Middle Miocene Charcoal Record in the Wushan Basin, Northeastern Margin of the Tibetan Plateau, and Its Paleoclimatic Significance (Postprint)

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Abstract

Fire is an important factor in ecosystems and a significant indicator reflecting paleoclimate and environmental changes. Therefore, reconstructing fire activity history can help us understand past climate change and the mechanisms of fire activity; however, there is currently a significant lack of research on high-resolution fire activity records from the Miocene period on a global scale. Charcoal has been proven to be an effective proxy indicator for reconstructing fire activity history. Based on high-resolution charcoal records from the Middle Miocene in the Wushan Basin on the northeastern margin of the Tibetan Plateau, we reconstructed the natural fire activity history of the study area and, combined with existing data, explored the relationship between fire-vegetation-climate and the response of fire activity in the study area to global changes. The results show: (1) During the period of 15.30~13.60 Ma, the total charcoal concentration ranged from 59~4324 particles $\cdot$ g^{-1}, with an average concentration of 835 particles $\cdot$ g^{-1}. The charcoal particles are predominantly sub-rounded in shape, and almost all charcoal particle sizes are less than 50 m, reflecting that natural fire activity in the study area was dominated by forest fires burning arboreal plants, mainly regional fire activity. Based on the variation trend of total charcoal concentration, the natural fire activity history of the study area is divided into two main stages. Stage I (15.30~14.00 Ma): The total charcoal concentration gradually increased, with an average concentration of 866 particles $\cdot$ g^{-1}. Among them, Stage I can be further subdivided into three sub-stages: Stage Ia (15.30~14.38 Ma): The total charcoal concentration was the lowest, with an average concentration of 693 particles $\cdot$ g^{-1}; Stage Ib (14.38~14.20 Ma): The total charcoal concentration rapidly decreased, with an average concentration of 1140 particles $\cdot$ g^{-1}; Stage Ic (14.20~14.00 Ma): The total charcoal concentration sharply increased, with an average concentration of 988 particles · g^{-1}. Stage II (14.00~13.60 Ma): The total charcoal concentration sharply decreased, with an average concentration of 777 particles · g^{-1}. (2) The vegetation and climate change results reconstructed from pollen data for the study area show that during 15.30~14.38 Ma, the vegetation was open forest with low humidity; during 14.38~14.00 Ma, arboreal plants increased and humidity increased; during 14.00~13.60 Ma, arboreal species significantly decreased and humidity decreased. (3) Through comparative analysis, the variation trend of total charcoal concentration is similar to the trend of arboreal pollen percentage, and the trend of sub-rounded charcoal concentration is significantly positively correlated with the percentage trend of broadleaf plant pollen. It is concluded that natural fire activity in the Wushan Basin during the Middle Miocene had a strong connection with forest vegetation coverage (especially broadleaf forest coverage), and charcoal concentration was high during periods of warm and humid climate. In addition, by comparing the trend of total charcoal concentration with changes in deep-sea benthic foraminiferal oxygen isotopes, it can be inferred that global temperature changes may have had an important impact on natural fire activity by influencing vegetation changes in the study area.

Full Text

Charcoal Records from the Middle Miocene in the Wushan Basin, Northeastern Margin of the Tibetan Plateau and Their Paleoclimatic Significance

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Abstract: Fire is a critical component of ecosystem dynamics and serves as an important indicator of paleoclimatic and paleoenvironmental change. Reconstructing fire history can thus enhance our understanding of past climate variability and the mechanisms governing fire activity. However, high-resolution fire records from the Miocene remain scarce globally. Charcoal has proven to be an effective proxy for reconstructing fire history. Based on high-resolution charcoal records from the Middle Miocene in the Wushan Basin on the northeastern margin of the Tibetan Plateau, we reconstruct the natural fire history of the study area and explore the relationship between fire activity and climate, as well as the response of regional fire regimes to global change. Results show that: (1) Total micro-charcoal concentration varies from 59 to 4324 grains g^{-1}, with sub-round particles dominating and almost all charcoal fragments smaller than 50 m, indicating that fire activity in the study area was dominated by regional forest fires fueled by woody plants. Based on trends in total charcoal concentration, the fire history can be divided into two main phases. Phase I (15.30-14.00 Ma) shows a gradual increase in total charcoal concentration, averaging 866 grains g^{-1}, and can be further subdivided into two sub-phases: 15.30-14.38 Ma with relatively low average concentration (685 grains g^{-1}), and 14.38-14.20 Ma with a sharp increase (average 1940 grains g^{-1}). Phase II (14.00-13.60 Ma) is characterized by a rapid decrease in total charcoal concentration, averaging 777 grains g^{-1}, and can be subdivided into 14.20-14.00 Ma (gradual increase, average 1295 grains g^{-1}) and 14.00-13.60 Ma (sharp decrease, average 271 grains g^{-1}). (2) Pollen-based vegetation and climate reconstructions indicate open forest vegetation with low humidity during 15.30-14.38 Ma, increasing tree cover and humidity during 14.38-14.00 Ma, and a significant reduction in both tree cover and humidity during 14.00-13.60 Ma. (3) Comparison of charcoal and pollen data reveals that total charcoal concentration trends closely match arboreal pollen percentages, while sub-round charcoal concentration correlates significantly with broadleaf pollen percentages. This suggests that Middle Miocene fire activity in the Wushan Basin was strongly linked to forest coverage, particularly broadleaf forest extent, with higher charcoal concentrations occurring during warm, humid periods. Furthermore, comparison of total charcoal concentration trends with deep-sea benthic foraminiferal $\delta^{18}O$ records suggests that global temperature changes may have influenced regional fire activity indirectly through effects on vegetation dynamics.

Keywords: Wushan Basin; Middle Miocene; charcoal; natural fire; paleoclimate

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Fire is an important factor in Earth' s ecosystems and is influenced by climatic and environmental changes. Natural fire activity during the Cenozoic is considered a key factor affecting modern vegetation and climate, and thus serves as an important indicator of climate change [1, 4, 10-11]. Charcoal is produced through incomplete combustion or pyrolysis of plant tissues and is transported by wind and water into sediments, where it can be preserved continuously. Charcoal concentration has been proven to be an effective proxy for fire activity intensity (e.g., burned area) [4, 10-11], particle size can reflect the distance and extent of fire activity [13, 33], and morphology can indicate the type of vegetation burned (herbaceous vs. woody) [14, 41]. Therefore, charcoal provides a basis for studying fire history [1, 16-17, 32] and the drivers of fire evolution, as well as climate and environmental change [11, 14, 16-17].

Currently, domestic research has focused on charcoal extraction from Holocene marine [7, 23-25] and loess [6, 26-27] deposits, using charcoal concentration and flux to reconstruct fire history and exploring relationships between fire, vegetation, human activity, and climate-environmental change in combination with proxies such as pollen, grain size, and magnetic susceptibility [28-31]. However, high-resolution fire records from earlier geological periods are lacking [1, 31-33], particularly for natural fire history and mechanisms in China' s inland regions.

This study selected the Nanyu section in the Wushan Basin on the northeastern margin of the Tibetan Plateau, which has high-resolution paleomagnetic age control [36, 38], to investigate high-resolution charcoal records from the Middle Miocene climate transition period [34, 36, 38]. We reconstructed the natural fire history of the Wushan Basin during the Middle Miocene and explored the evolution of fire activity mechanisms and responses to climate, environmental, and global changes.

1 Study Area and Profile Characteristics

Geomorphologically, the Wushan Basin is located on the northeastern margin of the Tibetan Plateau, in the western part of the Tianshui Basin, as a secondary basin of the Longzhong Basin, situated on the West Qinling fault zone in eastern Gansu Province (Fig. 1). Climatically, it lies at the intersection of the Tibetan Plateau alpine region, northwest inland arid region, and eastern monsoon region, at the apex of the "monsoon triangle," making it highly sensitive to climate change. The modern climate is temperate continental semi-arid and semi-humid monsoon climate, with cold but not severe winters, hot but not extreme summers, and distinct seasons. Annual average precipitation is 500 mm, with mean annual temperature of 9.6°C; rainfall is concentrated in summer. The main vegetation zones include coniferous and broadleaf mixed forest, mountain meadow, steppe, and dry steppe [34, 36-38].

The Nanyu section (104.9°E, 34.7°N) is located about 15 km south of Wushan County, at an altitude of 1809 m, with a section thickness of 171 m and an age range of 15.30-13.60 Ma (Megaannus/Million years) (Fig. 1). Previous lithological and sedimentary facies studies show that lacustrine deposits are mainly distributed in the 0–80 m depth interval, consisting of gray-green marl, brown-red mudstone, and brown siltstone, occasionally with gray-green sandstone; the 127–158 m depth interval consists mainly of floodplain deposits composed of siltstone, mudstone, and fine sandstone with calcareous concretions; and the 158–171 m depth interval is primarily fluvial deposits (Fig. 2).

2 Materials and Methods

We extracted charcoal from 103 samples using pollen extraction methods. First, a known quantity of Lycopodium spores (approximately 27,600 grains per tablet) was added to each sample to determine charcoal concentration [32, 39]. Samples were then treated with 10% hydrochloric acid (HCl) and 40% hydrofluoric acid (HF) to remove carbonates and silicates, followed by ultrasonic washing with a 10 m sieve to remove impurities [40]. Charcoal and pollen were extracted using heavy liquid (specific gravity 2.0–2.2), and processed samples were stored in 10 ml colorimetric tubes. Glycerin was added to prepared samples for slide preparation, and identification, counting, and photography were performed under a microscope. All samples were analyzed for charcoal and Lycopodium spores under a Leica DM 2000 optical microscope. Charcoal concentration was calculated using the following formula:

$$N_x/B_x \times 27600/W_x$$

where N_x is the micro-charcoal concentration (grains g^{-1}), N_x is the number of micro-charcoal particles counted, B_x is the number of Lycopodium spores counted, W_x is the sample weight (g), and x is the sample number.

Charcoal particles were classified by calculating the ratio of long axis to short axis. Particles with a ratio greater than 2.5 were classified as sub-long, and those with a ratio less than 2.5 as sub-round [1, 32-33]. Based on long-axis length, charcoal was divided into three size classes: <50 m, 50–100 m, and >100 m [13, 33]. To ensure data stability, each sample had more than 300 charcoal particles counted [41], and identified charcoal was photographed under a Leica DM5500B microscope (Fig. 3).

3 Results and Analysis

Overall, sub-round charcoal dominates, with average concentrations about 10 times higher than sub-long charcoal. In terms of particle size, charcoal <50 m forms the main component, with average concentrations several times higher than other size classes.

Phase I (15.30-14.00 Ma, 58 samples): In this phase, sub-round charcoal concentration ranges from 42 to 3591 grains g^{-1} (average 794 grains g^{-1}), sub-long charcoal from 2 to 732 grains g^{-1} (average 72 grains g^{-1}), and total charcoal from 60 to 4324 grains g^{-1} (average 866 grains g^{-1}). This phase can be subdivided into two sub-phases:

- **Sub-phase 1a (15.30-14.38 Ma, 35 samples):** Sub-round charcoal concentration ranges from 42 to 1940 grains g^{-1} (average 623 grains g^{-1}), sub-long charcoal from 2 to 732 grains g^{-1} (average 62 grains g^{-1}), and total charcoal from 60 to 2602 grains g^{-1} (average 685 grains g^{-1}). During this period, total charcoal, sub-round, and sub-long concentrations all gradually increase.
- **Sub-phase 1b (14.38-14.20 Ma, 23 samples):** Sub-round charcoal concentration ranges from 103 to 4324 grains g^{-1} (average 1940 grains g^{-1}), sub-long charcoal from 15 to 732 grains g^{-1} (average 102 grains g^{-1}), and total charcoal from 103 to 4324 grains g^{-1} (average 1940 grains g^{-1}). In this sub-phase, total charcoal, sub-round, and sub-long concentrations all increase sharply.

Phase II (14.00-13.60 Ma, 45 samples): In this phase, sub-round charcoal concentration ranges from 11 to 636 grains g^{-1} (average 708 grains g^{-1}), sub-long charcoal from 2 to 829 grains g^{-1} (average 69 grains g^{-1}), and total charcoal from 58 to 3955 grains g^{-1} (average 777 grains g^{-1}). This phase can be subdivided into:

- **Sub-phase 2a (14.20-14.00 Ma, 20 samples):** Sub-round charcoal concentration ranges from 271 to 3082 grains g^{-1} (average 1295 grains g^{-1}), sub-long charcoal from 2 to 829 grains g^{-1} (average 73 grains g^{-1}), and total charcoal from 271 to 3082 grains g^{-1} (average 1295 grains g^{-1}). During this period, total charcoal, sub-round, and sub-long concentrations all gradually increase.
- **Sub-phase 2b (14.00-13.60 Ma, 25 samples):** Sub-round charcoal concentration ranges from 11 to 636 grains g^{-1} (average 271 grains g^{-1}), sub-long charcoal from 2 to 837 grains g^{-1} (average 65 grains g^{-1}), and total charcoal from 58 to 3955 grains g^{-1} (average 271 grains g^{-1}). In this sub-phase, total charcoal, sub-round, and sub-long concentrations all decrease rapidly.

4 Discussion

4.1 Natural Fire History in the Wushan Basin During the Middle Miocene

Charcoal particle size reflects the distance and extent of fire activity. Modern charcoal transport studies indicate that only particles larger than 125 m can be assumed to be local [13, 33]. The charcoal record shows that MC<50 m concentrations are about 10 times higher than those >50 m, with particles >100 m being extremely rare, reflecting that fire activity in the study area was primarily large-scale regional fires.

Total charcoal concentration trends reflect changes in fire activity. Higher charcoal concentrations indicate more intense regional fire activity, and vice versa [1, 16-17, 32]. The charcoal record shows (Fig. 4) that MCtotal gradually increased during 15.30–14.00 Ma, then sharply decreased during 14.00–13.60 Ma, reflecting that natural fire activity gradually intensified and then rapidly diminished.

Different plant types produce charcoal with different morphologies. After laboratory processing, herbaceous charcoal has an average length-to-width ratio of 3.9$\pm$0.1, *whilewoodyplantcharcoalhasanaverageratioof* 1.8$\pm$0.1 [14, 41]. Therefore, sub-round charcoal concentration can reflect forest fire intensity, while sub-long charcoal concentration reflects grassland fire intensity. The Nanyu section charcoal record shows (Fig. 4) that sub-round charcoal (L/W<2.5) concentrations are much higher than sub-long charcoal (L/W>2.5), with sub-round average concentrations about 10 times those of sub-long charcoal, indicating that natural fire activity in the study area was dominated by woody plant combustion, primarily forest fires.

4.2 Mechanisms of Fire Activity in the Wushan Basin

4.2.1 Natural Fire Response to Vegetation Change Charcoal originates from plant combustion, and the relationship between vegetation and charcoal is most intimate. Plant burning is influenced by multiple factors including atmospheric humidity and temperature, vegetation type and quantity, lightning, and volcanic eruptions [4, 19, 42-44]. Pollen records show that during the Middle Miocene, vegetation in the Wushan Basin was coniferous and broadleaf mixed forest [36]. In terms of plant distribution, coniferous and broadleaf forests formed the forest canopy, with coniferous forests mainly growing at high altitudes and broadleaf forests at mid-low altitudes, while herbs and shrubs grew in the understory [36].

Comparing pollen data with charcoal concentration trends (Fig. 5), during sub-phase 1a (15.30–14.38 Ma), arboreal pollen percentages were relatively low, while total charcoal, sub-round charcoal, and broadleaf pollen percentages gradually increased, indicating relatively low humidity, open forest vegetation, and gradually increasing broadleaf forest coverage. During sub-phase 1b (14.38–14.20 Ma), arboreal pollen percentages increased while total charcoal, sub-round charcoal, and broadleaf pollen percentages decreased significantly, indicating increased overall forest coverage but reduced broadleaf forest coverage at low altitudes. During sub-phase 2a (14.20–14.00 Ma), arboreal pollen percentages were relatively high and stable, while broadleaf arboreal pollen, total charcoal, and sub-round charcoal concentrations all increased significantly, indicating increased humidity and broadleaf forest coverage. During phase 2b (14.00–13.60 Ma), total charcoal, sub-round charcoal, arboreal pollen percentages, and broadleaf arboreal pollen percentages all decreased significantly, indicating reduced forest vegetation and broadleaf forest coverage.

Fire activity intensity is related to climate conditions, fuel biomass, and vegetation type and flammability [45-48]. The trends of MCtotal and sub-round charcoal concentration correlate with arboreal pollen percentage trends (R^2=0.63) and are consistent with broadleaf plant pollen percentage trends (R^2=0.71), and charcoal data indicate that natural fire activity in the Wushan Basin was dominated by forest fires. Correlation analysis shows that sub-round charcoal concentration trends are significantly correlated with broadleaf pollen percentage ($p<0.01$). Pollen data show that during 15.30–13.60 Ma, broadleaf arboreal pollen averaged 58.3% of total arboreal pollen, while coniferous pollen averaged 41.7%. Comprehensive analysis of vegetation change trends and charcoal concentration trends in each phase suggests that natural fire activity in the Wushan Basin mainly occurred in low-altitude broadleaf forest areas, with fire intensity influenced by changes in broadleaf forest coverage. During warm, humid periods, MCtotal was higher than in relatively cold periods, and natural fire activity was more intense.

Modern forest fire dynamics show that under global warming, forest fires worldwide are increasing significantly, with fires becoming more frequent as temperatures rise, primarily because climate warming affects plant properties and forest vegetation distribution, influencing forest flammability and combustibility [49]. Additionally, warm, humid conditions are suitable for vegetation growth and development, leading to increased biomass accumulation that provides more fuel for fire activity, while frequent thunderstorms and lightning also contribute to increased forest fires [42, 50].

4.2.2 Natural Fire Response to Global Change in the Wushan Basin

To explore the relationship between natural fire activity and global change during the Middle Miocene in the Wushan Basin, we compared the MCtotal trend with deep-sea benthic foraminiferal δ^{18}O records [52] (Fig. 5). The analysis shows that during the transition from the Middle Miocene Climatic Optimum to the Middle Miocene Climate Transition, δ^{18}O content from deep-sea benthic foraminifera remained stable, with high global average temperatures and small variations [52]. Against this global temperature background, forest vegetation coverage and biomass in the Wushan Basin gradually increased, and natural fire activity gradually intensified. After 14.20 Ma, δ^{18}O content decreased significantly, indicating a global warming period that corresponds well with vegetation and climate changes reconstructed from pollen data [36, 52]. Charcoal records show that during this further warming period, MCtotal increased significantly. During 14.00–13.60 Ma, when MCtotal decreased sharply, deep-sea benthic foraminiferal δ^{18}O records increased significantly, indicating notable global cooling [52]. Pollen data show that forest coverage decreased dramatically during this period, mainly due to a sharp reduction in broadleaf arboreal pollen, with cold-tolerant coniferous forests replacing broadleaf forests as the main forest components [36], and forest fire activity decreased rapidly.

The most comparable global event to this phenomenon may be the Mi-3 event [55], which later split into Mi-3a (13.82–13.65 Ma) and Mi-3b (14.00–13.50 Ma) [56]. Mi-3 had significant impacts on vegetation and organisms, with a sudden end to the warm period recorded in mid-Miocene central Europe and regional extinction events of most thermophilic biological groups [56]. We hypothesize that during the Middle Miocene Climate Transition, global cooling caused large-scale die-offs of most organisms on Earth, leading to vegetation transformation in the Wushan Basin, significantly reduced forest coverage, and greatly decreased biomass, resulting in rapid reduction of natural fire activity. Comparing MCtotal trends in the Wushan Basin with global deep-sea benthic foraminiferal δ^{18}O records suggests that natural fire activity in the study area had a strong connection with global temperature changes, which may have influenced regional fire activity through effects on vegetation in the Wushan Basin.

5 Conclusions

Charcoal has proven to be an effective proxy for reconstructing paleofire activity. Based on high-resolution charcoal records from Middle Miocene sediments in the Wushan Basin, we reconstructed the natural fire history during 15.30–13.60 Ma. Charcoal records indicate that fire activity was dominated by forest fires fueled by woody plants, mainly occurring on a regional scale. The trend in total charcoal concentration reflects that natural fire activity gradually intensified during 15.30-14.00 Ma, then rapidly decreased during 14.00–13.60 Ma.

By comparing existing climatic and environmental proxy data, we explored the relationship between natural fire activity and climate-environmental changes, as well as responses to global temperature changes, reaching the following conclusions:

1) Natural fire activity in the Wushan Basin as reflected by charcoal records was dominated by forest fires, with fire intensity closely related to broadleaf forest coverage. Fire activity was influenced by climate change; under warm, humid conditions, forest vegetation coverage increased, natural fire activity intensified, and total charcoal concentration was high.

2) Comparison of total charcoal concentration trends with deep-sea benthic foraminiferal $\delta^{18}O$ records reveals a strong connection between charcoal concentration and global temperature changes. We infer that global temperature changes may have influenced natural fire activity in the study area through effects on vegetation in the Wushan Basin.

References

[1] Miao Y F, Wu F L, Warny S, et al. Miocene fire intensification linked to continuous aridification on the Tibetan Plateau[J]. Geology, 2019, 47(4): 303-307.

[2] Bowman D M J S, Balch J K, Artaxo P, et al. Fire in the earth system[J]. Science, 2009, 324(5926): 481-484.

[3] Guo Xiaoli. Advance of charcoal study for paleoenvironment in China[J]. Journal of Glaciology and Geocryology, 2011, 33(2): 342-348.

[4] Patterson W A, Edwards K J, Maguire D J. Microscopic charcoal as a fossil indicator of fire[J]. Quaternary Science Reviews, 1987, 6(1): 3-23.

[5] Leys B, Brewer S C, Mcconaghy S, et al. Fire history reconstruction in grassland ecosystems: Amount of charcoal reflects local area burned[J]. Environmental Research Letters, 2015, 10(11): 114009, doi: 10.1088/1748-9326/10/11/114009.

[6] Whitlock C, Millspaugh S H. Testing the assumptions of fire history studies: An examination of modern charcoal accumulation in Yellowstone National Park, USA[J]. The Holocene, 1996, 6(1): 7-15.

[7] Luo Yunli, Chen Huaicheng, Wu Guoxuan, et al. Records of natural fire and climate history during the last three glacial interglacial cycles around the South China Sea: Charcoal record from the ODP1114[J]. Scientia Sinica (Terrae), 2001, 31(10): 854-860.

[8] Sun Xiangjun, Li Xun, Chen Huaicheng. Natural fire and climate in the northern part of the South China Sea since the last 37 ka[J]. Scientia Sinica (Terrae), 2000, 30(2): 163-168.

[9] Wang Zisha, Miao Yunfa, Zhao Yongtao, et al. Characteristics of microcharcoal in the lake surface sediments in the northern margin of Qaidam Basin of China and its environmental significance[J]. Journal of Desert Research, 2020, 40(4): 10-17.

[10] Wu Li, Zhang Mengcui, Ji Chao, et al. Charcoal recorded fire environment change during the Holocene from the sediment of the Chaohu Lake, east China[J]. Scientia Geographica Sinica, 2016, 36(12): 1920-1928.

[11] Jia Tiefei, Gao Xin, Wang Feng. Significance of pollen and charcoal characteristics to the oxbow environmental change events at Jingzhou the Yangtze River in recent 100 years: A case study of Tian' e and Chiba Lake[J]. Resources and Environment in the Yangtze Basin, 2017, 26(10): 145-155.

[12] Tan Zhihai, Huang Chunchang, Pang Jiangli, et al. Charcoal recorded Holocene fire history in the northern part of the Longdong Loess Plateau[J]. Quaternary Sciences, 2008, 28(4): 733-738.

[13] Tan Zhihai, Huang Chunchang, Pang Jiangli, et al. Charcoal records of Holocene loess soil sequences and its paleoenvironmental significance in Weihe River Drainage[J]. Chinese Journal of Agriculture, 2010, 18(1): 25-30.

[14] Li X Q, Sun N, Dodson J, et al. Human activity and its impact on the landscape at the Xishanping site in the western Loess Plateau during 4800-4300 cal yr BP based on the fossil charcoal record[J]. Journal of Archaeological Science, 2012, 39(10): 3141-3147.

[15] Cai Xiaomin, Miao Yunfa, Jin Heling, et al. Mid Holocene charcoal records and fire history in the east edge of the Mu Us Sandy Land, China[J]. Journal of Desert Research, 2015, 35(5): 1156-1162.

[16] Zhang Jianping, Lü Houyuan. Preliminary study of charcoal morphology and its environmental significance[J]. Quaternary Sciences, 2006, 26(5): 857-863.

[17] Li Xiaoqiang, Zhou Xinying, Shang Xue, et al. Different size method of charcoal analysis in loess and its significance in the study of fire variation[J]. Journal of Lake Sciences, 2006, 18(5): 540-544.

[18] Xu Xin, Li Yiyin. Comparison of the fire history reconstructions from three different kinds of charcoal data on the same site, Daxing' an Mountain[J]. Quaternary Sciences, 2015, 35(4): 960-966.

[19] Li Yiyin, Hou Shufang, Zhao Pengfei. Comparison of different quantification methods for microfossil charcoal concentration and the implication for human activities[J]. Quaternary Sciences, 2010, 30(2): 356-363.

[20] Winkler M G. Charcoal analysis for paleoenvironmental interpretation: A chemical assay[J]. Quaternary Research, 1985, 23(3): 313-326.

[21] Swain A M. A history of fire and vegetation in northeastern Minnesota as recorded in lake sediments[J]. Quaternary Research, 1973, 3(3): 383-390.

[22] Filion L. A relationship between dunes, fire and climate recorded in the Holocene deposits of Quebec[J]. Nature, 1984, 309(5968): 399-401.

[23] Macdonald G M, Larsen C, Szeicz J M, et al. The reconstruction of boreal forest fire history from lake sediments: A comparison of charcoal, pollen, sedimentological, and geochemical indices[J]. Quaternary Science Reviews, 1991, 10(1): 53-71.

[24] Brown K J, Hebda N J, Conder N, et al. Changing climate, vegetation, and fire disturbance in a sub-boreal pine-dominated forest, British Columbia, Canada[J]. Canadian Journal of Forest Research, 2017, 47(5): 615-627.

[25] Edwards E J, Osborne C P, Stroemberg C A E, et al. The origins of C4 grasslands: Integrating evolutionary and ecosystem science[J]. Science, 2010, 328(5978): 587-591.

[26] Cao Yanfeng, Huang Chunchang, Han Junqing, et al. Changes of fire environment recorded by charcoal in Holocene profiles in the eastern and western Loess Plateau[J]. Geography and Information Science, 2007, 23(1): 92-96.

[27] Li Xiaoqiang, Sun N, Dodson J, et al. Human activity and its impact on the landscape at the Xishanping site in the western Loess Plateau during 4800-4300 cal yr BP based on the fossil charcoal record[J]. Journal of Archaeological Science, 2012, 39(10): 3141-3147.

[28] Shi Y L, Pan B L, Wei M L, et al. Wildfire evolution and response to climate change in the Yinchuan Basin during the past 1.5 Ma based on the charcoal records of the PL02 core[J]. Quaternary Science Reviews, 2020, 241: 106393, doi: 10.1016/j.quascirev.2020.106393.

[29] Kappenberg A, Amelung W, Conze N, et al. Fire vegetation relationships during the last glacial cycle in a low mountain range (Eifel, Germany)[J]. Palaeogeography, Palaeoclimatology, Palaeoecology, 2020, 562(6): 110140, doi: 10.1016/j.palaeo.2020.110140.

[30] Ma Y Z, Wu F L, Fang X M, et al. Pollen record from red clay sequence in the central Loess Plateau between 8.10 and 2.60 Ma[J]. Chinese Science Bulletin, 2005, 50(19): 2234-2242.

[31] Hoetzel S, Dupont L, Schefu E, et al. The role of fire in Miocene to Pliocene C4 grassland and ecosystem evolution[J]. Nature Geoscience, 2013, 6(12): 1027-1030.

[32] Miao Y F, Fang X M, Song C H, et al. Late Cenozoic fire enhancement response to aridification in mid-latitude Asia: Evidence from microcharcoal records[J]. Quaternary Science Reviews, 2016, 139: 258-265.

[33] Hui Z C, Gowan E J, Hou Z F, et al. Intensified fire activity induced by aridification facilitated Late Miocene C4 plant expansion in the northeastern Tibetan Plateau, China[J]. Palaeogeography, Palaeoclimatology, Palaeoecology, 2021, 573: 110437, doi: 10.1016/j.palaeo.2021.110437.

[34] Liu S P, Li J J, Stockli D, et al. Late Tertiary reorganizations of deformation in northeastern Tibet constrained by stratigraphy and provenance data from eastern Longzhong Basin[J]. Journal of Geophysical Research: Solid Earth, 2015, 120(8): 5804-5821.

[35] Li J J, Feng Z D. Late Quaternary monsoon patterns on the Loess Plateau of China[J]. Earth Surface Processes and Landforms, 1988, 13: 125-135.

[36] Hui Z C, Li J J, Song C H, et al. Vegetation and climatic changes during the Middle Miocene in the Wushan Basin, northeastern Tibetan Plateau: Evidence from a high resolution palynological record[J]. Journal of Asian Earth Sciences, 2017, 147: 116-127.

[37] Wang Z C, Zhang P Z, Garzione C N, et al. Magnetostratigraphy and depositional history of the Miocene Wushan Basin on the NE Tibetan Plateau, China: Implications for middle Miocene tectonics of the west Qinling fault zone[J]. Journal of Asian Earth Sciences, 2012, 44: 189-202.

[38] He Kuang. Magnetostratigraphy and paleoclimatic significance of Miocene sediment in Wushan Region[D]. Lanzhou: Lanzhou University, 2013.

[39] Maher L J. Statistics for microfossil concentration measurements employing samples spiked with marker grains[J]. Review of Palaeobotany and Palynology, 1981, 32(2): 153-191.

[40] Wang Zisha, Zhao Yongtao, Miao Yunfa, et al. Statistical problem of microcharcoal in loess sediments based on the pollen methodology[J]. Arid Land Geography, 2020, 43(3): 661-670.

[41] Umbanhowar C E, Mcgrath M J. Experimental production and analysis of microscopic charcoal from wood, leaves and grasses[J]. Holocene, 1998, 8(3): 341-346.

[42] Earle C J, Brubaker L B, Anderson P M. Charcoal in northcentral Alaskan Lake sediments: Relationships to fire and late Quaternary vegetation history[J]. Review of Palaeobotany & Palynology, 1996, 92(1-2): 83-95.

[43] Thinon C M. Pedoanthracological contribution to the study of the evolution of the upper treeline in the Maurienne valley (north French Alps): Methodology and preliminary data[J]. Review of Palaeobotany and Palynology, 1996, 91(1): 399-416.

[44] Marlon J R. Wildfire responses to abrupt climate change in North America[J]. Proceedings of the National Academy of Sciences, 2009, 106(8): 2519-2524.

[45] Chandler C C, Roberts C F. Problems and priorities for forest fire research[J]. Journal of Forestry, 1973, 71(10): 625-626.

[46] Clark J S. Effect of climate change on fire regimes in northwestern Minnesota[J]. Nature, 1988, 334(6179): 233-235.

[47] Neary D G, Klopatek C C, Debano L F, et al. Fire effects on below-ground sustainability: A review and synthesis[J]. Forest Ecology and Management, 1999, 122(1): 51-71.

[48] Hu Haiqing, Wei Shujing, Sun Long, et al. Interaction among climate change, fire disturbance and ecosystem carbon cycle[J]. Arid Land Geography, 2013, 36(1): 57-75.

[49] Belcher C M, Mander L, Rein G, et al. Increased fire activity at the Triassic/Jurassic boundary in Greenland due to climate-driven floral change[J]. Nature Geoscience, 2010, 3(6): 426-429.

[50] Li S F, Hughes A C, Su T, et al. Fire dynamics under monsoonal climate in Yunnan, SW China: Past, present and future[J]. Palaeogeography, Palaeoclimatology, Palaeoecology, 2016, 465: 168-176.

[51] Lundeen Z J, Brunelle A. A 14,000 year record of fire, climate, and vegetation from the Bear River Range, southeast Idaho, USA[J]. The Holocene, 2016, 26(6): 833-842.

[52] Zachos J. Trends, rhythms, and aberrations in global climate 65 Ma to present[J]. Science, 2001, 292(5517): 686-693.

[53] Zachos J C, Dickens G R, Zeebe R E. An early Cenozoic perspective on greenhouse warming and carbon cycle dynamics[J]. Nature, 2008, 451(7176): 279-283.

[54] Miller K G, Mountain G S. Drilling and dating New Jersey Oligocene-Miocene sequences: Ice volume, global sea level, and exxon records[J]. Science, 1996, 271(5252): 1092-1095.

[55] Abels H A, Hilgen F J, Krijgsman W, et al. Long period orbital control on middle Miocene global cooling: Integrated stratigraphy and astronomical tuning of the blue clay formation on Malta[J]. Paleoceanography, 2005, 20(4): PA4012, doi: 10.1029/2004pa001129.

[56] Madelaine B. The Miocene climatic optimum: Evidence from ectothermic vertebrates of central Europe[J]. Palaeogeography, Palaeoclimatology, Palaeoecology, 2003, 195(3): 389-401.

Note: Figure translations are in progress. See original paper for figures.