PNAS Nexus, 2023, **2**, 1–9
https://doi.org/10.1093/pnasnexus/pgad408
Advance access publication 19 December 2023
Research Report

Warfare impact overtakes climate-controlled fires in the eastern Silk Roads since 2000 B.P.

Shanjia Zhang[a], Hao Liu[b], Gang Li[c], Zhiping Zhang[d], Xintong Chen[e], Zhilin Shi[f], Aifeng Zhou[a,*] and Guanghui Dong[a,*]

[a]College of Earth and Environmental Sciences, Lanzhou University, Lanzhou 730000, China
[b]College of Atmospheric Sciences, Lanzhou University, Lanzhou 730000, China
[c]Lanzhou Institute of Arid Meteorology, China Meteorological Administration, No. 2070 Donggang East Road, Lanzhou 730000, Gansu Province, China
[d]School of Geography, Nanjing Normal University, Nanjing 210023, China
[e]State Key Laboratory of Cryospheric Science, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China
[f]School of History and Culture, Lanzhou University, No. 222, Tianshui South Road, Chengguan, Lanzhou 730000, Gansu Province, China
*To whom correspondence should be addressed: Email: zhouaf@lzu.edu.cn (A.Z.); Email: ghdong@lzu.edu.cn (G.D.)
Edited By: Emilio Moran

Abstract

Warfare has played an important role in fire regimes; however, it remains unclear whether and when it may have impacted fire history along the Silk Roads. Based on a high-resolution record of black carbon in alpine-lake sediment, and warfare data from historical documents, we explore the relationships between fire, fuel, climate, and human activity along the eastern Silk Roads over the past 6,000 years. Results show that fire activities were low in the middle Holocene but gradually increased in the late Holocene, a pattern closely related to the intensification of drought and the expansion of herbaceous vegetation. However, the intensity and amplitude of paleo-fires increased significantly in the past 2,000 years, a pattern that was no longer synchronized with climate and vegetation changes on centennial timescales; rather, the sequence demonstrated a significant positive correlation with the documented number of wars in different dynasties. We argue that warfare between different political powers may have been the primary influence on the occurrence of five high-intensity fires since 2000 B.P. on centennial timescales in the eastern Silk Roads. Our study certainly reveals the impact of warfare activities related to dynastic change on fire regimes in Chinese history, providing a novel perspective for understanding the impact of human activities on the environment.

Keywords: black carbon, fire regimes, warfare, climate change, Silk Road

Significance Statement

Warfare has accompanied the development of human society. The Silk Road was an important land route through Eurasia during the historical period, causing multiple regimes to compete for its control. However, it is unclear when and how the wars caused changes in the fire regimes of the region. Here, we report the findings from a new high-resolution sedimentary black carbon record from the eastern Silk Road region. Combined with the unparalleled documentary record on warfare, this study reveals the relationship between warfare and fire in the study area for the first time. We conclude that warfare activities between different political powers since 2000 B.P. have altered long-term climate-controlled fires commensurate with the change of Chinese dynasties.

Introduction

Human activities are having an unprecedented impact on Earth's environment. The concept of "Anthropocene" has greatly promoted related research (1) and has become a hot issue on the frontier of science in academic circles. Among them, the relationship between human activities and fire has received much attention (2–4). Understanding when, and at what spatial scales, humans have influenced fire is of great value to the discussion of the Anthropocene. Numerous studies have shown that human activities such as agriculture, pastoralism, and metallurgy have promoted or suppressed the occurrence of fire in the past (5–8). However, whether war activities that were closely related to the development of human civilization affected changes in fire occurrence is unclear because of the limited research that has been conducted, especially in central East Asia.

The areas along the Silk Road have been the subject of intense competition among political forces for control of transportation routes due to their unique strategic position (9) (Fig. 1). The eastern section of the Silk Road was the most war-prone area (10). However, the ephemeral changes and spatial distribution characteristics of war activities in the region during the historical period, and their possible effects on paleo-fires, have yet to be clearly elucidated. Recently, black carbon (BC) has been widely used in the reconstruction of fire history on various timescales. Its two

Competing Interest: The authors declare no competing interest.
Received: December 20, 2022. **Accepted:** November 15, 2023

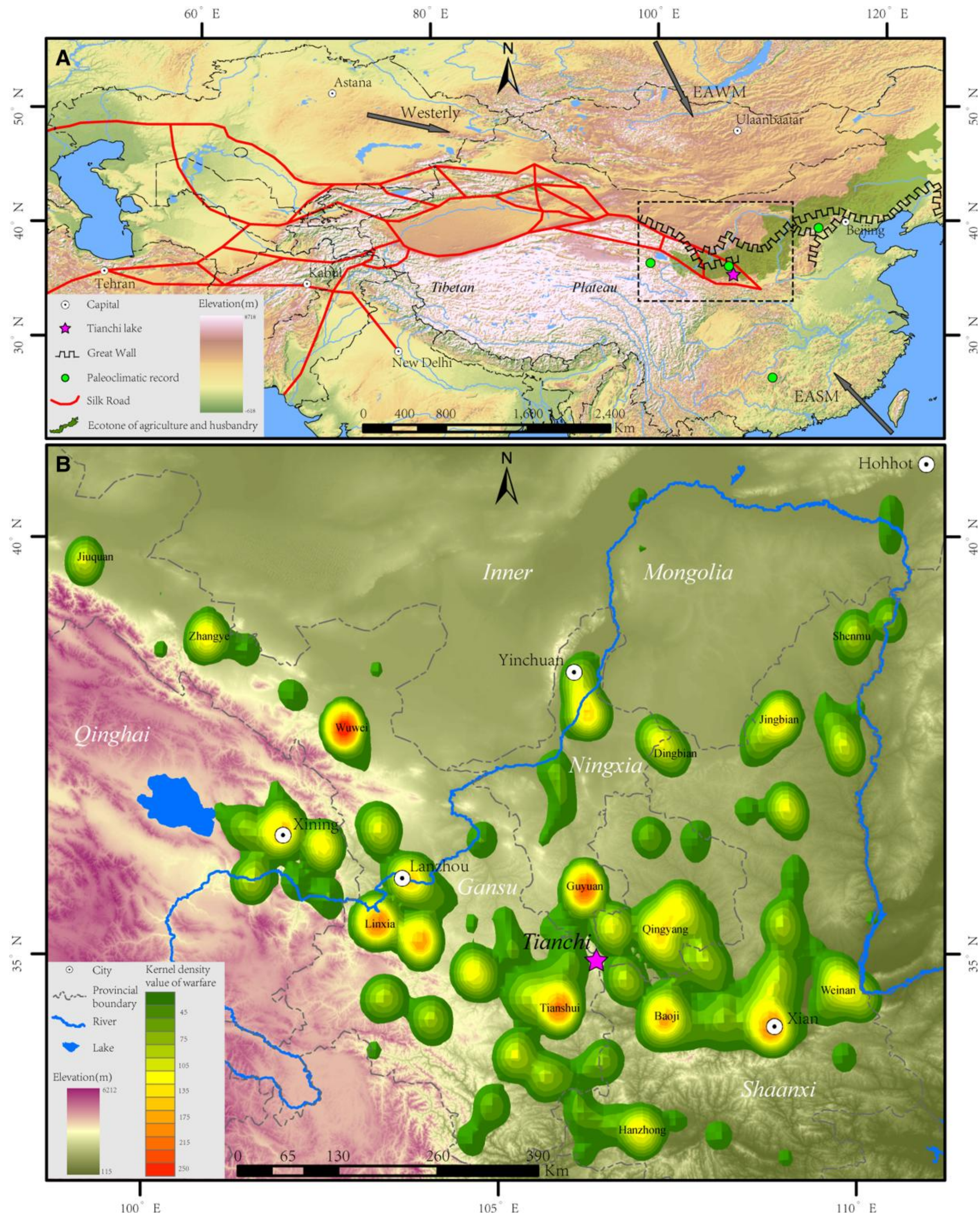

Fig. 1. The study area. A) The location of Tianchi Lake and the paleo-climatic records mentioned in this study are indicated by the stars and circles, respectively. The arrows illustrate the main trajectories of the Westerly, East Asian summer monsoon (EASM), and East Asian winter monsoon (EAWM). B) Kernel density analysis of warfare activities in the eastern Silk Road over the past 2,000 years (Table S3).

subtypes, soot and char, have different physical and chemical properties and formation processes (11, 12). Specifically, char particles (>1 μm) are micrometer-sized residues produced by local fire combustion (11). In contrast, soot particles have finer submicrometer sizes (<1 μm), thus indicating regional to subcontinental scale fires (13). The respective size difference provides us with an approach to study the interactions between fire, climate, and human activities. This discerning characteristic, combined with a good high-resolution paleo-environmental archive in the study area (Tianchi Lake) (14), laid the foundation for this study.

Here, we measured BC, char, and soot in sediments from the Tianchi Lake core spanning the past 6,000 years. The spatial range of the study area is determined based on the potential source contribution function (PSCF) analysis for modern particulate matter.

We also compared our results with the paleo-climatic records and evidence of human activity in the study area. Our key objectives are (i) to reconstruct the fire history during the mid-late Holocene using soot record; (ii) to reveal the interaction process and driving mechanisms among climate, vegetation, and fire; and (iii) to assess the importance of warfare to fire regimes during the historical periods along the eastern Silk Road.

Results

Changes in fires during the mid-late Holocene

BC preserved in accretionary lake sediment recorded changes in paleo-fires. This may be due to climate change, changes in vegetation, and human activities. The BC, char, and soot fluxes show similar variation trends on centennial and millennial timescales (Fig. S2). There are significant ($P < 0.01$) positive correlations among BC and char, BC and soot, and char and soot, with correlation coefficients of 0.99, 0.871, and 0.867, respectively. The BC, char, and soot fluxes were 0.24–5.02, 0.23–4.95, and 0.01–0.10 mg/(cm^2·year), respectively; with mean values 2.44, 2.40, and 0.04 mg/(cm^2·year), respectively, since 6000 B.P. (Table S1). Specifically, the three proxies gradually increased from the middle Holocene to the late Holocene. They attained the highest value around 400 years ago, and then sharply decrease. The high-amplitude variations of BC show that it has undergone a major transition over the last 2,000 years, characterized by five peak values on centennial timescales.

PSCF analysis

Potential source analyses of modern pollutants around Tianchi Lake can provide a reference for judging the possible source range of particulate matter, which in turn can contribute to distinguishing the range of BC sources in the study area. As shown in Fig. 2, the potential sources of $PM_{2.5}$ in the area in different seasons vary to some extent. For example, in spring and winter, there is a 50–60% probability of long-distance fine particulate matter transport along the northwest direction (Hexi Corridor), but the transit distance is significantly reduced in summer. However, the results of PSCF in different seasons showed more commonalities; the closer to the analyzed point, the higher the probability of a potential source area of particulate matter (mostly 80–90%). Specifically, high-potential sources of particulate matter around Tianchi are mainly from southwestern Shaanxi, central and eastern Gansu, the entirety of Ningxia, central Inner Mongolia, and northeastern Qinghai.

Spatial–temporal variations of warfare activities

Statistics and analysis of war information recorded in historical documents can provide diachronic changes in regional warfare activities. A total of 1,251 valid warfare data were counted (Table S3). These wars include four main types: (i) unified wars, which are wars fought in different parts of the country; (ii) civil war, namely wars between different interest groups within the ruling group; (iii) wars between different regimes, including the wars between the Central Plains dynasties and minority regimes, and the wars between different minority nationalities; and (iv) the peasant war, that is, the war between the ruled class and the ruling class. The overall situation of warfare activities in the eastern Silk Road in the past 2,000 years is presented in Fig. 1B. Spatially, there have been some obvious high-incidence periods of war activities in the study area over the past 2,000 years. Around Tianchi, there are three high-incidence war zones. The nearest ones are Baoji, Qingyang, Guyuan, and Tianshui, followed by Xi'an, Weinan, Jingbian, Dingbian, Yinchuan, Lanzhou, Linxia, Hanzhong, Xining, Wuwei, Zhangye, and Jiuquan (Fig. S3). Temporally, the warfare activities in Eastern Han Dynasty, Eastern Jin Dynasty, Southern and Northern Dynasties, late Tang Dynasty, Northern Song Dynasty, and Ming Dynasty were the most frequent periods (Table S2). It should be noted that the Tang Dynasty (618–907 AD) basically lost its control over the northwest after the An Shi Rebellion (755–763 AD), which resulted in frequent wars in the region (15). Therefore, this paper takes 755 AD as the temporal boundary to divide the Tang Dynasty into early and late periods.

Notably, in spite of the fact that human warfare activities occurred locally, human energy consumption and warfare destruction during the historical period strictly involved biomass fuels. The soot from their combustion can be transported on a regional scale and become embedded in sediments. As an alpine lake, Tianchi could record paleo-fire variability on a regional scale revealed by the PSCF analysis. Considering that the spatial extent of our study area clearly exceeds the local scale and reaches the regional scale (Fig. 1), it matches the spatial scale associated with soot. Therefore, it is feasible to compare the paleo-fire history reconstructed using soot with war activities in the eastern Silk Roads.

Discussion

Aridity and herbaceous vegetation controlled the fire regimes on millennial timescales

Studies have shown that climate change and vegetation composition are decisive factors affecting fire at various timescales (16). For example, the dominant influencing factor of Holocene fires in North America and Europe was temperature, but for the Asian monsoon region, it was humidity (17). The amount of vegetation is a limiting factor for fire in arid and semiarid regions, but not in humid regions (18). This demonstrates that their relationship is complex and exhibits significant regional variations.

Temperature and fuel availability are important factors that control fire occurrence under natural conditions (19). The increase in temperature was considered to have contributed to fire occurrence. However, reconstructed temperatures in the Northern Hemisphere (30–90°N) and the branched glycerol dialkyl glycerol tetraethers (brGDGTs)based temperatures of Beilianchi Lake in the Liupan Mountains (Fig. 3A and B) have been gradually decreasing since the middle Holocene. Both demonstrate a significant negative correlation ($P < 0.01$) with soot fluxes of −0.43 and −0.38, respectively. This suggests that a cooler climate would likely not contribute to fire occurrence. In addition, the pollen record from Tianchi Lake shows that there was more woody vegetation (i.e. high biofuel) during the middle Holocene than in the late Holocene (Fig. 3E). However, there was actually an enhancement of fire activities during the latter periods (Fig. 3F) when biomass was less abundant, likely indicating that biofuel availability was not the main factor that controlled wildfires in this area.

On the millennial timescale, there was a significant negative correlation ($P < 0.01$) between soot flux and precipitation ($r = -0.41$), implying that increased aridity was an important environmental factor. During the middle Holocene, multiple paleo-climate records show that precipitation and humidity were higher in both the monsoon and the marginal monsoon regions (24–26). The enhancement of the summer monsoon at this stage will initiate the rainy season ahead of time, thus increasing fuel moisture

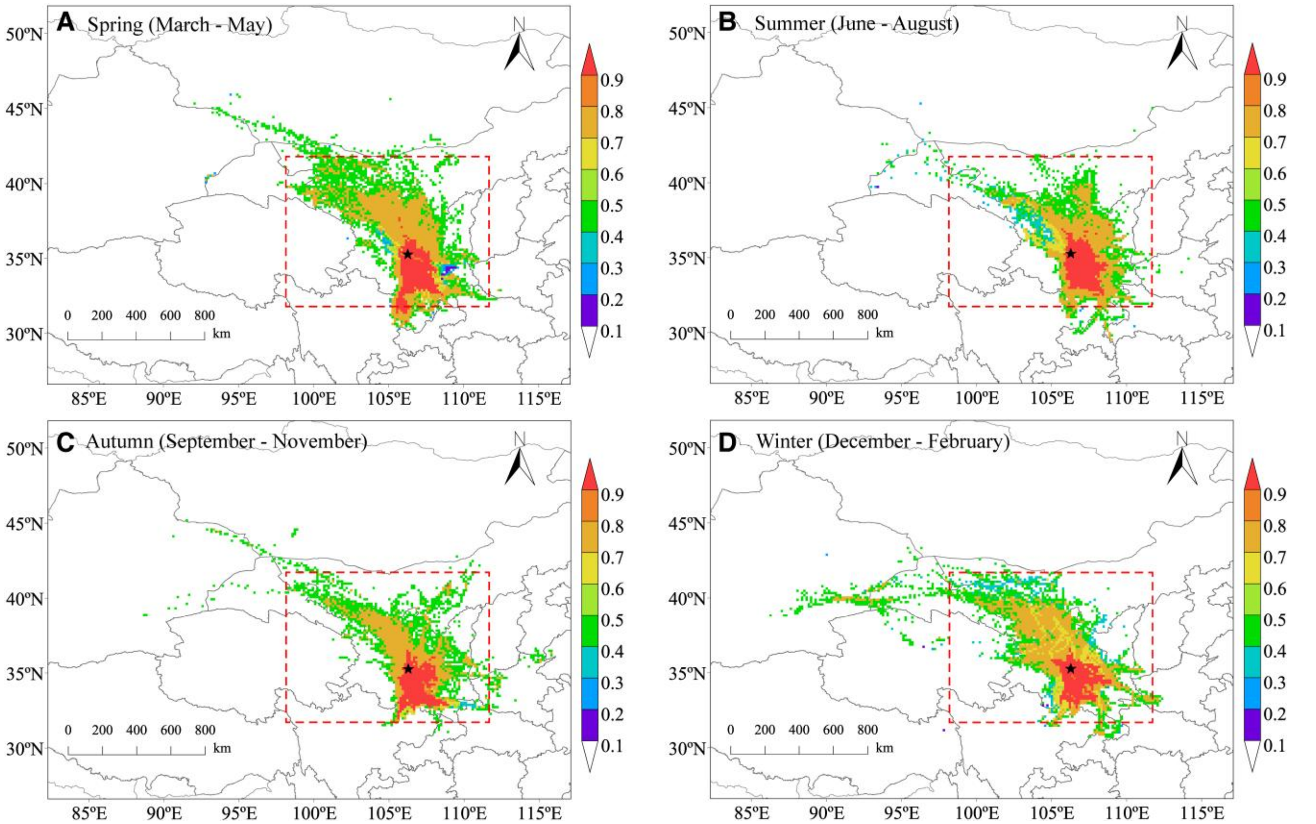

Fig. 2. Potential source contributions of $PM_{2.5}$ in different seasons (A-D) around Tinachi Lake (black star) in 2019. The red dotted box is the study area, same as Fig. 1.

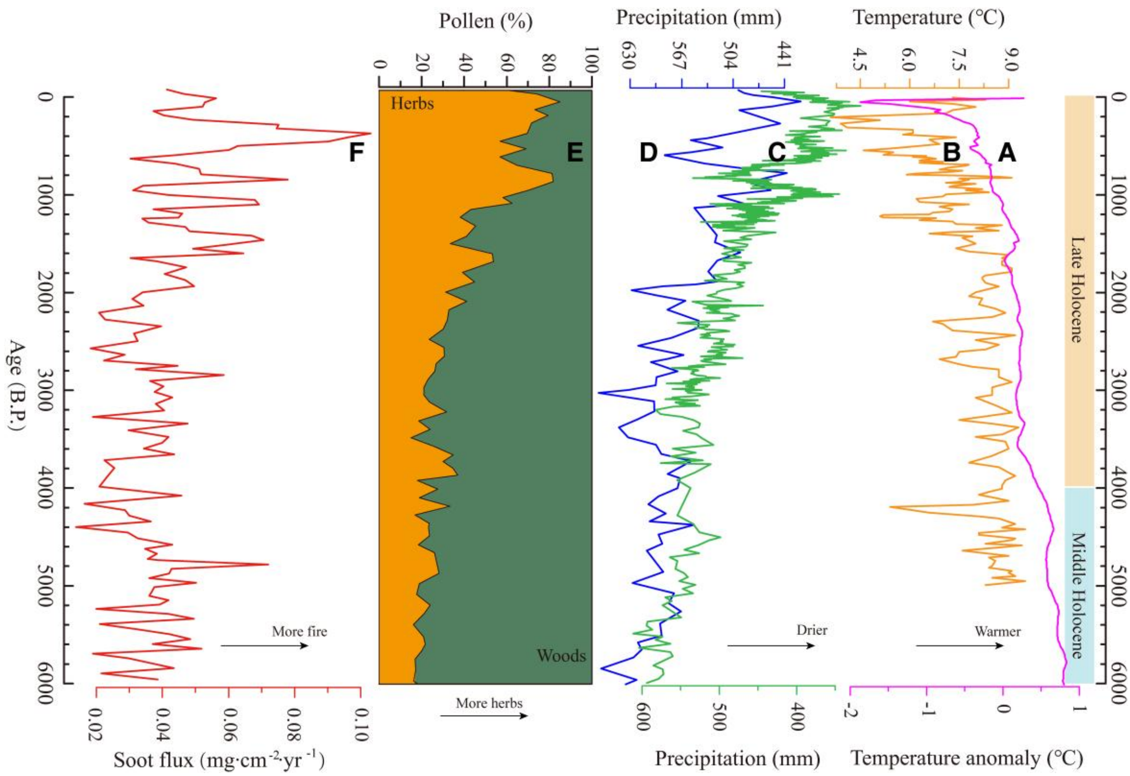

Fig. 3. Comparison of the paleo-fire history with the paleo-climatic records during the mid-late Holocene. A) Temperature anomalies in the Northern Hemisphere (30–90°N) (20). B) Reconstructed temperature in Beilianchi Lake based on GDGTs (21). Reconstructed precipitation in C) Gonghai Lake and D) Tianchi Lake based on pollen (22). E) Tree and herb pollen from Tianchi (23). F) Reconstructed fire history based on soot flux from Tianchi Lake (this study).

and shortening the fire season (27). The climate deteriorated gradually in the late Holocene and trended toward aridity (Fig. 3C and D). Under such a climate background, the vegetation was in a state of long-term water shortage, providing rich combustible material. An increase in dry weather would lengthen the fire season by reducing the number of days of rain, thus increasing the probability of fire occurrence (28). Contemporary observations also reveal that wildfires occur mainly in the dry spring and autumn (29). Clearly, the gradual trend toward aridity in the mid-late Holocene should be responsible for the intensification of wildfires in the study area.

Moreover, there is a significant positive correlation ($P < 0.01$) between soot flux and herb pollen ($r = 0.48$), indicating that the occurrence of fire also depends on vegetation composition (i.e. tree vs. grass cover). Observational studies in southern Africa have found that fire activity declines rapidly when woody vegetation exceeds 40% (30). This may also be a reason for the low fire intensity in the eastern Silk Road during the middle Holocene. In contrast, herbaceous vegetation is flammable and can provide highly combustible fuel for fire activity (31). Climatic drought intensified in the late Holocene, and the vegetation in the study area changed from a mixed deciduous and coniferous-dominated forest to an herb-dominated steppe forest landscape (25, 32), which was probably conducive to the occurrence and spread of fire. Previous studies have shown that grassland expansion corresponds to frequent fire activity in the Loess Plateau during the last glacial period and early Holocene (33, 34). This collective evidence suggests that the vegetative transition to steppe during the late Holocene was another important factor influencing the fire history.

Overall, the temporal patterns in the soot flux record are strongly correlated with the increased aridity and steppe expansion during the mid-late Holocene. These conditions contributed to fire enhancement in the study area. This is similar to the situation in the East Asian monsoon and monsoon fringe regions (17), suggesting that climate controls the occurrence of fires on the millennial timescale. Nevertheless, the high-amplitude changes of fire on the centennial timescale since 2000 B.P. seem to have decoupled from climate and vegetation. Studies have shown that human activities have significantly increased impacts on the historical environment in the area (23, 35, 36).

Warfare dominated the fires over the past 2,000 years on centennial time scales

Previous studies show that population change, land use, and climate change all impacted paleo-fire (3, 6, 8). However, at present, we cannot isolate the signal related to the individual contributions of these factors. Two possible approaches exist: (i) by determining the asynchrony between fire history and natural influences, i.e. when fire increases, climatic conditions and vegetation conditions are not conducive to such an increase (16); and (ii) by assessing the temporal and spatial synchronicity of paleo-fire changes and indicators of human activity, i.e. forensic evidence of a sudden increase in fire intensity in a certain area during a certain stage that is consistent with archeological evidence of human presence in an area (6, 37). In these cases, the premise that fire status changes were attributed to human influence is strengthened.

After 2000 B.P., the paleo-fire curve significantly changed, as shown by the peak values of soot flux in I–V (Fig. 4A). The average value of soot flux in this period was 0.05 mg/(cm^2·year), which was higher than 0.035 mg/(cm^2·year) before 2000 B.P. The coefficient of variation of soot fluxes also increased by 10.6% after 2000 B.P., indicating that the data become more discrete, which is consistent with the high amplitude and fluctuations shown by soot flux curves (Fig. 3F). Moreover, correlation analysis showed that there were relatively weak correlation coefficients between fire and precipitation, fire and herb pollen, and fire and population, which were −0.23, 0.28, and 0.07, respectively (Fig. 4C–E). On the contrary, there is a significant positive correlation between warfare and fire ($r = 0.69$; Fig. 4B), indicating that the increased warfare may have played a crucial role.

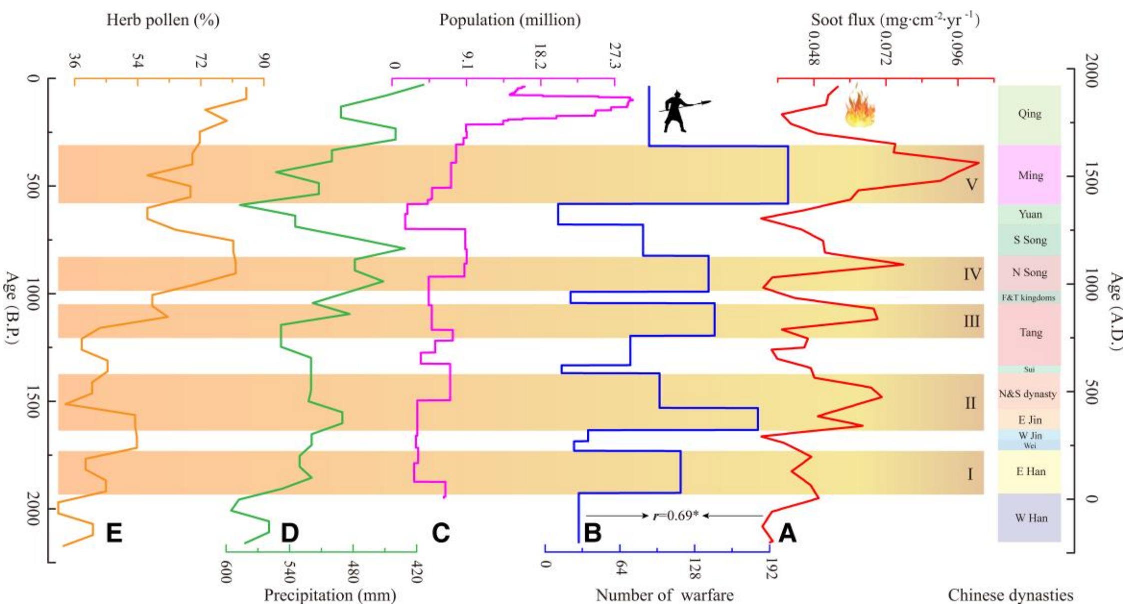

Fig. 4. Comparison of paleo-fire history with human activities and paleo-climatic records in the past 2,000 years. A) Reconstructed fire history based on soot flux from Tianchi Lake (this study). B) The number of warfare activities in the eastern Silk Road (Table S2). C) The historical population of the study area (38). D) Reconstructed precipitation in Tianchi Lake based on pollen (22). E) Herb pollen from Tianchi Lake (23). The shadow indicates the five intensified periods of fire regime. The left and right time axes are represented by B.P. (1950) and AD.

Human activities, such as land use, do lead to an increase in fires (6, 8). Although we were unable to obtain high-resolution, land-use-area change data for the past 2,000 years, comparative analyses of population data (which are closely correlated with the intensity of human activity) and paleo-fire show that these variables do not correlate well (Fig. 4). We cannot rule out the influence of land use, and more evidence of paleo-fire and human activity is needed in the future to shed light on this issue. It is worth noting that fire attack has always been a common tactic in ancient Chinese warfare (39). As a result, war was China's first known cause of fire accidents over the past two millennia (9). Sun Tzu put forward five military strategies to use fire 2,500 years ago, namely to burn soldiers; to burn stores; to burn baggage trains; to burn arsenals and magazines; to hurl dropping fire at the enemy (40). In addition to military uses, fire was also used in warfare activity to burn buildings for destructive purposes, to burn firewood for heating and cooking, and to strengthen the defenses and clear the fields for strategic objectives (41).

The Silk Road was the most important land route in Eurasia during the historical period and was considered the center of world civilization at that time (42). Chinese dynastic rulers attached importance to the operation of the Silk Road to ensure smooth traffic between the East and the West, resulting in inevitable wars between different regimes along the eastern Silk Road (10). Fire peak I corresponds to the Eastern Han Dynasty (25–220 AD), a regime involved in 115 military clashes with the Kuixiao and Qiang tribes (Table S3). Among them, the Qiang and Han wars lasted for over 100 years, nearly spanning the entirety of the Eastern Han Dynasty (43). With the decline of the Eastern Han regime, endless civil wars, uprisings, and rebellions frequently occurred, as did the study area.

Fire peak II corresponds to the Eastern Jin (317–420 AD) and Northern and Southern Dynasties (420–589 AD), with 182 and 96 documented wars, respectively (Fig. 4B). At this stage, China was in a chaotic state of numerous political powers and dismemberment. In the eastern Silk Road, there were several regimes, including the Qin, Liang, Xia, Zhao, Jin, Tuyuhun, Di, Rouran, Wei, Song, etc. (44), who constantly clashed with and attacked each other. In addition to the unification war and civil war, there were also national uprisings and peasant uprisings against the ruling class (Table S3). Therefore, this period saw the most frequent and long-lasting wars in Chinese history.

Fire peak III corresponds to the late Tang Dynasty (755–907 AD). In the early Tang Dynasty (618–755 AD), most wars were fought with the Goguryeo in the northeast and the Turks in North China (45). However, the territory of the Tang Dynasty was reduced after the An Shi Rebellion (755–763 AD), and its rule over the northwest region ceased to exist. In turn, the late Tang Dynasty had to face frequent invasions by nomadic tribes such as the Tubo and Dangxiang; consequently, the documented number of warfare activities quickly increased to 139 (Fig. 4B), including some recorded fire attacks, including a rebel attack on Tang forces at Xianyang in 756 AD, that included 2,000 chariots loaded with firewood.

Fire peak IV corresponds to the Northern Song Dynasty (960–1127 AD). During the Tang and Song dynasties, the transition from cold weapons to firearms was realized in the war history of China, and the protocol of fire is always used in every battle was followed (41). In the study area, 141 wars took place during this period, mainly between the Northern Song Dynasty and the Western Xia, Tubo, Qiang, and Liao, and between the Western Xia and Uighur, Liao, and Gusiluo (Table S3). Among them, Song and Xia attacked each other several times by burning grassland (a total of about 35,000 km^2) in the border area (46).

Peak V, the highest fire peak, occurred during the Ming Dynasty (1368–1644 AD) when the most wars occurred ($n = 201$; Fig. 4B). This regime fought a war with the Tartars for >100 years. To prevent an invasion of Tatars from the south, the Ming army set fire to the grassland in winter and spring, often forming a dazzling sea of fire (41). Toward the end of the Ming Dynasty, large-scale peasant uprising wars frequently occurred. Many cases of fire were recorded in the literature (e.g. "the official civilian houses were burnt out," "the firewood was transported to the inner hall first and the fire was set off," and "the fire lit the sky overnight").

Some climatic events in historical periods, such as the Medieval Warm Period (MWP, 10th–14th century) and the Little Ice Age (LIA, 16th–19th century), may have influenced paleo-fire activity to some extent (8). The relatively arid climate in the LIA as well as the warmer climate condition in MWP, coupled with the abundance of herbs, appear to be conductive to the fire occurrence. However, what we see on long timescales is that the five peak changes in paleo-fire over the past 2,000 years are always consistent with war activity, rather than other influences (Fig. 4A–E). More importantly, the LIA spanned the Ming and Qing dynasties, but the Tianchi paleo-fire record shows a peak in paleo-fire only during the Ming Dynasty and a significant decline during the Qing Dynasty (Fig. 4A). Similarly, the MWP spanned the Northern Song, Southern Song, and Yuan dynasties, yet only the Northern Song Dynasty saw a peak in paleo-fire (Fig. 4A). These inconsistent changes may indicate that climatic events were not the dominant factor in paleo-fire changes during these periods.

To sum up, the relationship between paleo-fire and climate, vegetation, and human activities in the eastern Silk Roads, especially during the historical periods, is complex. Although fire changes in the study area over the past 2,000 years are not necessarily caused solely by warfare activities, a comprehensive analysis based on multiple pieces of evidence from paleoclimatology, historical documentation, fire science, and meteorology points to a dominant contribution from warfare activities on the centennial timescale. This phenomenon is known to have occurred in Vietnam (47), the Classic Maya (48), and the Central Plains of China (49) during historical times. This suggests that the effects of warfare activities on fires in historical periods may be pervasive on a global scale, at least in some specific periods and regions where conflicts were frequent. Additional future, in-depth research on this issue will help us understand the history and processes of human activities as important camp forces affecting the Earth system.

Conclusion

Based on a high-resolution record (~50 a) of soot flux from alpine-lake sediment in the eastern Silk Road, we explored the interactions between fire, vegetation, climate, and human activity during the mid-late Holocene. The results show that fire regimes have experienced a gradual upward trend over the past 6,000 years, which is controlled by the intensification of drought and the expansion of herbaceous vegetation. However, the record of soot flux during the last two millennia undergone an obvious transition, revealing five periods of fire intensification on centennial timescales in the study area. They correspond well with the reigns of Eastern Han Dynasty, Eastern Jin and Northern and Southern Dynasties, late Tang Dynasty, Northern Song Dynasty, and Ming Dynasty, when war and conflicts occurred frequently. We conclude that the fire regime along the eastern Silk Roads over the past 2,000 years probably was critically impacted by human warfare activities, despite climate and vegetation may have contributed to some extent.

Materials and methods

Study area

The eastern Silk Roads refer to the land communication channel from Xi'an to Dunhuang. This region has a typical continental climate, mainly under the influence of East Asian monsoon and the westerly (Fig. 1A). From east to west, it can be divided into Loess Plateau, northeastern Tibetan Plateau, and Hexi Corridor based on the characteristics of natural geographical environment. The average annual precipitation decreased from ∼600–800 to ∼50–100 mm, and vegetation transitions from forest steppe to desert steppe. The study area is located in the northern agricultural and pastoral ecotone, which is also the area where the Great Wall is concentrated (Fig. 1A). Because of its important strategic value, there was a long struggle for control of the transportation routes between the agrarian peoples of the Central Plains and the nomadic peoples of the northwest, as well as between different nomadic peoples, resulting in very frequent war activities (10).

Sediment core of Tianchi Lake

Tianchi Lake (106.30°E, 35.25°N, 2,430 m a.s.l.) is located near the top of Liupan Mountain. The lake covers an area of 0.02 km^2 with a drainage area of 0.2 km^2 and has a maximum depth of about 9 m. The main source of its replenishment is atmospheric precipitation, and its connection to the outside world is mainly through groundwater infiltration. Under the influence of modern human activities, the original coniferous forest has been destroyed, and the vegetation in the lake basin is mainly shrub and meadow vegetation (14). The average annual temperature is 8°C, and the average annual precipitation is 480 mm, mainly from May to September, accounting for >78% of the annual total. In September 2007, core GSA07 (11.2 m) was drilled in the center of Tianchi using the UWITEC platform. A Bayesian age model for the Tianchi core was constructed with Bacon 2.2 programs, using the IntCal20 dataset. A Bayesian accumulation model allows for variable sedimentation rates and assumes only the superposition of the samples in a coherent stratigraphic sequence (50). Initially, accelerator mass spectrometry radiocarbon data from 28 terrestrial plant samples (leaves) (51) were considered in the development of the age model. Depths that correspond to four radiocarbon ages (554, 758, 769, and 980 cm) that fell outside the 95% uncertainty range of the age-depth model were removed as outliers from the final age model (Fig. S1). BC was extracted from 113 samples at 8–10 cm intervals in cores with an average temporal resolution of approximately 50 years. Among them, the sediment thickness of the last 2,000 years is about 2 m, which is consistent with a high resolution.

BC measurement

After the chemical pretreatment and filtering of lake sediment samples, the BC concentration was measured with a Model 2001 Thermal/Optical Carbon Analyzer using the thermal/optical reflectance method as specified by the Interagency Monitoring of Protected Visual Environments (IMPROVE) protocol from the Lanzhou Institute of Arid Meteorology, China Meteorological Administration. A punch filter, with an area of 0.296 cm^2, was delivered into an oven for carbon quantification. It first heats up to 550°C in an environment of 100% helium to obtain the organic carbon. Then the temperature was raised to 700 and 800°C in a mixture of 2% oxygen and 98% helium to obtain EC1 and EC2, representing the char and soot components, respectively (52). The BC is the sum of EC1 and EC2. The detection limit of the instrument for the BC test is 0.84 ± 0.5 μg/cm^2. We controlled the data quality mainly by considering the following aspects: (i) BC testing using the DRI instrument testing requires the calibration peak area to be greater than 17,000, all data in this article are >27,000; (ii) the system blank self-test requires the total carbon content to be <0.5 μg/cm^2, the data in this batch are 0.24 ± 0.2 μg/cm^2; (iii) after completing the test, six filter membranes were repeatedly tested, and the errors were all <6%. The mass concentration of BC (mg/g) is 4π (filter membrane area) multiplied by the instrument-measured area concentration (μg/cm^2) divided by the sample mass multiplied by 1,000. The BC flux (mg/(cm^2·year)) is calculated by multiplying the BC concentration (mg/g) by the sedimentation rate (cm/year) and sample density (g/cm^3).

PSCF analysis

The PSCF is a method that combines air mass trajectory and particulate matter concentration to identify pollution source areas (53). Meteorological data from the global data assimilation system (GDAS) meteorological data in 2019, including temperature, pressure, relative humidity, precipitation, and horizontal and vertical wind speeds, etc. (https://www.ready.noaa.gov/data/archives/gdas1/). GDAS has a temporal and spatial resolution of 3 h and 1° × 1°, respectively. The pollutant concentration data are based on the hourly monitoring data in 2019 (54) from the Air Quality Status Control Monitoring Station (106.20°E, 35.01°N) in Zhangjiachuan Hui Autonomous County, Tianshui City.

Considering that the soot component (<1 μm) of BC has a similar particle size (micrometer level) to $PM_{2.5}$ (≤2.5 μm) and therefore is likely to have similar transport properties, this paper selects it for PSCF analysis to provide a reference for the possible spatial range of BC sources. We used Meteoinfo software based on the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Version 4) to simulate the backward trajectories of Tianchi Lake at 1-h intervals for every day in 2019. Each backward trajectory is calculated for 500 m above ground level. The spatial variance clustering algorithm is used to cluster all the air mass trajectories that reach the receiving point of the model (55). Finally, the study area was divided into a 0.15° × 0.15° horizontal grid, and a threshold was set for the elements of the study, namely the average value of $PM_{2.5}$ observed in different seasons. When the corresponding concentration value of a given trajectory is higher than this threshold, the track is considered a pollution trajectory.

Warfare data collection and statistics

Based on the results of the PSCF, we delineate the space for collecting information on warfare activities, including Shaanxi Province, Gansu Province, Qinghai Province, the Inner Mongolia Autonomous Region, and the Ningxia Hui Autonomous Region. The period spans from Western Han Dynasty (202 B.C.–8 AD) to the Qing Dynasty (1636–1912 AD). The data on war activities in the eastern Silk Road over the past 2,000 years mainly come from *List of Wars in Historical China* (45). Relevant information includes the time and place of the war, the name of the warfare, and the belligerent army.

The data were compiled according to the following criteria: (i) wars without explicit mention of location were excluded; (ii) those involving confrontation but no substantive military conflict were not included; (iii) campaigns, battles, and conflicts were all counted as a war; and (iv) a full spatial assessment of the occurrence of the war was taken, and a detailed account of all battle locations was recorded. According to the location names of the wars mentioned in the literature, we extracted the corresponding approximate latitude and longitude data from Google Earth software. Then, the kernel density analysis tool in GIS 10.3 software was used to visualize the spatial–temporal distribution map of warfare activities in the study area.

Acknowledgments

The authors thank Dr. Yuan Li (Northwest Institute of Eco-Environment and Resources) and Dr. Jie Chen (Lanzhou University) for their help. The authors also want to thank the three anonymous reviewers for their constructive comments.

Supplementary Material

Supplementary material is available at *PNAS Nexus* online.

Funding

This work was supported by The National Natural Science Foundation of China (grant nos. 41825001 and 41991251), and the International Partnership Program of Chinese Academy of Sciences (131C11KYSB20190035).

Author Contributions

S.Z.: wrote the manuscript. H.L.: conducted PSCF analysis. G.L. and S.Z.: performed the BC experiments. Z.Z., X.C., L.S., and S.Z.: analyzed the data. A.Z.: provided lake sediment samples. S.Z., A.Z., and G.D.: designed the research. All authors discussed the results and contributed to the final manuscript.

Data Availability

All data discussed in this article are available in supplementary Information, Tables S1–S3.

References

1 Crutzen PJ. 2002. Geology of mankind. *Nature*. 415:23.
2 Andela N, *et al.* 2017. A human-driven decline in global burned area. *Science*. 356(6345):1356–1362.
3 Marlon JR. 2020. What the past can say about the present and future of fire. *Quat Res*. 96:66–87
4 Higuera PE, Shuman BN, Wolf KD. 2021. Rocky mountain subalpine forests now burning more than any time in recent millennia. *Proc Natl Acad Sci U S A*. 118(25):e2103135118.
5 Zhang SJ, *et al.* 2021. Human activities have altered fire-climate relations in arid Central Asia since ∼1000 a B.P.: evidence from a 4200-year-old sedimentary archive. *Sci Bull*. 66(8):761–764.
6 Bowman DMJS, *et al.* 2011. The human dimension of fire regimes on Earth. *J Biogeogr*. 38(12):2223–2236.
7 Pei W, *et al.* 2020. Human impact overwhelms long-term climate control of fire in the Yangtze River Basin since 3.0 ka B.P. *Quat Sci Rev*. 230:106165.
8 Zhang ZP, *et al.* 2022. Anthropogenic origin of a change in the fire-climate relationship in northern China after∼2000yr B.P.: evidence from a 15,500-year black carbon record from Dali Lake. *J Geogra Sci*. 32(6):1136–1156.
9 Zhong H. 2004. History of fire in China (221 B.C.–1949 A.D.). *China Saf Sci J*. 14(5):67–71 (in Chinese).
10 Shi HJ. 1995. The geographical distribution of wars in ancient China. *His Geogr*. 12:139–150 (in Chinese).
11 Masiello CA. 2004. New directions in black carbon organic geochemistry. *Mar Chem*. 92(1–4):201–213.
12 Yokelson RJ, *et al.* 2011. Trace gas and particle emissions from open biomass burning in Mexico. *Atmos Chem Phys*. 11(14): 6787–6808.
13 Han YM, *et al.* 2016. Climate and fuel controls on North American paleofires: smoldering to flaming in the late-glacial-holocene transition. *Sci Rep*. 6(1):1–8.
14 Zhou AF, *et al.* 2010. High-resolution climate change in mid-late Holocene on Tianchi Lake, Liupan Mountain in the Loess Plateau in central China and its significance. *Chinese Sci Bull*. 55(20):2118–2121.
15 Wang XF. 2015. Spatial and temporal distribution of wars in the middle Tang Dynasty. *Tangshiluncong*. 27:127–139 (in Chinese).
16 Marlon JR, *et al.* 2013. Global biomass burning: a synthesis and review of Holocene paleofire records and their controls. *Quat Sci Rev*. 65:5–25.
17 Xu X, *et al.* 2021. Holocene fire history in China: responses to climate change and human activities. *Sci Total Environ*. 753: 142019.
18 Krawchuk MA, Moritz MA. 2011. Constraints on global fire activity vary across a resource gradient. *Ecology*. 92(1):121–132.
19 Daniau AL, *et al.* 2012. Predictability of biomass burning in response to climate changes. *Global Biogeochem Cy*. 26(4):GB4007.
20 Marcott SA, *et al.* 2013. A reconstruction of regional and global temperature for the past 11,300 years. *Science*. 339(6124): 1198–1201.
21 Zhang C, *et al.* 2021. Quantification of temperature and precipitation changes in northern China during the "5000-year" Chinese history. *Quat Sci Rev*. 255:106819.
22 Chen FH, *et al.* 2015. East Asian summer monsoon precipitation variability since the last deglaciation. *Sci Rep*. 5(1):1–11.
23 Zhao Y, *et al.* 2010. Vegetation history, climate change and human activities over the last 6200 years on the Liupan Mountains in the southwestern Loess Plateau in central China. *Palaeogeogr Palaeocl Palaeoecol*. 293(1–2):197–205.
24 Wang Y, *et al.* 2005. The holocene Asian monsoon: links to solar changes and North Atlantic climate. *Science*. 308(5723): 854–857.
25 Zhao Y, *et al.* 2009. Vegetation response to Holocene climate change in monsoon-influenced region of China. *Earth Sci Rev*. 97(1–4):242–256.
26 Yang B, *et al.* 2021. Long-term decrease in Asian monsoon rainfall and abrupt climate change events over the past 6,700 years. *Proc Natl Acad Sci U S A*. 118(30):e2102007118.
27 Lafon CW, Quiring SM. 2012. Relationships of fire and precipitation regimes in temperate forests of the eastern United States. *Earth Interact*. 16(11):1–15.
28 Wang X, *et al.* 2013. Holocene changes in fire frequency in the Daihai Lake region (north-central China): indications and implications for an important role of human activity. *Quat Sci Rev*. 59: 18–29.
29 Yi K, Bao Y, Zhang J. 2017. Spatial distribution and temporal variability of open fire in China. *Int J Wildland Fire*. 26(2):122–135.
30 Archibald S, *et al.* 2009. What limits fire? An examination of drivers of burnt area in Southern Africa. *Global Change Biol*. 15(3): 613–630.
31 Tan Z, *et al.* 2018. The linkages with fires, vegetation composition, and human activity in response to climate changes in the Chinese Loess Plateau during the Holocene. *Quat Int*. 488:18–29.

32 Shen J, *et al.* 2005. Palaeoclimatic changes in the Qinghai Lake area during the last 18,000 years. *Quat Int*. 136(1):131–140.
33 Huang CC, *et al.* 2006. Charcoal records of fire history in the Holocene loess–soil sequences over the southern Loess Plateau of China. *Palaeogeogr Palaeocl Palaeoecol*. 239(1–2):28–44.
34 Wang X, Ding Z. 2012. Changes in fire regimes on the Chinese Loess Plateau since the last glacial maximum and implications for linkages to paleoclimate and past human activity. *Palaeogeogr Palaeocl Palaeoecol*. 315:61–74.
35 Sun H, *et al.* 2011. Fir trees disappeared 500 years ago in the Liupan Mountains on the southwestern Loess Plateau, China. *Rev Palaeobot Palyno*. 166(1–2):69–75.
36 Li J, *et al.* 2014. Human influence as a potential source of bias in pollen-based quantitative climate reconstructions. *Quat Sci Rev*. 99:112–121.
37 Bradshaw RHW, *et al.* 2010. The role of fire in southern Scandinavian forests during the late Holocene. *Int J Wildland Fire*. 19(8):1040–1049.
38 Zhao WL, Xie SJ. 1988. *History of population in China*. Beijing: People's Publishing House (in Chinese).
39 Liu SQ. 1986. On the fire attack in ancient China. *Mil Hist*. 1:62–63 (in Chinese).
40 Sun T. 1994. *The art of war*. Boulder: Westview Press.
41 Li CQ. 2010. *History of fire in China*. Shanghai: Shanghai Science and Technology Press (in Chinese).
42 Frankopan P. 2015. *The silk roads: a new history of the world*. London: Bloomsbury Publishing.
43 Wang X. 2008. A new study on the causes of the war between Qiang and Eastern Han Dynasty. *China Borderl His Geogra Stud*. 18(2):15–21. (in Chinese).
44 Tan QX. 1982. *The historical atlas of China*. Beijing: China Cartographic Publishing House (in Chinese).
45 Editorial Committee of Chinese Military History. 2003. *List of wars in historical China*. Beijing: Chinese People's Liberation Army Publishing House (in Chinese).
46 Jin YQ. 2010. War between Song and Xia and grassland changes in central and western of the Loess Plateau. *J Arid Land Resour Environ*. 24(7):192–195 (in Chinese).
47 Li Z, *et al.* 2009. Warfare rather than agriculture as a critical influence on fires in the late Holocene, inferred from northern Vietnam. *Proc Natl Acad Sci U S A*. 106(28):11490–11495.
48 Wahl D, *et al.* 2019. Palaeoenvironmental, epigraphic and archaeological evidence of total warfare among the classic Maya. *Nat Hum Behav*. 3(10):1049–1054.
49 Zou S, *et al.* 2010. Paleofire indicated by polycyclic aromatic hydrocarbons in soil of Jinluojia archaeological site, Hubei, China. *J Earth Sci*. 21(3):247–256.
50 Blaauw M. 2010. Methods and code for 'classical' age-modeling of radiocarbon sequences. *Quat Geochronol*. 5(5):512–518.
51 Sun HL. 2011. Paleoenvironment reconstruction of the middle to late Holocene in a high-resolution sediment core from Tianchi lake on Liupan Mountains [Doctoral dissertation]. China: Lanzhou University (in Chinese).
52 Zhang SJ. 2022. Temporal-spatial differences and influencing factors of paleo-fire history during middle and late Holocene in northwest China [Doctoral dissertation]. China: Lanzhou University (in Chinese).
53 Zeng YS, Hopke PK. 1994. Comparison of the source locations and seasonal patterns for acidic species in precipitation and ambient particles in Southern Ontario, Canada. *Sci Total Environ*. 143(2–3): 245–260.
54 Department of Ecology and Environment of Tianshui City. 2020. Report on the state of the ecology and environment in Tianshui City (in Chinese).
55 Dorling SR, Davies TD, Pierce CE. 1992. Cluster analysis: a technique for estimating the synoptic meteorological controls on air and precipitation chemistry—method and applications. *Atmos Environ*. 26(14):2575–2581.