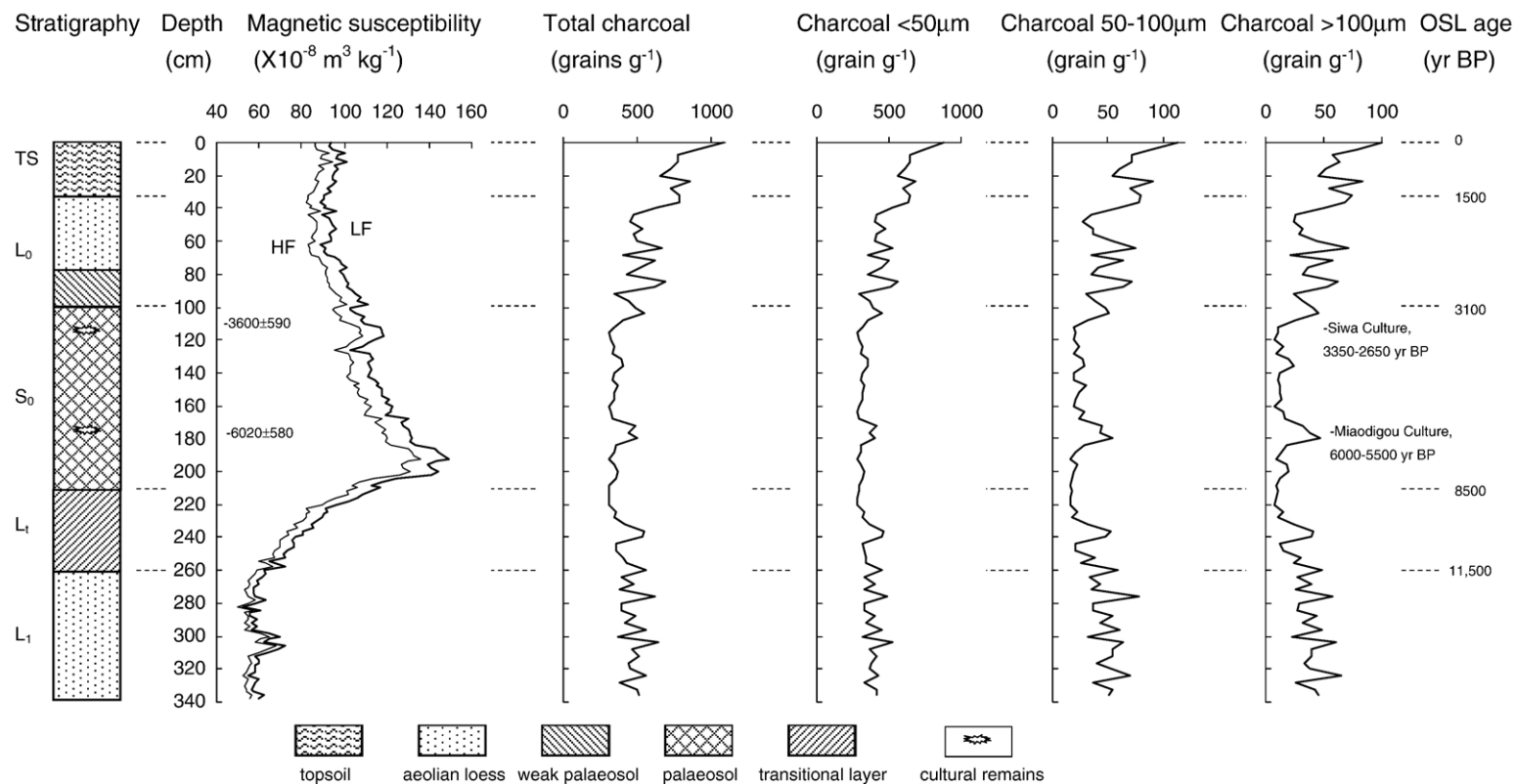


Fig. 6. Diagrams showing charcoal concentrations in the Holocene loess–soil profile at the Xujianian site (XJN) in the southern Loess Plateau of China.

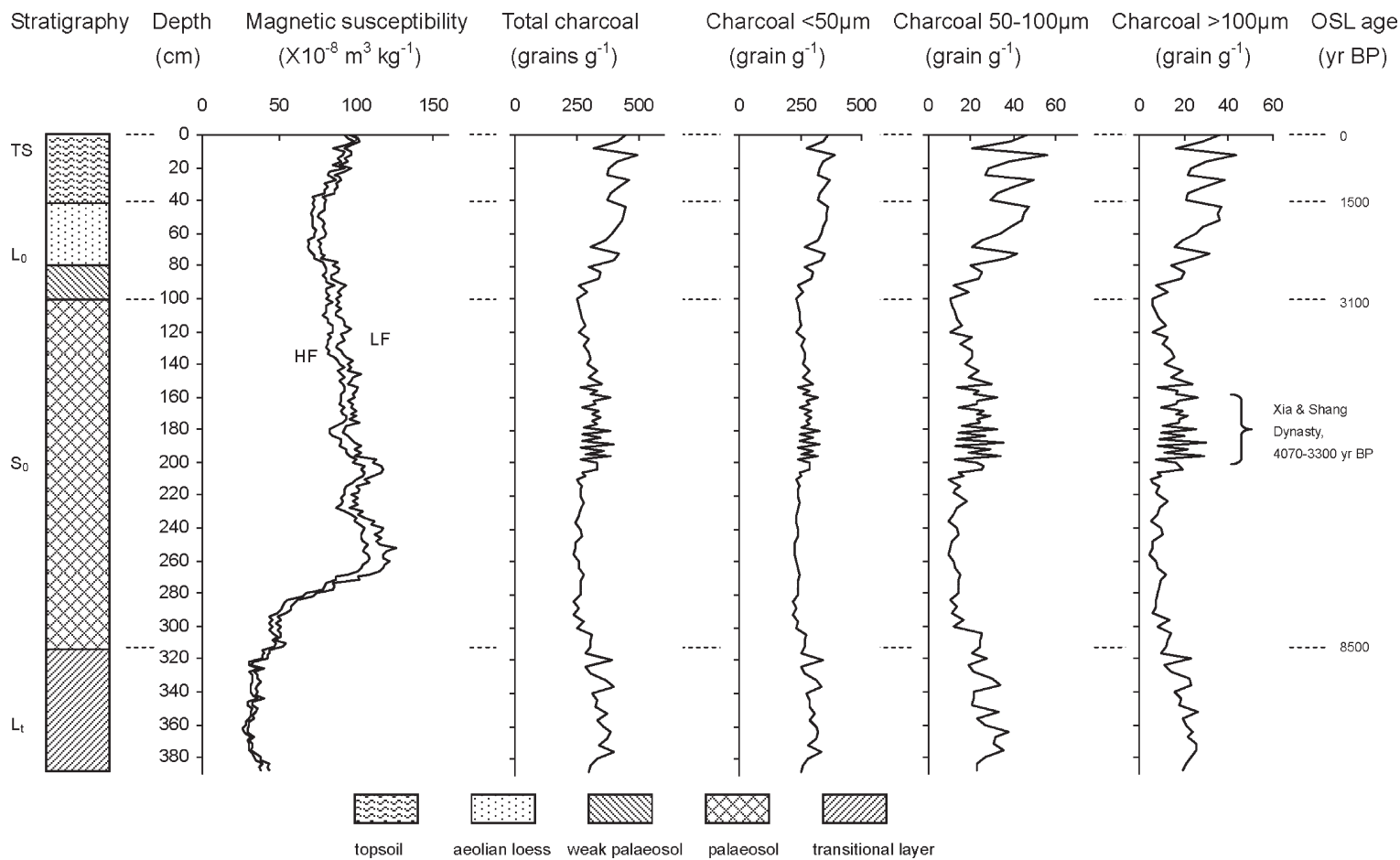


Fig. 7. Diagrams showing charcoal concentrations in the Holocene loess–soil profile at the Dongxiafeng South site (DXF-S) in the southern Loess Plateau of China.

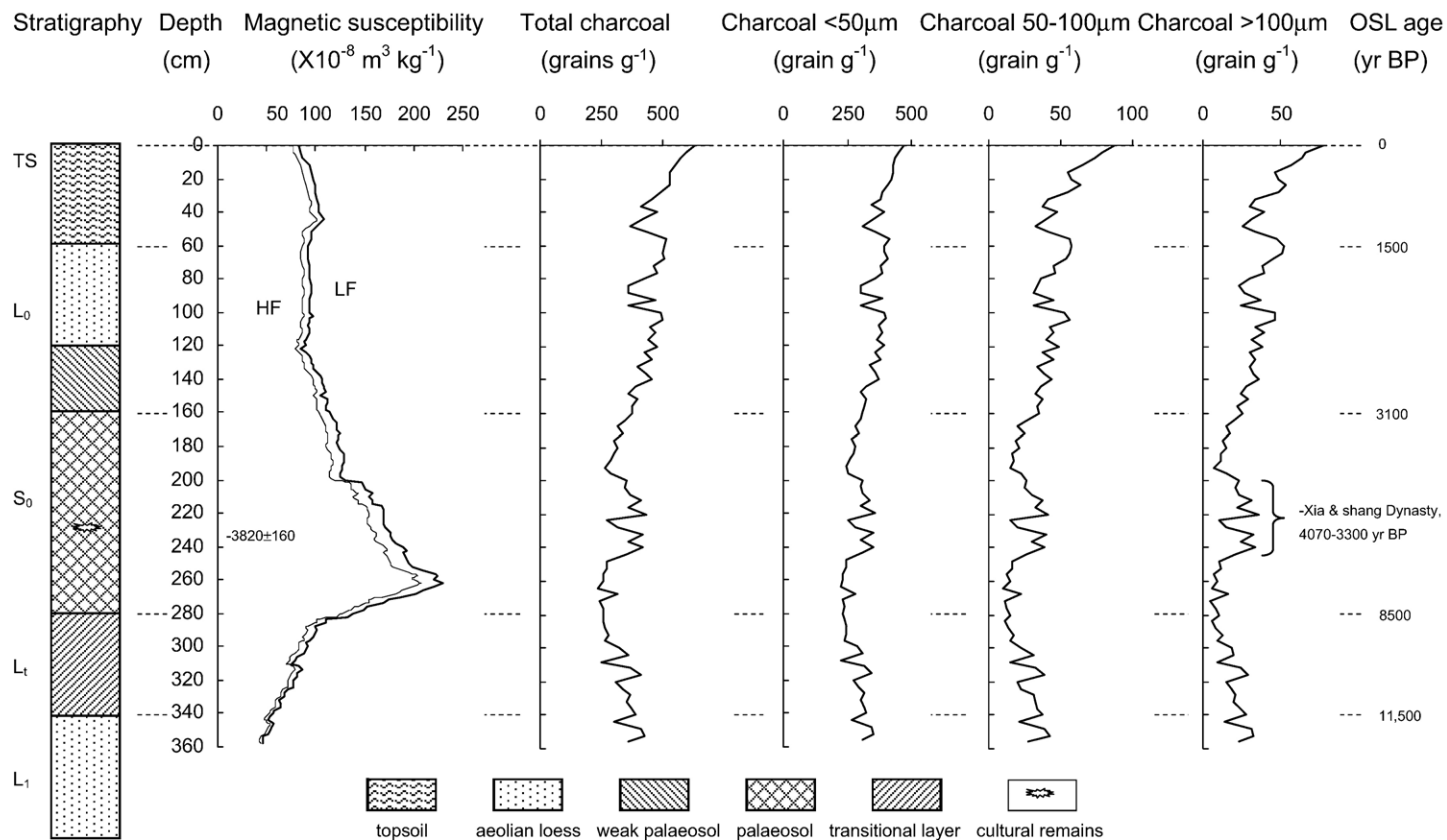


Fig. 8. Diagrams showing charcoal concentrations in the Holocene loess–soil profile at the Dongxiafeng North site (DXF-N) in the southern Loess Plateau of China.

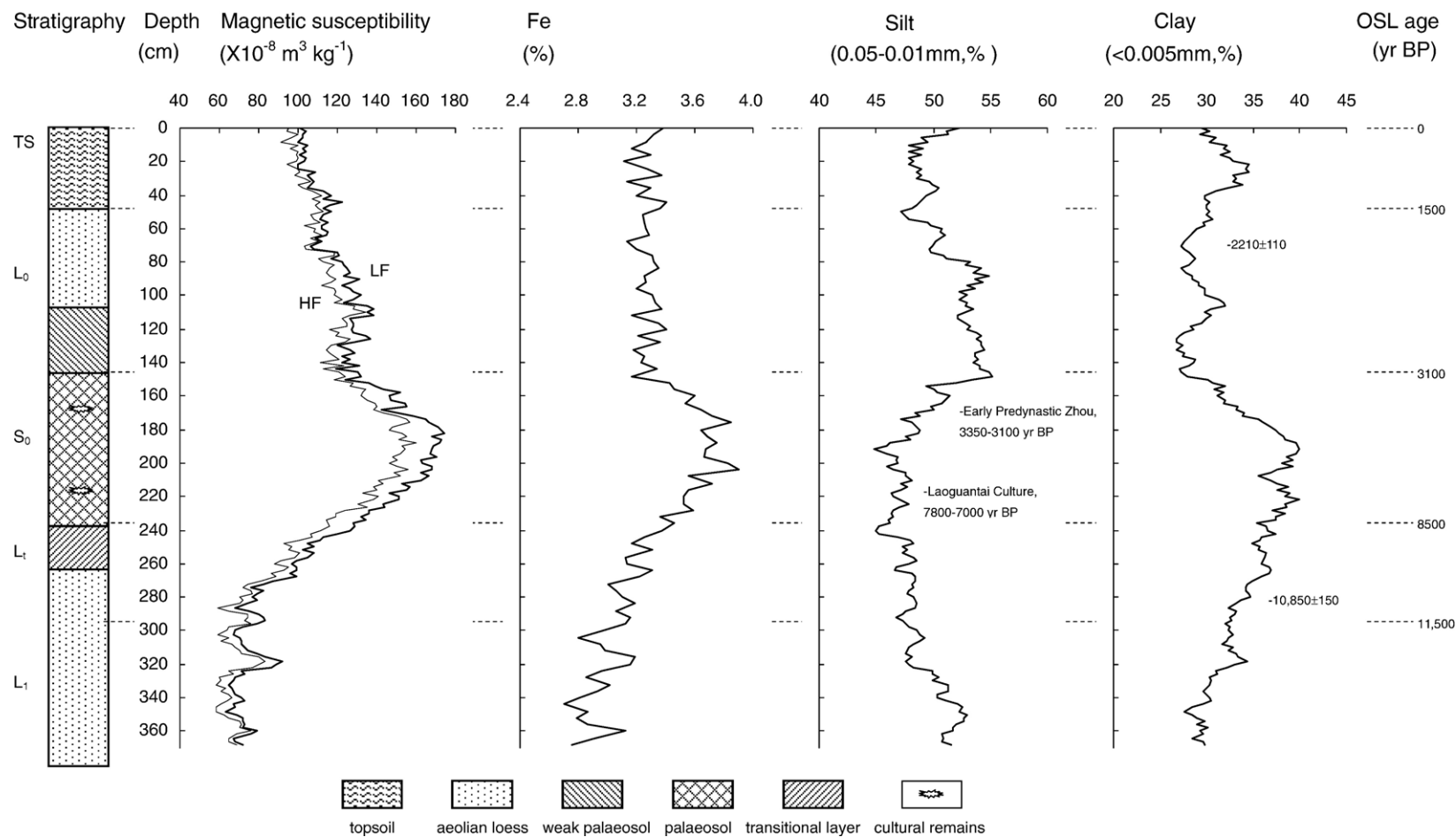


Fig. 9. Diagrams showing the magnetic susceptibility, total Fe, silt and clay contents in the Holocene loess–soil profile at the Ertangcun site (ETC) in the southern Loess Plateau of China.

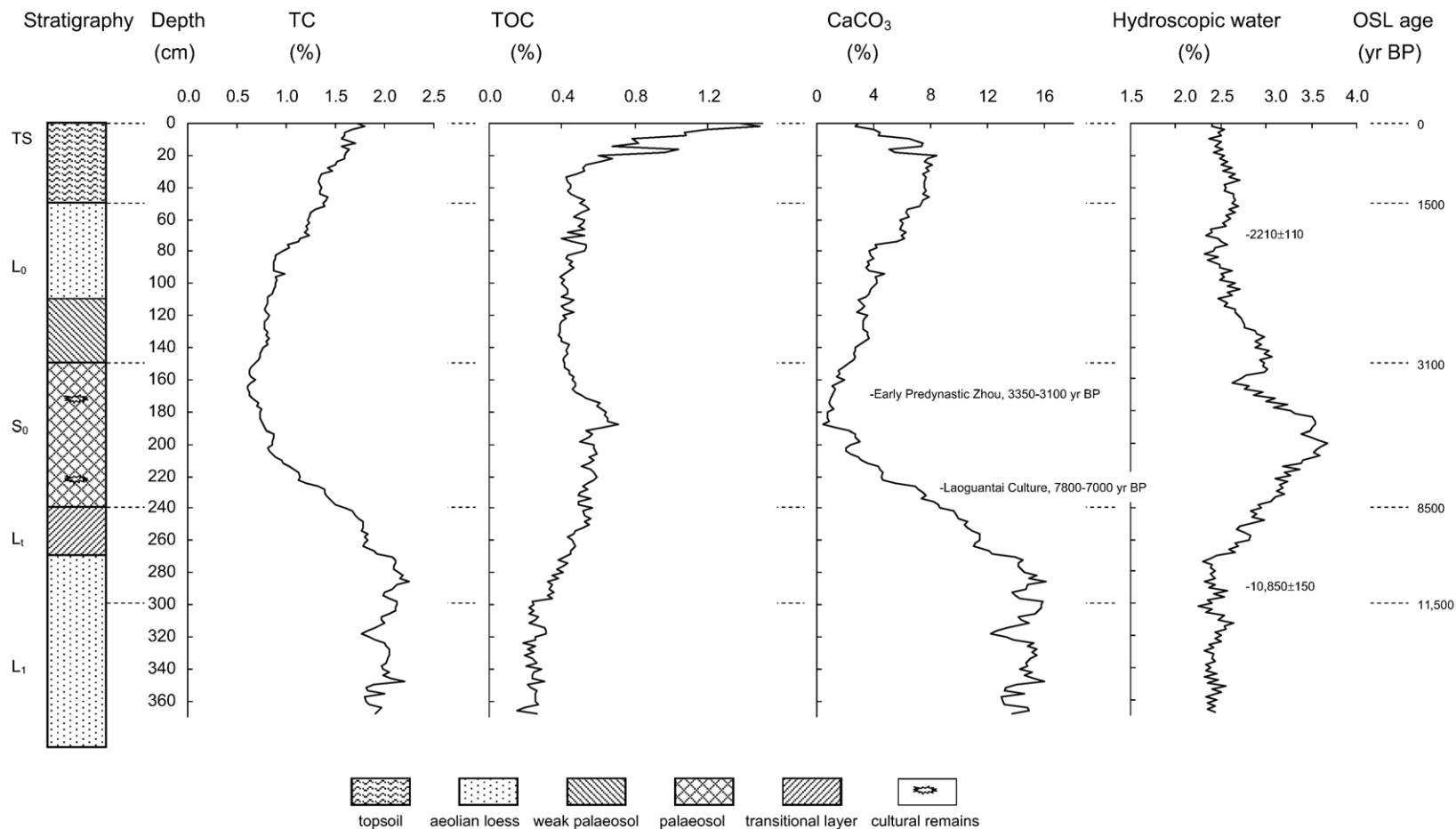


Fig. 10. Diagrams showing the total carbon (TC), total organic carbon (TOC), CaCO₃ and hydroscopic water contents in the Holocene loess–soil profile at the Ertangcun site (ETC) in the southern Loess Plateau of China.

450 grain g^{-1} , indicating that fire events have occurred locally. In the two profiles at the Dongxiafeng site (DXF-S/N), total charcoal concentrations vary between 200 and 500 grain g^{-1} in (Figs. 7 and 8). Concentrations of small-sized charcoal ($<50\mu m$) vary between 250 and 400 grain g^{-1} . Concentrations of large-sized charcoal ($>50\mu m$) vary between 20 and 100 grain g^{-1} . The charcoal concentrations in all of the five loess–soil profiles show a pattern of low concentrations in the mid-Holocene Luvisol/Isohumisol (S_0). In the Malan Loess (L_1) of the last glaciation and the transitional loess (L_t) of the early Holocene, charcoal concentration are higher, and the highest charcoal concentrations are present in the recent loess (L_0) and the loessial topsoil (TS) of the late Holocene.

Magnetic susceptibility is one of the most important climate proxies in the study of Chinese loess–palaeosol sequences (Kukla et al., 1988; Maher, 1998). It records the change in intensity of pedogenesis during dust accumulation, resulting predominantly from precipitation change related to monsoonal climatic variation (Maher, 1998). Magnetic susceptibility varies between 50 and $250 \times 10^{-8} m^3 kg^{-1}$ in the five study profiles (Figs. 4–8). Higher values ($120–250 \times 10^{-8} m^3 kg^{-1}$) are observed in the Luvisol/Isohumisol (S_0) of the Holocene climatic optimum, in contrast to the low values ($50–80 \times 10^{-8} m^3 kg^{-1}$) in the Malan Loess (L_1) of the last glaciation and the transitional loess (L_t) of the early Holocene. The values decrease to below $120 \times 10^{-8} m^3 kg^{-1}$ in the recent loess (L_0) and topsoil (TS) because of the climate aridity and intensified human disturbance by arable cultivation. It should be noted that in the topsoil (TS) of the Jiangyangcun profile (JYC) where recent human disturbance was minimum, magnetic susceptibility increased again ($>120 \times 10^{-8} m^3 kg^{-1}$).

Total iron (Fe) content is generally very low in the loess and soils formed in semi-arid and arid regions. Fe content is used to identify iron enrichment during pedogenic alteration of accumulated dust in the loess–palaeosol sequence. In the ETC profile, total Fe varies between 2.8% and 4.0% and shows a similar trend to magnetic susceptibility (Fig. 9). This suggests that both the dust accumulation and the pedogenic alteration to the accumulated dust occurred under an oxidization condition without water saturation.

Total organic carbon (TOC) content indicates variation in intensity of bio-pedogenesis during dust accumulation and soil formation throughout the profile. The highest TOC content in the topsoil in the ETC profile is caused by the presence of highly decomposable organic matter. High TOC values (0.4–0.6%) are present

in the Isohumisol (S_0) of the mid-Holocene and extremely low TOC values (0.2–0.3%) are found in the Malan Loess (L_1) of the last glaciation in the ETC profile (Fig. 10). Changes in hygroscopic water content are closely connected to changes in TOC and clay content in soil profile. In the ETC profile, hygroscopic water content varies between 2.4% and 3.7% with high values present in the Isohumisol (S_0) of the mid-Holocene (Fig. 10).

Carbonates in accumulated dust are highly soluble during pedogenesis. $CaCO_3$ content is therefore used to identify changes in precipitation and soil moisture during the dust accumulation and pedogenic alteration (Zhao, 2002). $CaCO_3$ content varies between 0.5% and 15% in the ETC profile, with lower values present in the Isohumisol (S_0) and higher values present in the loess levels (L_1 , L_t , L_0). Under the present climatic conditions and intensive arable cultivation, leaching has removed part of the $CaCO_3$ in the present topsoil (Fig. 10).

The content of coarser silt (0.05–0.01 mm) in the loess–soil sequence is generally used as an index illustrating the change in the strength of dust storms and dust-falls, and thus, of the northwestern continental monsoon. Clay fraction ($<0.005 mm$) is used to identify the changes in intensity of pedogenic alteration of accumulated dust in connection with soil moisture and precipitation brought by the southeastern maritime monsoon (Liu, 1988). In the ETC profile, coarser silt varies between 45% and 55% with high percentages present in the Malan Loess (L_1) and the recent Loess (L_0), and low percentages present in the mid-Holocene Heilusol (S_0). Clay content varies inversely between 25% and 40% in the ETC profile (Fig. 9).

6. Discussion and conclusions

Charcoal preserved in the Holocene loess–soil profiles at the study sites shows that wildfires have occurred throughout the later part of the last glaciation and the Holocene. Small-sized charcoal ($<50\mu m$) is recorded in both loess and palaeosol layers at the sites (Figs. 4–8). The small charcoal fragments are easily transported over long distances by wind in dry environments. The seasonality of modern wildfires suggests that most of the fires occur during March, April and May over the Inner Mongolia steppe when northwest winds are very strong (Fig. 11A; Yue et al., 1999; Guo et al., 2003). The record of modern dust storms shows that most of the strong dust storms occur during March to May when the northwest continental monsoon is extremely active and surface soil is arid and loose after a cold-dry winter over the Inner Mongolian

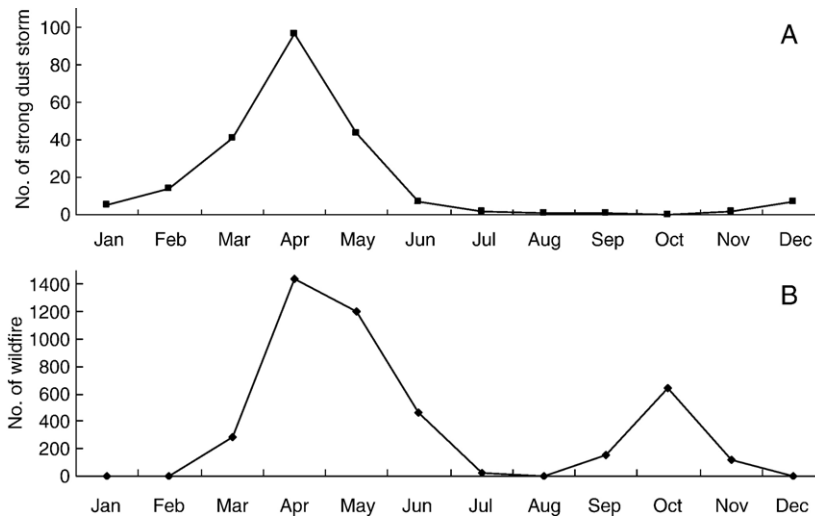


Fig. 11. Diagrams showing (A) the monthly occurrence of strong dust storms in Northern China during 1954–2002 (data from Zhou, 2003); (B) the monthly occurrence of grassland and forest fires in the Inner Mongolian during 1981–2000 (data from Guo, 2003).

steppe and the Loess Plateau (Fig. 11B; Natsagdorj et al., 2003; Zhou and Zhang, 2003). The small-sized ($<50\mu\text{m}$) charcoal produced by wildfires over the Inner Mongolian steppe and the northern Loess Plateau may have been resuspended and transported hundreds of kilometers southeastward with silt-sized dust ($50\text{--}10\mu\text{m}$), and deposited in the southern part of the Loess Plateau. In the study profiles, part of the small charcoal component may have deposited from atmospheric fall-out together with the eolian dust sourced from the north and northwestern steppes. This implies that regional wildfires may have always occurred over the northern Loess Plateau and the neighboring inner Mongolian Plateau during both the late last glaciation and the Holocene. The decreased concentrations of the small-sized charcoal in the mid-Holocene Luvisol/Isohumisol (S_0) indicate that during the Holocene climatic optimum, regional wildfire was reduced greatly (Figs. 4–8). On the other hand, the occurrence of local fire events recorded by large-sized charcoal ($>50\mu\text{m}$) shows different temporal patterns during the late last glaciation and the Holocene period.

6.1. Frequently occurring wildfires during the late last glaciation and early Holocene

High concentrations of large-sized charcoal ($>50\mu\text{m}$) are present in the Malan Loess (L_1) and the transitional loess (L_t) at the study sites, demonstrating that local fires occurred frequently before 8500 years BP (Figs. 4–8). Climatic proxies from the Malan Loess (L_1) and the transitional loess (L_t) at the ETC site indicate that the climate was dry-cold during those periods. Very

high carbonate content (12–16%) and low hygroscopic water content (2.3–2.5%) show that the soil was dry and the water-soluble components were retained in the topsoil (Fig. 10). High coarse silt content (47–53%) indicates that dust storms were intensive, as was the northwestern monsoon (Fig. 9). Magnetic susceptibility is very low ($50\text{--}80 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$) in all of the study profiles and is exactly comparable to that in the loessial topsoil in the modern Russian steppe where annual precipitation is ca. 350–450 mm (Maher et al., 2002). Low TOC (0.2–0.3%), total Fe (2.8–3.2%) and clay content (28–34%) show that bio-pedogenic alteration of the accumulated dust was minimal because of the lack of soil moisture and rainfall, as well as vegetative cover (Figs. 9 and 10). Previous investigations show that fossil pollen and spores are scarce in the Malan Loess (L_1), and about 80–90% of countable pollen in it is Compositae, *Artemisia*, *Chenopodium*, Gramineae and Leguminosae (Sun and Zhao, 1991; Zhao and Huang, 1999; Zhao, 2002). This is comparable to the modern surface pollen spectrum in the southern part of the Inner Mongolia steppe (Zhou, 1984; Sun and Zhao, 1991). It can be inferred that steppe vegetation developed over the Loess Plateau during the late last glaciation and the early Holocene. This result implies that the Asian steppe expanded south over the Loess Plateau. Archaeological records indicate a lack of human activities in the southern Loess Plateau during the late last glaciation and the early Holocene. Therefore, the frequent steppe fires recorded by large-sized charcoal before 8500 years BP must have occurred naturally from the Inner Mongolian Plateau through to the Loess Plateau.

6.2. Localized human fires during the mid-Holocene

Theoretically, it is not possible to identify human-ignited fires from naturally ignited wildfires at a site with charcoal concentration data alone. Charcoal records of mid-Holocene fire patterns differ among the study sites. At the JYC site without the Neolithic cultural remains found in the vicinity and minimum human disturbance, the concentration of large-sized charcoal decreased to very low values in the palaeosol (S_0) of the Holocene climatic optimum (Fig. 5). Therefore, it can be inferred that natural local fire was infrequent at the YJC site during the Holocene climatic optimum between 8500 years BP and 3100 years BP.

The mid-Holocene palaeosol (S_0) was identified as mature Luvisols <1000 m asl in the valley, and Isohumisols >1000 m asl on top of the plateau, from which the proxies suggest that the climate was relatively warm and humid during the mid-Holocene. The very low CaCO_3 content (<2.0%, mostly the illuviation from overlying recent loess L_0 accumulated after 3100 years BP) and high hygroscopic water content (>3.0%) show that soil moisture and precipitation levels were high, and the solutes released by weathering were removed by leaching during the soil (S_0) formation between 8500 years BP and 3100 years BP (Fig. 10). The decreased silt content and accumulation rate indicate that the intensity of dust storms was reduced, and as was the intensity of the northwestern continental monsoon. The highest magnetic susceptibility ($120\text{--}250 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$), total Fe (3.4–3.8%), clay (35–40%) and TOC (>0.5%) show that bio-pedogenic alteration of the accumulating dust was very strong because of increased precipitation, soil moisture and vegetation cover during the Holocene climatic optimum (Figs. 9 and 10). Taxa recorded include *Pinus*, *Quercus*, *Ulmus*, *Tilia*, *Acer*, *Rhus*, with *Artemisia*, Compositae, *Chenopodium* in the pollen spectrum in the palaeosol S_0 over the southern Loess Plateau (Sun and Zhao, 1991; Zhao and Huang, 1999; Zhao, 2002), which suggests that a mixed forest and forest-steppe landscape developed during the formation of the Luvisol/Isohumisol (S_0) during this period. Compared to modern temporal and spatial fire patterns over the Inner Mongolia Plateau (Yue, et al., 1999; Guo et al., 2003), the mid-Holocene climatic conditions were not conducive to wildfires. The low concentration of large-size charcoal in the palaeosol (S_0) in the JYC profile (Fig. 5) suggests infrequent fires in a forest or forest steppe landscape under a warm-humid Holocene climatic optimum between 8500 years BP and 3100 years BP. At the other four sites, several large peaks are seen in the amount of large-sized charcoal in

the palaeosol (S_0) although the charcoal concentrations are generally low (Figs. 4, 6–8). These peak values of large-sized charcoal are observed at different levels in the palaeosol (S_0). The fires may have occurred at different times between 8500 years BP and 3100 years BP. At these four study sites, there are several archaeological sites within a radius of 3 km of them and they are well ^{14}C dated (Institute of Archaeology, CASS, 1991). This suggests the charcoal could be anthropogenic in origin.

For example, at the Dongxiafeng site, the DXF-N profile is situated at the center of the archaeological site of the Xia and Shang Culture (4070–3300 cal. years BP; Institute of Archaeology, CASS, 1991). The rope-patterned grey pottery of the Xia Culture was found at depth of 240–230 cm in the soil (S_0) and OSL dated to 3820 ± 160 years BP. At 240–200 cm in the DXF-N profile, peak concentrations of larger-sized charcoal are found (Fig. 8), which are believed to be a record of human fires during the period 4070–3300 years BP. In the DXF-S profile that is situated outside the archaeological site, and without noticeable cultural remains, comparable charcoal peaks are observed at 200–140 cm in the soil (S_0). These charcoals suggest that human fires did occur here during the period 4070–3300 years BP (Fig. 7).

Similarly, in the ETC profile which is situated a few kilometers from the Xiamengcun archaeological site, the large-sized charcoal peaks are found at 230–200 cm and 170–160 cm (Fig. 4). It is inferred that they are records of human fires that occurred during 7800–5500 cal. years BP, and 3350–3100 cal. years BP of the Laoguantai Neolithic Culture (7800–7000 cal. years BP), the Banpo and the Miaodigou periods of the Yangshao Neolithic Culture (7000–6000 and 6000–5500 cal. years BP) and the Pre-dynastic Zhou (3350–3100 cal. years BP). Fire must have been used for forest clearance for millet cultivation during the Neolithic and the early Bronze Age at the ETC site.

In the XJN profile which is situated near the archaeological site of the Siwa Nomadic Culture (3350–2650 cal. years BP), the charcoal peaks at 180–170 cm and 120–60 cm are most likely records of human fires occurring during the periods of 6000–5500 cal. years BP and 3350–2650 cal. years BP and assigned to the Miaodigou Period of the Yangshao Neolithic Culture, and the Siwa Nomadic Culture, respectively (Fig. 6).

During the mid-Holocene climatic optimum, the mixed forest or forest-steppe vegetation may have produced more fuel than the steppe vegetation prior to it, while the increased precipitation and soil moisture may

have caused an increase in fuel moisture under the vegetative cover. Therefore, natural wildfires were less common and human fires occurred in localized areas over the southern Loess Plateau.

6.3. Widespread biomass burning during the late Holocene

Very high concentrations of large-sized charcoal were found in the loess (L_0) and the topsoil (TS) accumulated during the late Holocene at the study sites (Figs. 4–8). It suggests that local biomass burning was very high during the last 3100 years. Judging from the charcoal records and regional land-use history, human-set fires were more common than the natural fires during the late Holocene.

Field observations show that the formation of palaeosol (S_0) was interrupted and replaced by the accumulation of the recent loess (L_0) and topsoil (TS) approximately 100–160 cm thick at the study sites from 3100 years BP (Fig. 2). The increased CaCO_3 (4–8%) and decreased hygroscopic water content (2.3–2.7%) in L_0 and TS in the ETC profile indicate reduced soil moisture caused by decreased precipitation (Fig. 10). Increased silt content (51–55%) shows intensified dust storms and northwestern continental monsoon. Decreased magnetic susceptibility ($100\text{--}120 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$), total Fe content (3.1–3.4%) and TOC (0.4–0.5%) indicate reduced pedogenic alteration of the accumulating dust (Figs. 9 and 10). This pedogenic change resulted from a widespread climatic aridity over the Loess Plateau (Huang et al. 2004; Sun and Zhao, 1991). The pollen data show that *Pinus*, *Betula*, *Quercus*, *Ulmus*, and *Salix* are present in the Chenopodium–Artemisia–Compositae–Cruciferae-dominated pollen spectrum in the recent loess L_0 over the southern Loess Plateau (Sun and Zhao, 1991; Zhao and Huang, 1999; Zhao, 2002) indicating that the vegetation had changed to a forest steppe by the late Holocene.

In China, agricultural land-use becomes more and more important after ca. 3000 years ago over the southern Loess Plateau (Shi, 2001). The accumulation rate of the recent loess (L_0) and topsoil (TS) is far greater than that of the Malan Loess (L_1) of the last glaciation in the study profiles (Fig. 3). This probably resulted from the addition of erosion-derived materials from intensifying human disturbance in the landscape by burning and land reclamation for cereal cultivation. Therefore, frequent biomass burning occurred during the last 3100 years when climate became more arid and land reclamation for arable cultivation intensified.

Charcoal concentrations show an increasing trend in loess (L_0) and topsoil (TS) in the DXF-S/N and XJN profiles (Figs. 6–8). It seems the intensity of human disturbance by fire and cultivation increased continuously at these two sites during the last 3100 years. However, in the ETC and JYC profiles, charcoal concentrations increase to their highest in L_0 that accumulated during the period 3100–1500 years BP, but decrease in the topsoil accumulated from 1500 years BP onward (Figs. 4 and 5). This suggests that the period of the late Bronze Age and the early Iron Age (3100–1500 years BP) was the time of greatly increased biomass burning for land reclamation for arable farming. Apparently by the Sui Dynasty (ca. 581–618 A.D.), all of the cultivable land had been reclaimed and the agricultural landscape had already been fully established at the JYC and ETC sites. Thereafter, human burning of the vegetation was reduced largely. The extremely high concentration of large-sized charcoal in the present ploughed layer at DXF, JYC and XJN sites has resulted from the burning of wheat and maize stalks in fields after harvest since the 1990s, when villagers replaced the stalks with coal as cooking and heating fuel.

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