Front. Earth Sci. 2023, 17(4): 1059−1069
https://doi.org/10.1007/s11707-023-1095-5

RESEARCH ARTICLE

Spatial distribution of charcoal in topsoil and its potential determinants on the Tibetan Plateau

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Abstract As an important proxy for investigating past fire activities, charcoal is often used to explore the characteristics of fire distribution and its relationships with vegetation, climate, and human activities. Research into the spatial distribution and environmental determinants for charcoal, however, is still limited. In this study, we identified and counted charcoal from topsoil samples covering the Tibetan Plateau using the pollen methodology, and investigated its relationships with vegetation net primary production (NPP), elevation, climate (precipitation, mean temperature of the coldest month and warmest month) and human population by boosted regression trees (BRT). Results reveal that the concentration of microscopic charcoal, macroscopic charcoal, and total charcoal all increase from south-west to north-east, which is consistent with the trend that the population density on the Tibetan Plateau is high in the east and low in the west, suggesting that an increase in human activity is likely to promote the occurrence of fire. The BRT modeling reveals that NPP, elevation, and mean temperature of the coldest month are important factors for total charcoal concentration on the Tibetan Plateau, and the frequency and intensity of fires further increase with increasing vegetation biomass, decreasing elevation, and decreasing mean temperature of the coldest month. The spatial variation characteristics of charcoal from topsoil on the Tibetan Plateau not only reflect well the spatial fire situation in the region, but also have a good indicative significance for vegetation, climate, and human activities.

Keywords BRT, charcoal, fire regime, climate, vegetation, human activities

Received February 27, 2023; accepted July 21, 2023

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1 Introduction

As an ecological factor of nature, fire is closely related to global climatic and environmental changes and human activities (Kaiser et al., 2009; Li et al., 2009). Through the study of ancient fire, we cannot only explore the evolution of ecosystems and the succession of vegetation types since geological times but also document the development of human social civilization since the late Holocene (Tan et al., 2013; Glückler et al., 2021). Relationships between modern fire and climatic environments and human activities form the basis for explaining the ancient fire regimes (Zhan et al., 2011; Qin et al., 2018). The analysis of modern fires and the reconstruction of ancient fires are beneficial to the correct understanding and prediction of fire episodes (Marlon et al., 2008, 2013; Bowman et al., 2020), which can help inform effective prevention and control of fires and the protection of ecosystems in the future.

Charcoal is produced by the incomplete combustion of biomass (Patterson et al., 1987; Clark et al., 1998; Hayashi et al., 2010) and is an important proxy for studying fire regimes and fire influencing factors because of its high production, wide distribution, and stable preservation in sediment (Clark, 1982; Power et al., 2008; Li et al., 2010). Current charcoal studies mainly interpret fire regimes through charcoal concentration and grain size (Xu and Li, 2015). The charcoal concentration indicates the intensity and frequency of fire episodes, with a higher concentration representing higher intensity and frequency of fire episodes, and a lower concentration representing lower intensity and frequency of fire episodes (Clark, 1988; Guo et al., 2011; Xu and Li, 2015). Large-grained charcoal (> 125 μm), known as macroscopic charcoal (Froyd, 2006), represents local fire regimes; smallgrained charcoal (< 125 μm), known as microscopic charcoal, represents regional fire regimes (Clark, 1988; Li et al., 2006; Zhan et al., 2011; Xu and Li, 2015).

There are multiple explanations for variations in the intensity and frequency of fires. For example, frequent fires may be the result of an arid climate (Tan et al., 2015), or they may be an indication of a warm and humid climate with increased vegetation biomass (Zhou et al., 2022), therefore modern topsoil charcoal needs to be investigated to properly understand charcoal data. In studies about modern charcoal, the relationship between fire, the characteristics of the affected site, and charcoal have been analyzed (Whitlock and Millspaugh, 1996) as well as the spatial distribution of modern charcoal (Wang et al., 2020) and its relationship with regional vegetation and human activities (Qin et al., 2018). Nevertheless, these studies from China are mainly located at low elevations, and few topsoil charcoal studies have been conducted at high elevations in western China. In particular, studies on the spatial distribution of charcoal from widespread surface sediments on the Tibetan Plateau and on the modern fire-driven regime on the Tibetan Plateau are lacking, limiting the application of charcoal in paleoclimatic and paleoenvironmental studies.

The Tibetan Plateau is an important ecological security barrier and a national strategic resource reserve base in China due to its geographical location and climatic environment (Yao et al., 2017). It is also a key location for studying the paleoenvironment and past human activities in China (Dong et al., 2012, 2013; Marlon et al., 2013). The first broad-scale topsoil charcoal study on the Tibetan Plateau will provide a reference for the study of fire history on the Tibetan Plateau and for exploring the relationship between fire, climate change, and human activities, which can then underpin the scientific basis for the environmental protection and management of the Plateau.

In this study, charcoal was extracted and analyzed from 183 soil-surface samples on the Tibetan Plateau and charcoal concentrations of different grain sizes were calculated to explore the distribution of charcoal and the pattern of charcoal concentration in the regional space. The relationship between total charcoal concentration and fire drivers (NPP, elevation, climate, population density) was modeled by a boosted regression tree (BRT: a type of machine learning) to analyze the mechanisms driving fire, in order to provide a foundation for the study of charcoal indicators in fire regime research.

2 Study area

The soil-surface charcoal data used in the study cover a latitudinal range of 29.916°–39.816° N and a longitudinal range of 80.427°–102.716° E, with elevation ranging from 1873 to 5563 m a.s.l. The study area has a diverse topography and numerous mountains, including the Tanggula Mountains, the Kunlun Mountains, and the Qilian Mountains. The climate is affected by a combination of the East Asian monsoon, the Indian monsoon, the westerlies, and the Plateau's topography, with a general change from warm and humid in the south-east to cold and arid in the north-west (Wu et al., 2005). The mean annual temperature (T_{ann}) decreases from 20°C in the south-east to below −6°C in the north-west, while annual precipitation (P_{ann}) decreases from 2000 mm to below 50 mm due to the multiple high mountains blocking the warm and humid marine airflow in the south (Li et al., 2021a). The vegetation on the Tibetan Plateau is mainly steppe and meadow, with shrub, forests (coniferous forest, broad-leaved forest, mixed coniferous and broad-leaved forest), and cultivated vegetation (crop field, fruit orchard, plantation forest, etc.) in the eastern, southern, and south-eastern parts of the Plateau; and alpine vegetation and desert in the north-west and north (Fig. 1). The vegetation of the study area from north-west to south-east generally shows a transition from desert through alpine vegetation, steppe, meadow, and shrub to forests.

The study area involves six regions in China: Xizang, Qinghai, Xinjiang, Gansu, Sichuan, and Yunnan, and the population of the Tibetan Plateau reached 12923300 in 2010 (Ye et al., 2019). The spatial distribution of population density is dense in the eastern regions (particular on the north-eastern Tibetan Plateau) and sparse in the western regions (Qi et al., 2020). There are many Tibetans engaged in both agriculture and animal husbandry in the study area, and they use biomass as their main energy, among which animal dung, fuel-wood, and straw are the most common (Xian, 2005). Restricted by the ecological environment of the Tibetan Plateau, Tibetan pastoral areas use yak dung as fuel almost all year round (Xian, 2005).

3 Methods and techniques

3.1 Charcoal extraction and concentration calculation

In this study, a total of 183 topsoil samples, comprising the upper 0–2 cm of surface sediments, were collected from areas on the Tibetan Plateau that are more representative and less affected by human activities. Charcoal was extracted using the standard pollen methodology: the samples were treated with 10% HCl, 10% KOH, 40% HF (Miao et al., 2017). Treated charcoal was mixed with glycerol and dropped onto a slide to make fixed specimens for microscopic counting. Charcoal was classified as microscopic charcoal (< 125 μm) or macroscopic charcoal (> 125 μm) according to the longest axis of the charcoal grain (Zhao et al., 2016). The total number of charcoal in the slides was counted by the

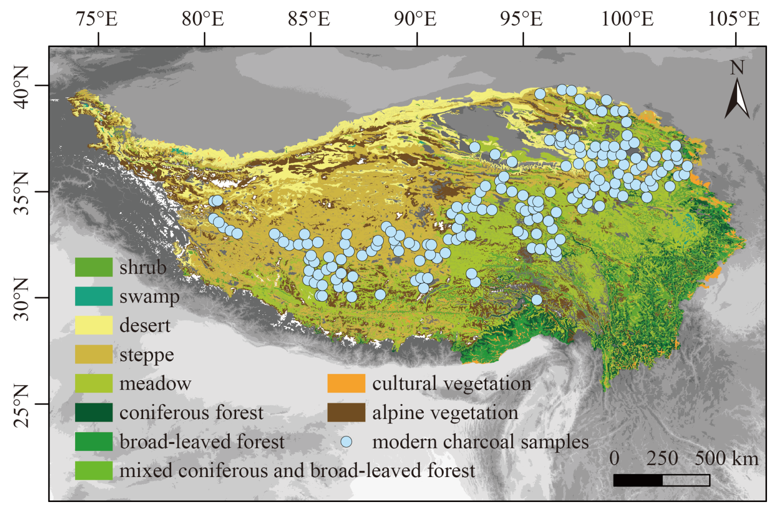


Fig. 1 Vegetation map of the Tibetan Plateau and the spatial distribution of the modern charcoal samples.

grains counting method (Li et al., 2010), and charcoal concentration was calculated based on the added *Lycopodium* following the formula: GC = G × L/(l × V) where GC is the concentration of charcoal (grains/g), G is the total number of counted charcoal grains, L is the number of added *Lycopodium* spores, l is the number of counted *Lycopodium* spores, and V is the weight of the sample (Li et al., 2010; Xu and Li, 2015).

3.2 Data sources

Net primary production (NPP) data of the sampling sites were obtained from the MOD17A3HGF Version 6 product on NASA's Earth Data website. It provides annual NPP products with a pixel resolution of 500 m and a data format of HDF-EOS (Running and Zhao, 2019). The data used in this paper were obtained by calculating the average of annual NPP products from 2000 to 2018.

The population density data of the sampling sites were obtained from the 2010 national population density distribution map provided by Ye et al. (2019) with a spatial resolution of 100 m and the data format of TIFF, which was obtained by dis-aggregating the 2010 county-level census population data by combining points-of-interest (POIs) and multi-source remote sensing data in a random forest model. In this paper, the 2010 population density data of China were extracted and clipped according to the county-level administrative boundaries of the Tibetan Plateau, and the stretched type in the symbiology system was set to the standard deviations to obtain the 2010 population density distribution map of the county-level administrative regions of the Tibetan Plateau. The raster pixel values of the corresponding sampling sites were extracted to obtain the 2010 population density data of the sampling sites.

Modern climate data of the sampling sites were obtained from the China meteorological forcing data set (1978–2018). The China meteorological forcing data set (CMFD) is a gridded near-surface meteorological data set with a temporal resolution of 3 h and a spatial resolution of 0.1°. It combines remote sensing products, reanalysis data sets, and *in situ* observed data from weather stations from January 1979 to December 2018 (He et al., 2020). He et al. (2020) determined the reliability of CMFD's application to the Tibetan Plateau and western China. In this paper, the geographical distance from each sampling site to each pixel in the CMFD was first calculated using the *rdist.earth* function in the *fields* package version 14.1 (Nychka et al., 2021) in R 4.2.1 (R Core Team, 2022) and the latitude and longitude coordinates of the sampling sites (Cao et al., 2021). Then, the meteorological data of the pixel with the closest distance to the sampling site was set as the climate condition of that sampling site. Finally, based on the long-term continuous meteorological data (1979.1–2018.12), annual precipitation (P_{ann}), mean annual temperature (T_{ann}), and the mean temperature of the coldest month (Mt_{co}) and warmest month (Mt_{wa}) were calculated for each sampling site. Afterwards, a scatterplot matrix of the relationships between climate indicators was generated using the *pair* function in the *graphics* package version 4.2.1 (R Core Team, 2022) in R 4.2.1 (Fig. 2), and T_{ann}, which is highly correlated with Mt_{co} and Mt_{wa} (correlations of 0.91 and 0.94, respectively), was excluded from this study.

3.3 Numerical analyses

Machine learning has been widely used in geosciences in recent years (Li et al., 2021b; Singer, 2021). The boosted regression tree (BRT) methodology has been applied in hydrology, soil science, and ecology due to its ability to estimate the relationship between response variables and their predictors without pre-specifying the underlying response model and determining the relative importance of each predictor (Salonen et al., 2014; Tian et al., 2017). BRT has also been applied to paleoclimate

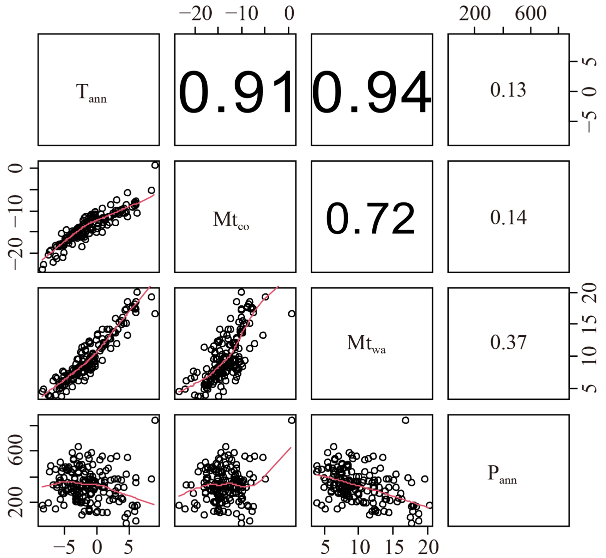


Fig. 2 Modern climate scatterplot matrix.

reconstructions in recent years to establish pollen-climate models, as first proposed by Salonen et al. (2014) and applied to northern Europe. Since then, Tian et al. (2017), Liu et al. (2020), and Cao et al. (2021) have successfully applied BRT to paleoecological data from East Asia (Tibetan Plateau, Inner Mongolian Plateau, and northern China).

Given the proportion of microscopic charcoal to macroscopic charcoal (99.50%: 0.50%), total charcoal concentration was selected as a predictor in this study, and the BRT model was used to determine the influence of NPP, elevation, climate (P_{ann}, Mt_{co}, Mt_{wa}), and population density variables on total charcoal concentration, namely the percentage of influence of each variable on total charcoal concentration. The BRT model in this study was built using the *gbm.step* function from the *dismo* package version 1.3-8 (Hijmans et al., 2015) in R 4.2.1, with the following main parameters: family = "gaussian", tree.complexity = 5, learning.rate = 0.005, bag.fraction = 0.5, tolerance.method = "fixed", and tolerance = 0.1. The local polynomial regression (LOESS) curves were fitted using the *loess* function in R 4.2.1 with a span of 0.75 to validate the obtained BRT curves (Appendix A, Tian et al., 2017).

4 Results

4.1 Spatial variation of charcoal concentration

Charcoal in the surface sediments of the Tibetan Plateau is dominated by microscopic charcoal (< 125 μm), with minor amounts of macroscopic charcoal (> 125 μm). The concentration of microscopic charcoal, macroscopic charcoal, and total charcoal all increase from south-west to north-east (Fig. 3), and higher values are found in areas of high population density such as north-west of Qinghai Lake and Gansu Province.

Total charcoal concentration ranges from 10 to 131,460 grains/g, with an average value of 4916 grains/g. The lowest value appears in Coqen County, Ngari Prefecture, Xizang, north-west of Thari Namtso, with a vegetation of Poaceae / *Carex* alpine steppe and an NPP of 779 g $C·m^{-2}·yr^{-1}$. The elevation here is 4731 m, annual precipitation is 323 mm, mean annual temperature is −0.28°C, mean temperature of the coldest month is −10.83°C and of the warmest month 10.03°C, and the population density is 0.48 people per hectare. The highest value occurs in Tianjun County, Haixi Mongolian and

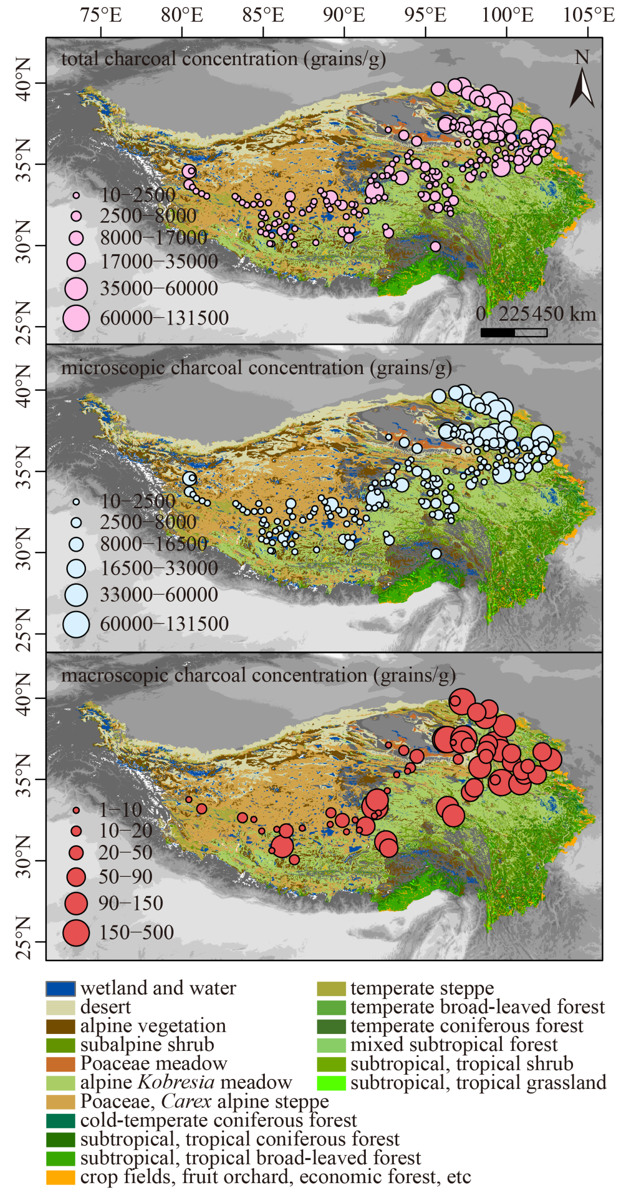


Fig. 3 Spatial variation of charcoal concentration on the Tibetan Plateau.

Tibetan Autonomous Prefecture, Qinghai Province, south of the Buha River, with a vegetation of alpine *Kobresia* meadow and an NPP of 3323 g $C\cdot m^{-2}\cdot yr^{-1}$. The elevation is 3455 m, annual precipitation is 373 mm, mean annual temperature is −0.76°C, mean temperature of the coldest month is −13.67°C and of the warmest month 10.55°C, and the population density is 0.02 people per hectare.

Microscopic charcoal concentration ranges from 10 to 131052 grains/g, with an average value of 4887 grains/g. The spatial variation of microscopic charcoal concentration follows that of total charcoal concentration, with the lowest and highest values occurring at the same sites.

The concentration of macroscopic charcoal is significantly lower than that of microscopic charcoal, and there were 118 samples without macroscopic charcoal when counted under the microscope. The remaining 65 samples had concentrations of 2 to 494 grains/g, with an average value of 80 grains/g. The lowest value occurs in Xainza County, Nagqu Prefecture, Xizang, between Silin Co and Goganzuo, with a vegetation of Poaceae/*Carex* alpine steppe and NPP of 659 g $C\cdot m^{-2}\cdot yr^{-1}$. The elevation is 4664 m, annual precipitation is 329 mm, mean annual temperature is −1.69°C, mean temperature of the coldest month is −12.47°C and of the warmest month 8.69°C, and the population density is 0.18 people per hectare. The highest value occurs in Maqen County, Golog Tibetan Autonomous Prefecture, Qinghai Province, east of the Maqing Gangri Mountain, along the Beijing–Lhasa Expressway in a vegetation of subalpine deciduous broad-leaved shrub where NPP reaches 1847 g $C\cdot m^{-2}\cdot yr^{-1}$. Annual precipitation is 506 mm, mean annual temperature is −3.18°C, mean temperature of the coldest month is −15.58°C and of the warmest month 7.57°C, and the population density is 1.14 people per hectare.

4.2 Environmental determinant of charcoal distribution

The BRT modeling results reveal that NPP, elevation, and Mt_{co} are the top three drivers of total charcoal concentration, accounting for 54.6%, 20%, and 14.4%, respectively, while Mt_{wa}, population density, and P_{ann} only influence total charcoal concentration at 4.2%, 3.4%, and 3.3%, respectively. BRT results indicate that NPP and Mt_{wa} are positively correlated with total charcoal concentration (Mt_{wa} is less significant), elevation and Mt_{co} are negatively correlated with total charcoal concentration, while population density and P_{ann} do not show significant correlations with total charcoal concentration (Fig. 4). It can be seen that for the modern Tibetan Plateau, NPP is the most important influence on the charcoal concentration, followed by elevation and climate; among the climatic factors, temperature is more important than precipitation, and mean temperature of the coldest month is more important than mean temperature of the warmest month. The model curves indicate that total charcoal concentration is usually higher when NPP > 2500 $g\cdot C\cdot m^{-2}\cdot yr^{-1}$, Elevation < 4000 m, and Mt_{co} < −10°C.

5 Discussion

5.1 Influence of human activities on fire regime on the Tibetan Plateau

Humans have been one of the main drivers influencing

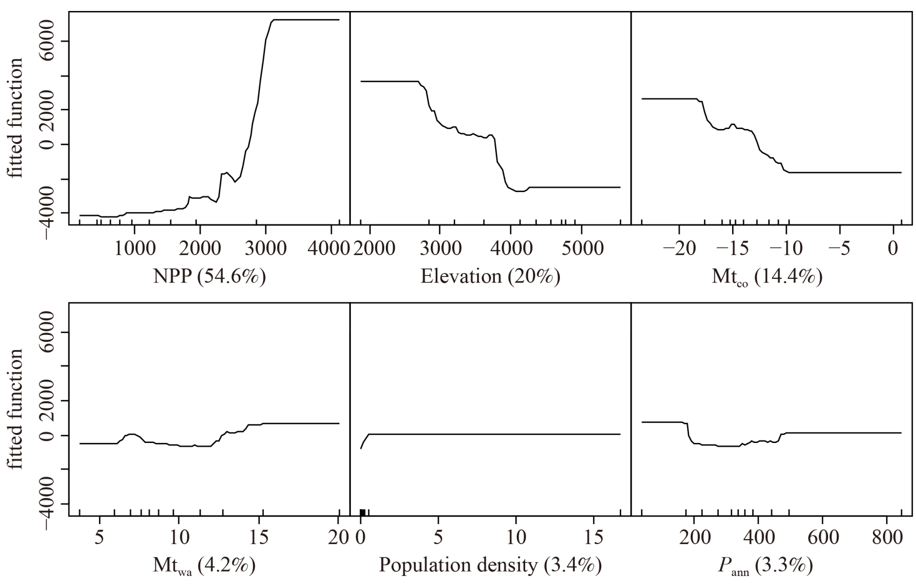


Fig. 4 Boosted regression tree (BRT) simulated the effects of vegetation, elevation, climate, and population on charcoal concentration.

vegetation landscapes and fire regimes for a long time (Li et al., 2017; Li and Wang, 2020; Glückler et al., 2021). This influence is multifaceted, including an increase in the frequency of fire episodes due to agricultural activities (e.g., slash-and-burn), mining, and regional religious activities (Vannière et al., 2008; Ma et al., 2023), as well as landscape fragmentation and fuel reduction due to increased human activity, which in turn suppresses the occurrence of fire (Andela et al., 2017; Yuan et al., 2022). Marlon et al. (2016) proposed that human activity is an important factor influencing global fire regimes over the past 50 years.

However, in this study, the results of the BRT model show that the population density has little effect (3.4%) on the total charcoal concentration, and there is no significant correlation between them. We think that this result, which is contrary to previous studies, may be due to: a) sampling sites are located in areas that are less affected by human activities; b) the large effect that land cover and elevation have on population distribution on the Tibetan Plateau (Jin et al., 2022), making it difficult for the BRT to distinguish the highly correlated multi-index superposition; and c) the population density data of the sampling sites do not simply reflect human activities that affect the concentration of charcoal. First, charcoal, especially microscopic charcoal, can spread widely (Li et al., 2006), and the sampling sites in the study are not necessarily where the fires occurred. Secondly, Marlon et al. (2013) proposed that the influence of human activities on fire regimes is difficult to quantify. Besides, in such a special region like the Tibetan Plateau, it is difficult to quantify the spatial heterogeneity of the population, the mobility of nomads, the extent of human fire use, and other complex factors. Finally, the extremely low population density in most areas of the Tibetan Plateau means there is little variation in the parameters, which affects the BRT modeling results.

It has been proposed that human fire-use patterns and life-style attitudes can better explain the variation of fire regimes than population density (Glückler et al., 2021). Our analysis suggests that fire regimes on the Tibetan Plateau are influenced by human activities (Fig. 5(c)). Both population density and total charcoal concentration on the Tibetan Plateau gradually increase from west to east (Fig. 5(c)). From the report of the Annual Scientific and Technical Conference of China Fire Protection Association (available at cFPA website), it can be seen that fires have occurred frequently in the agricultural and pastoral areas on the north-east Tibetan Plateau in recent years, and the minorities living there often cause fires, due to their religious culture, for heating, and for making tea while livestock herding. Sampling sites near roads (about 500 m from roads) have higher charcoal concentrations than sites further away. Previous studies have suggested that proximity to roads is an important factor in fire occurrence (Jiang et al., 2018; Ma et al.,

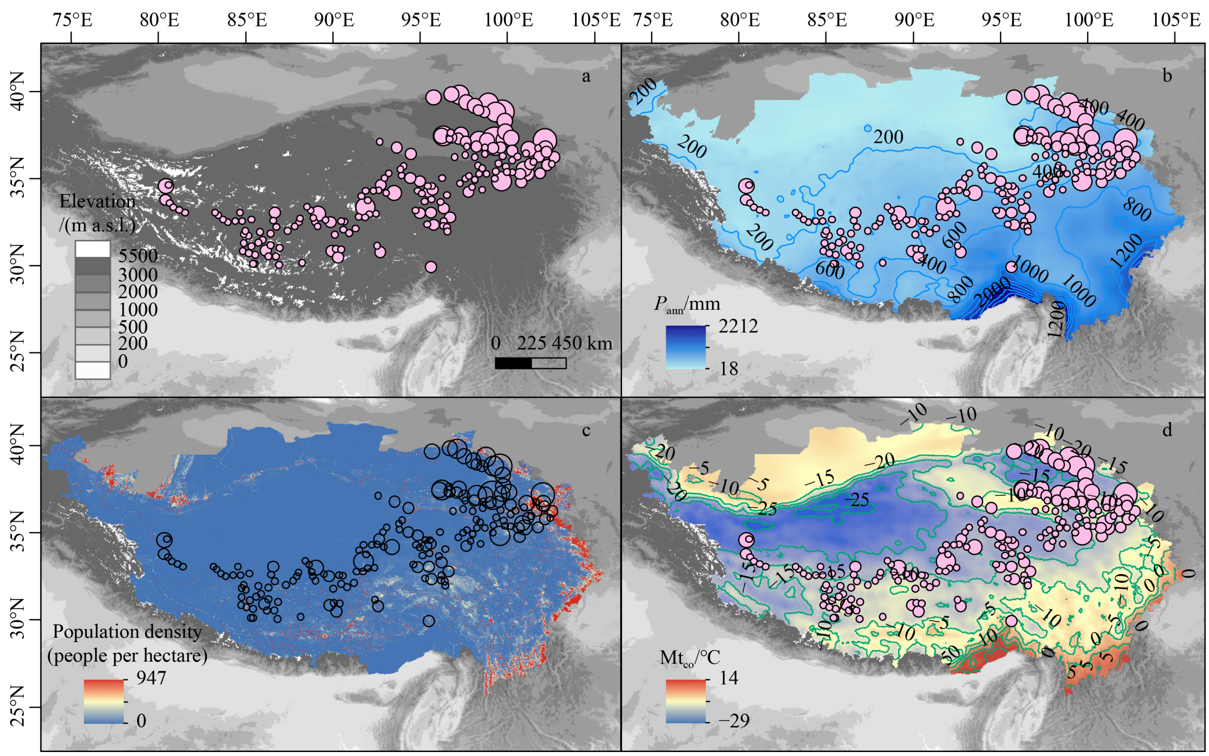


Fig. 5 Relationship between total charcoal concentration and (a) elevation, (b) annual precipitation (P_{ann}), (c) population density, and (d) mean temperature of the coldest month (Mt_{co}). Pink dots represent the total charcoal concentration. The larger the dot, the greater the charcoal concentration at the sampling site. The graphic ranking is the same as in Fig. 3.

2020), which coincides with our findings. In summary, we suggest that the increase in human activities on the Tibetan Plateau is likely to contribute to an increase in fire frequency.

5.2 Influence of environmental factors on fire regime on the Tibetan Plateau

Although human activities have played an important role in fire regimes from the early Holocene to the present day (Vannière et al., 2008), fire regimes are fundamentally influenced by fuel (flammability, availability, and connectivity) and burning (climatic conditions, seasonality, and landscape conditions) (Vannière et al., 2008, 2016). In this study, we will discuss the influence of environmental factors on fire regimes from three aspects: vegetation (fuel), elevation (landscape conditions), and climate.

5.2.1 Vegetation and elevation

Terrestrial net primary production (NPP) represents the amount of atmospheric CO_2 fixed by plants and accumulated as biomass (Zhao and Running, 2010), which means that NPP can represent the amount of combustible vegetation (biomass, namely fuel) of the sampling sites. Vegetation has always been emphasized in fire-related research (Miao et al., 2019; Glückler et al., 2021). In this study, NPP accounts for 54.6% as the most influential factor of the total charcoal concentration at the sampling sites, and total charcoal concentration increases with an increase in NPP (Fig. 4). It can be said that the amount of vegetation biomass on the Tibetan Plateau has a major influence on the frequency and intensity of fires (the amount of fuel is the limiting factor of fire regimes on the Tibetan Plateau), and the increase in vegetation biomass is associated with an increase in the occurrence of fire.

In this study, the vegetation near most sampling sites located on the central and western Tibetan Plateau is steppe and meadow, while the vegetation near the few sampling sites located on the eastern Tibetan Plateau is coniferous or broad-leaved forests, and the total charcoal concentration also increases from steppe, meadow to forests (Fig. 3). This is because grassland fires, where herbaceous plants and animal dung are the main fuel for burning, occur mostly in the central and western parts of the Tibetan Plateau (Jiang et al., 2018), while in the eastern part of the Tibetan Plateau woody plants provide abundant fuel and increase the probability of forest fires (Li et al., 2017; Glückler et al., 2021). This change in vegetation type is inseparable from the change in elevation of the Tibetan Plateau. The degree of pairwise interaction between the influencing factors was calculated using the *gbm.interactions* function in R 4.2.1, which shows that the NPP of vegetation on the Tibetan Plateau is highly correlated with the elevation (Table 1). Elevation has been mentioned as a fire driver in research in recent years, and it has been observed that the number of fires in the Altai-Sayan region decreases exponentially from lower to higher elevations (Zhang et al., 2022). The BRT modeling results also indicate that the higher the elevation of the Tibetan Plateau, the lower the total charcoal concentration (the rising elevation of the Tibetan Plateau suppresses fire). This is because elevation influences the climate, which in turn influences the nature, biomass, and structure of vegetation (Vannière et al., 2016; Miao et al., 2017), which means that different vegetation structures at different elevations lead to variation in the amount of fuel (Vannière et al., 2016), affecting the frequency and intensity of fires.

5.2.2 Climate

The influence of climate on fire is reflected in two aspects: by affecting vegetation to provide combustibles for fire (the effect on vegetation biomass and water content in vegetation (flammability or not)), and by controlling flammable weather to increase the probability of fire occurrence (Daniau et al., 2010; Wang and Feng, 2013; Jiang et al., 2018). The most important climate indicators for fire regimes are temperature and precipitation, which influence the net primary production, abundance, composition, and structure of vegetation (fuels) (Moritz et al., 2012; Marlon et al., 2013). In this study, annual precipitation, and mean temperature of the

Table 1 Results from the *gbm.interactions* function to evaluate the extent of pairwise interactions in response variables in a boosted regression tree (BRT) model

Rank	Var1 names	Var2 names	Interaction size
1	Mt_{co}	Elevation	1 503 203 118
2	NPP	Elevation	234 732 614
3	P_{ann}	NPP	75 449 068
4	Mt_{co}	NPP	41 438 745
5	Mt_{wa}	Mt_{co}	9 375 674
6	Population	Mt_{co}	6 864 452
7	Mt_{wa}	NPP	6 513 899
8	Population	NPP	5 760 146
9	Mt_{wa}	Elevation	5 060 027
10	Mt_{co}	P_{ann}	3 088 945
11	P_{ann}	Elevation	2 990 156
12	Population	Elevation	2 134 957
13	Mt_{wa}	P_{ann}	1 167 605
14	Population	Mt_{wa}	418 278
15	Population	P_{ann}	143 250

Notes: NPP: net primary productivity, Mt_{co}: mean temperature of the coldest month, Mt_{wa}: mean temperature of the warmest month, P_{ann}: annual precipitation.

coldest month and the warmest month were selected as indicators to study the influence of climate on fire regimes, and the BRT modeling results reveal that the influence of Mt_{co} (14.4%) on total charcoal concentration was much higher than Mt_{wa} (4.2%) and P_{ann} (3.3%). It can be seen from the data that for fire regimes on the Tibetan Plateau: a) the influence of temperature is higher than precipitation; and b) the influence of cool/dry season temperature is higher than warm/rainy season temperature. The importance of temperature and precipitation on fire regimes on the Tibetan Plateau has long been verified by previous studies, which have shown that temperature is the decisive factor directly affecting fire regimes in the high elevation areas of central Asia, while humidity is not a limiting factor for fire occurrence in this region, and the influence of precipitation on wildfires may be insignificant (Li et al., 2017; Jiang et al., 2018; Zhang et al., 2022). In addition, the studies of fires on the Tibetan Plateau and Yunnan show that the cool/dry season temperature is the main driver of fire regimes (Li et al., 2017; Jiang et al., 2018; Miao et al., 2019). Vegetation grows in the rainy season when increased water is available, but becomes dry and flammable due to water scarcity in the dry season, making winter and spring the high fire season (Zhang et al., 2013; Miao et al., 2019; Ma et al., 2020).

Much literature suggests that an increase in temperature during winter and spring enhances the frequency and intensity of fires (Westerling et al., 2006; Li et al., 2017), which is inconsistent with our result that Mt_{co} is inversely proportional to the total charcoal concentration as shown in Fig. 4. We conjecture the reason for this discrepancy could be: a) the cooling reduces the water vapor content in the atmosphere and causes vegetation to dry up and wither, creating dry fuels that are conducive to fire (Miao et al., 2012, 2019; Jiang et al., 2018); and b) as mentioned earlier, heating is an important cause of fires on the Tibetan Plateau, and thus the higher frequency of fires in the colder winter and spring is perhaps influenced by human activities. Since the population density of the sampling sites does not represent all that well the influence of human activities on fire regimes, we intend to determine the proportion of yak dung in charcoal from the sampling sites (previously mentioned that Tibetans mainly use yak dung as fuel) to test our conjecture.

6 Conclusions

Charcoal concentrations were calculated and analyzed for 183 topsoil samples covering the Tibetan Plateau. Results show that the concentration of microscopic charcoal, macroscopic charcoal, and total charcoal increased from south-west to north-east on the Tibetan Plateau, and this trend was the same as the trend of population density from sparse to dense, vegetation from grassland to forest, and elevation from high to low on the Tibetan Plateau. Numerical analyses reveal that increasing NPP, decreasing elevation, and lower Mt_{co} on the Tibetan Plateau are associated with an increase of charcoal concentration, while the effect of population density on charcoal concentration is weak. We suggest that human activity cannot be represented by population density alone at the sample sites and that an increase in human activity on the Tibetan Plateau is likely to promote the occurrence of fires, judging from the comparison of trends in charcoal concentration and population density. Our study complements the data on topsoil charcoal on the Tibetan Plateau and facilitates the analysis of the modern fire regime and its drivers across the Tibetan Plateau.

Acknowledgments This research was supported by the Basic Science Center for Tibetan Plateau Earth System (BSCTPES, NSFC project No. 41988101). Cathy Jenks provided help with language editing.

Competing interests The authors declare that they have no competing interests.

References

Andela N, Morton D C, Giglio L, Chen Y, van der Werf G R, Kasibhatla P S, DeFries R S, Collatz G J, Hantson S, Kloster S, Bachelet D, Forrest M, Lasslop G, Li F, Mangeon S, Melton J R, Yue C, Randerson J T (2017). A human-driven decline in global burned area. Science, 356(6345): 1356–1362

Bowman D M J S, Kolden C A, Abatzoglou J T, Johnston F H, van der Werf G R, Flannigan M (2020). Vegetation fires in the Anthropocene. Nat Rev Earth Environ, 1(10): 500–515

Cao X Y, Tian F, Li K, Ni J, Yu X S, Liu L N, Wang N N (2021). Lake surface sediment pollen dataset for the alpine meadow vegetation type from the eastern Tibetan Plateau and its potential in past climate reconstructions. Earth Syst Sci Data, 13(7): 3525–3537

Clark J S (1988). Particle motion and the theory of charcoal analysis: source area, transport, deposition and sampling. Quat Res, 30(1): 67–80

Clark J S, Lynch J, Stocks B J, Goldammer J G (1998). Relationships between charcoal particles in air and sediments in west-central Siberia. Holocene, 8(1): 19–29

Clark R L (1982). Point count estimation of charcoal in pollen preparations and thin sections of sediments. Pollen Spores, 24: 523–535

Daniau A L, Harrison S P, Bartlein P J (2010). Fire regimes during the last glacial. Quat Sci Rev, 29(21–22): 2918–2930

Dong G H, Jia X, An C B, Chen F H, Zhao Y, Tao S C, Ma M M (2012). Mid-Holocene climate change and its effect on prehistoric cultural evolution in eastern Qinghai Province, China. Quat Res, 77(1): 23–30

Dong G H, Jia X, Elston R, Chen F H, Li S C, Wang L, Cai L H, An C B (2013). Spatial and temporal variety of prehistoric human settlement and its influencing factors in the upper Yellow River valley, Qinghai Province, China. J Archaeol Sci, 40(5): 2538–2546

Froyd C A (2006). Holocene fire in the Scottish Highlands: evidence from macroscopic charcoal records. Holocene, 16(2): 235–249

Glückler R, Herzschuh U, Kruse S, Andreev A, Vyse S A, Winkler B, Biskaborn B K, Pestryakova L, Dietze E (2021). Wildfire history of the boreal forest of south-western Yakutia (Siberia) over the last two millennia documented by a lake-sediment charcoal record. Biogeosciences, 18(13): 4185–4209

Guo X L, Zhao W W, Sun J H, Li F R, Zhang K, Zhao Y (2011). Advances of charcoal study for paleoenvironment in China. J Glaciol Geocryol, 33(02): 342–348 (in Chinese)

Hayashi R, Takahara H, Hayashida A, Takemura K (2010). Millennial-scale vegetation changes during the last 40,000 yr based on a pollen record from Lake Biwa, Japan. Quat Res, 74(1): 91–99

He J, Yang K, Tang W, Lu H, Qin J, Chen Y, Li X (2020). The first high-resolution meteorological forcing dataset for land process studies over China. Sci Data, 7(1): 25

Hijmans R J, Phillips S, Leathwick J, Elith J (2015). Dismo: Species Distribution Modeling, version 1.0–12. Available at CRAN website

Jiang L, Yu S, Wu L T Y, Du W L (2018). Summary of grassland fire research. Acta Agrestia Sin, 26(04): 791–803 (in Chinese)

Jin S M, Hou G L, Xu C J, Wen D Z M, Gao J Y (2022). Extreme environmental risk assessment of human activities on the Qinghai-Tibet Plateau. Resources and Environment in the Yangtze Basin, 31(09): 2048–2059 (in Chinese)

Kaiser K, Lai Z P, Schneider B, Schoch W H, Shen X H, Miehe G, Bruckner H (2009). Sediment sequences and paleosols in the Kyichu Valley, southern Tibet (China), indicating Late Quaternary environmental changes. Isl Arc, 18(3): 404–427

Li J Y, Wang N L (2020). Holocene grassland fire dynamics and forcing factors in continental interior of China. Geophys Res Lett, 47(13): e2020GL088049

Li S F, Hughes A C, Su T, Anberree J L, Oskolski A A, Sun M, Ferguson D K, Zhou Z K (2017). Fire dynamics under monsoonal climate in Yunnan, SW China: past, present and future. Palaeogeogr Palaeoclimatol Palaeoecol, 465: 168–176

Li S, Chen J, Liu C, Wang Y (2021b). Mineral prospectivity prediction via convolutional neural networks based on geological big data. J Earth Sci, 32(2): 327–347

Li W J, Li P, Feng Z M, You Z, Xiao C W (2021a). Spatial definition of “Unpopulated Areas (UPAs)” based on the characteristics of human settlements in the Qinghai-Tibet Plateau, China. Acta Geogr Sin, 76(09): 2118–2129

Li X Q, Zhou X Y, Shang X, Dodson J (2006). Different-(kPa/°C) size method of charcoal analysis in loess and its significance in the study of fire variation. J Lake Sci, 18(5): 540–544

Li Y Y, Hou S F, Zhao P F (2010). Comparison of different quantification methods for microfossil charcoal concentration and the implication for human activities. Quat Sci, 30(02): 356–363 (in Chinese)

Li Z, Saito Y, Dang P X, Matsumoto E, Vu Q L (2009). Warfare rather than agriculture as a critical influence on fires in the late Holocene, inferred from northern Vietnam. Proc Natl Acad Sci USA, 106(28): 11490–11495

Liu L N, Wang W, Chen D X, Niu Z M, Wang Y, Cao X Y, Ma Y Z (2020). Soil-surface pollen assemblages and quantitative relationships with vegetation and climate from the Inner Mongolian Plateau and adjacent mountain areas of northern China. Palaeogeogr Palaeoclimatol Palaeoecol, 543: 109600

Ma X Y, Wu D, Liang Y, Yuan Z J, Wang T, Li Y M, Gyatso N N (2023). Changes in regional religious activities in the last millennium recorded by black carbon in Lake Dalzong, northeastern Tibetan Plateau. Sci China Earth Sci, 66(2): 303–315

Ma Y L, Ma W M, Wang C, Fu S Y, Ma M X (2020). Study on the occurrence and prevention and control of forest fires in the Marco River Forest region of Qinghai Province. Sci and Techn Qinghai Agri Forest, (01): 37–41 (in Chinese)

Marlon J R, Bartlein P J, Carcaillet C, Gavin D G, Harrison S P, Higuera P E, Joos F, Power M J, Prentice I C (2008). Climate and human influences on global biomass burning over the past two millennia. Nature Geosci, 1: 697–702

Marlon J R, Bartlein P J, Daniau A L, Harrison S P, Maezumi S Y, Power M J, Tinner W, Vannière B (2013). Global biomass burning: a synthesis and review of Holocene paleofire records and their controls. Quat Sci Rev, 65: 5–25

Marlon J R, Kelly R, Daniau A L, Vanniere B, Power M J, Bartlein P, Higuera P, Blarquez O, Brewer S, Brucher T, Feurdean A, Romera G G, Iglesias V, Maezumi S Y, Magi B, Courtney Mustaphi C J, Zhihai T (2016). Reconstructions of biomass burning from sediment-charcoal records to improve data-model comparisons. Biogeosciences, 13(11): 3225–3244

Miao Y F, Herrmann M, Wu F L, Yan X L, Yang S L (2012). What controlled Mid–Late Miocene long-term aridification in Central Asia?—Global cooling or Tibetan Plateau uplift: a review. Earth Sci Rev, 112(3–4): 155–172

Miao Y F, Wu F L, Warny S, Fang X M, Lu H J, Fu B H, Song C H, Yan X L, Escarguel G, Yang Y B, Meng Q Q, Shi P L (2019). Miocene fire intensification linked to continuous aridification on the Tibetan Plateau. Geology, 47(4): 303–307

Miao Y F, Zhang D J, Cai X M, Li F, Jin H L, Wang Y P, Liu B (2017). Holocene fire on the northeast Tibetan Plateau in relation to climate change and human activity. Quat Int, 443: 124–131

Moritz M A, Parisien M A, Batllori E, Krawchuk M A, Van Dorn J, Ganz D J, Hayhoe K (2012). Climate change and disruptions to global fire activity. Ecosphere, 3(6): 49

Nychka D, Furrer R, Paige J, Sain S (2021). “Fields: Tools for spatial data.” R package version 14.1

Patterson W A III, Edwards K J, Maguire D J (1987). Microscopic charcoal as a fossil indicator of fire. Quat Sci Rev, 6(1): 3–23

Power M J, Marlon J, Ortiz N, Bartlein P J, Harrison S P, Mayle F E, Ballouche A, Bradshaw R H W, Carcaillet C, Cordova C, Mooney S, Moreno P I, Prentice I C, Thonicke K, Tinner W, Whitlock C, Zhang Y, Zhao Y, Ali A A, Anderson R S, Beer R, Behling H, Briles C, Brown K J, Brunelle A, Bush M, Camill P, Chu G Q, Clark J, Colombaroli D, Connor S, Daniau A L, Daniels M, Dodson J, Doughty E, Edwards M E, Finsinger W, Foster D, Frechette J, Gaillard M J, Gavin D G, Gobet E, Haberle S, Hallett D J, Higuera P, Hope G, Horn S, Inoue J, Kaltenrieder P, Kennedy L, Kong Z C, Larsen C, Long C J, Lynch J, Lynch E A, McGlone M, Meeks S, Mensing S, Meyer G, Minckley T, Mohr J, Nelson D M, New J, Newnham R, Noti R, Oswald W, Pierce J, Richard P J H, Rowe C, Sanchez Goñi M F, Shuman B N, Takahara H, Toney J, Turney C, Urrego-Sanchez D H, Umbanhowar C, Vandergoes M, Vanniere B, Vescovi E, Walsh M, Wang X, Williams N, Wilmshurst J, Zhang J H (2008). Changes in fire regimes since the Last Glacial Maximum: an assessment based on a global synthesis and analysis of charcoal data. Clim Dyn, 30(7–8): 887–907

Qi W, Liu S H, Zhou L (2020). Regional differentiation of population in Tibetan Plateau: insight from the “Hu Line”. Acta Geogr Sin, 75(02): 255–267

Qin D, Shen C M, Meng H W, Huang L P (2018). Relationship between modern pollen/charcoal assemblages and vegetation/fire in northeast Yunnan. J Yunnan Normal U (Nat Sci Ed), 38(03): 70–78 (in Chinese)

R Core Team (2022). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria

Running S, Zhao M (2019). MOD17A3HGF MODIS/Terra Net Primary Production Gap-Filled Yearly L4 Global 500 m SIN Grid V006 [Data set]. NASA EOSDIS Land Processes DAAC. Accessed 2023–01–28 from

Salonen J S, Luoto M, Alenius T, Heikkila M, Seppa H, Telford R J, Birks H J B (2014). Reconstructing palaeoclimatic variables from fossil pollen using boosted regression trees: comparison and synthesis with other quantitative reconstruction methods. Quat Sci Rev, 88: 69–81

Singer D A (2021). How deep learning networks could be designed to locate mineral deposits. J Earth Sci, 32(2): 288–292

Tan Z H, Han Y M, Cao J J, Huang C C, An Z S (2015). Holocene wildfire history and human activity from high-resolution charcoal and elemental black carbon records in the Guanzhong Basin of the Loess Plateau, China. Quat Sci Rev, 109: 76–87

Tan Z H, Huang C C, Pang J L, Zhou Y L (2013). Wildfire history and climatic change in the semi-arid loess tableland in the middle reaches of the Yellow River of China during the Holocene: evidence from charcoal records. Holocene, 23(10): 1466–1476

Tian F, Cao X Y, Dallmeyer A, Zhao Y, Ni J, Herzschuh U (2017). Pollen-climate relationships in time (9 ka, 6 ka, 0 ka) and space (upland vs. lowland) in eastern continental Asia. Quat Sci Rev, 156: 1–11

Vannière B, Blarquez O, Rius D, Doyen E, Brücher T, Colombaroli D, Connor S, Feurdean A, Hickler T, Kaltenrieder P, Lemmen C, Leys B, Massa C, Olofsson J (2016). 7000-year human legacy of elevation-dependent European fire regimes. Quat Sci Rev, 132: 206–212

Vannière B, Colombaroli D, Chapron E, Leroux A, Tinner W, Magny M (2008). Climate versus human-driven fire regimes in Mediterranean landscapes: the Holocene record of Lago dell’ Accesa (Tuscany, Italy). Quat Sci Rev, 27(11–12): 1181–1196

Wang W, Feng Z D (2013). Holocene moisture evolution across the Mongolian Plateau and its surrounding areas: a synthesis of climatic records. Earth Sci Rev, 122: 38–57

Wang Z S, Miao Y F, Zhao Y T, Li F, Lei Y, Xiang M X, Zou Y G (2020). Characteristics of microcharcoal in the lake surface sediments in the northern margin of Qaidam Basin of China and its environmental significance. J Desert Res, 40(04): 10–17

Westerling A L, Hidalgo H G, Cayan D R, Swetnam T W (2006). Warming and earlier spring increase western U.S. forest wildfire activity. Science, 313(5789): 940–943

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

Wu S H, Yin Y H, Zhen D, Yang Q Y (2005). Climate changes in the Tibetan Plateau during the last three decades. Acta Geogr Sin, 60(1): 3–11

Xian B (2005). About the Tibetan energy culture in the vision of ecology. Qinghai J Ethno, 16(03): 42–47 (in Chinese)

Xu X, Li Y Y (2015). Comparison of the fire history reconstructions from three different kinds of charcoal data on the same site, Daxing’an Mountain. Quat Sci, 35(4): 960–966 (in Chinese)

Yao T D, Chen F H, Cui P, Ma Y M, Xu B Q, Zhu L P, Zhan F, Wang W C, Ai L S, Yang X X (2017). From Tibetan Plateau to Third Pole and Pan-Third Pole. Bull Chinese Academy Sci, 32(09): 924–931 (in Chinese)

Ye T, Zhao N, Yang X, Ouyang Z, Liu X, Chen Q, Hu K, Yue W, Qi J, Li Z, Jia P (2019). Improved population mapping for China using remotely sensed and points-of-interest data within a random forests model. Sci Total Environ, 658: 936–946

Yuan Z J, Wu D, Wang T, Ma X Y, Li Y M, Shao S, Zhang Y, Zhou A F (2022). Holocene fire history in southwestern China linked to climate change and human activities. Quat Sci Rev, 289: 107615

Zhan C L, Cao J J, Han Y M, An Z S (2011). Research progress on reconstruction of paleofire history. Adv Earth Sci, 26(12): 1248–1259

Zhang D, Huang X, Liu Q, Chen X, Feng Z (2022). Holocene fire records and their drivers in the westerlies-dominated Central Asia. Sci Total Environ, 833: 155153

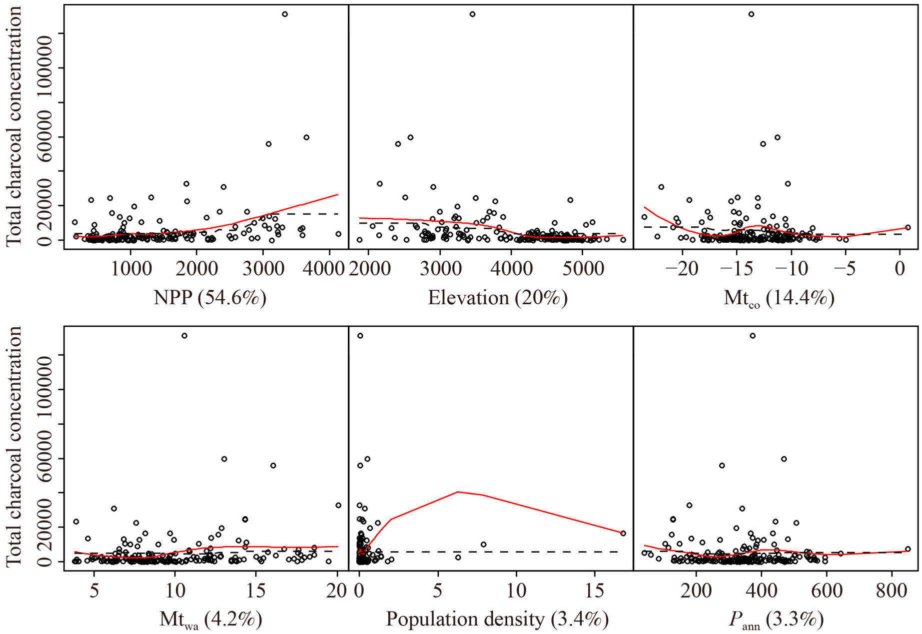
Zhang J, Bao G Y, Zhang J H (2013). Characteristic analysis of grassland fire meteorological factor in Haidong Area of Qinghai. Sci Techn Qinghai Agri Fores, 90(02): 17–20 (in Chinese)

Zhao M, Running S W (2010). Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. Science, 329(5994): 940–943

Zhao Y J, Hou G L, E C Y, Yang L, Wang Q B (2016). Charcoal concentration reflect of environment change and human activities in Xiadawu Relic, Qinghai-Tibet Plateau. J Earth Environ, 7(01): 19–26 (in Chinese)

Zhou X W, Wei X, Chen P, Shi T Y, Hui Z C (2022). Charcoal records during the Middle Miocene and its paleoclimatic significance in the Wushan Basin, northeastern Tibetan Plateau. Arid Land Geogr, 45(03): 826–835 (in Chinese)

Appendix



Appendix A Boosted regression tree (BRT) charcoal responses (black line) compared with vegetation, elevation, climate, and population density. The red curves are local polynomial regression (LOESS) curves. The vertical axis is the total charcoal concentration. NPP: net primary productivity, MT_{co}: mean temperature of the coldest month, Mt_{wa}: mean temperature of the warmest month, P_{ann}: annual precipitation.