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Stability of the permafrost peatlands carbon pool under climate change and wildfires during the last 150 years in the northern Great Khingan Mountains, China

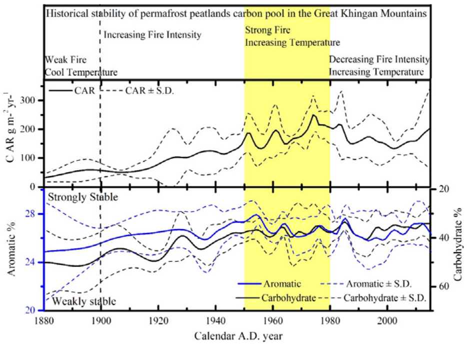
Jinxin Cong [a,b], Chuanyu Gao [a,*], Dongxue Han [a,b], Yunhui Li [a,b], Guoping Wang [a,*]

[a] *Key Laboratory of Wetland Ecology and Environment, Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Shengbei Street 4888, 130102 Changchun, China*
[b] *University of Chinese Academy of Sciences, Beijing 100049, China*

HIGHLIGHTS

- Historical carbon (C) stability in permafrost peatlands were evaluated.
- The mean July temperature is the major climate factor that influences C stability.
- Increasing temperature and decreasing precipitation increased C stability.
- Severe wildfires increase the stability of peatlands C in the Great Khingan Mountains.
- Climate change became the major factor affecting C stability after 2000.

GRAPHICAL ABSTRACT



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ABSTRACT

Peatlands store one-third of the total global soil carbon (C.) despite covering only 3–4% of the global land surface. Most peatlands are distributed in mid-high latitude regions and are even in permafrost regions, are sensitive to climate change and are disturbed by wildfire. Although several studies have focused on the impact of historical climate change and regional human activities on the C. accumulation process in these peatlands, the impact of these factors on the stability of the C. pool remains poorly understood. Here, based on the ^{210}Pb age-depth model, we investigated the historical variations of C. stability during the last 150 years for five typical peatlands in the northern Great Khingan Mountains (Northeast China), an area located in a permafrost region that is sensitive to climate change and to wildfires, which have clearly increased due to regional human activities. The results showed that low C. accumulation rates (CARs) and weakly C. stability in studied peatlands before 1900. While, the increasing anthropogenic wildfire frequency and the residual products (e.g. pyrogenic carbon) increased the CARs and C. stability in peatlands from 1900 to 1980. The mean July temperature is the most important climate factor for peatlands C. stability. After 1980, due to the low wildfire frequencies influenced by human policies, increasing temperatures and decreasing precipitation not only increased the CARs but also markedly increased the C. stability of the peatlands C. pool in the northern Great Khingan Mountains, especially after 2000.

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* Corresponding authors.
E-mail addresses: gaochuanyu@iga.ac.cn (C. Gao), wangguoping@neigae.ac.cn (G. Wang).

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1. Introduction

Peatlands are arguably the most effective terrestrial ecosystems for sequestering carbon (C.) over millennial timescales due to their water-saturated environments (Loisel et al., 2017). Peatlands cover approximately 3% of the total global land area and store approximately 540 Pg of C, which accounts for a substantial fraction (30%) of the global soil C. pool (Gorham, 1991; Dise, 2009; Yu et al., 2010). Carbon storage in peat soils is much higher than for other soils and the C. cycling in peatlands ecosystems is an important component of global C. cycling (Millennium Ecosystem Assessment, 2000). Most peatlands are distributed across the northern mid- and high-latitude regions (45–70°N), and 144 Pg of C. are stored in continuous permafrost regions, which are more sensitive to climate change than other regions (Shindell and Faluvegi, 2009; Tarnocai et al., 2009; Koven et al., 2011). Previous studies have suggested that the increasing temperatures and decreasing precipitation have enhanced peat decomposition and have released more C. into the atmosphere (Treat et al., 2014; Turetsky et al., 2014). In permafrost peatlands, the impact of increasing temperature on permafrost thaws has even caused peatlands collapse and has affected methane emissions and the decomposition of more C. (Treat et al., 2016). Unlike the C. dynamics, the impact of climate change on the stability of the peatlands C. pool remains uncertain (Loisel et al., 2017).

In addition to climate change, wildfire also influences C. dynamics in peatlands through direct burning of biomass or surface peat soils and with deposition of the fire products on the peatlands surface (Belcher, 2013; Turetsky et al., 2015). The impacts of wildfire on the peatlands C. pool gradually intensify with wildfire frequency and directly reduce the accumulation rates of peat and C. (Marrs et al., 2018). Wildfire also increases species diversity and the abundance of peat-forming species, which increase the plant C. that accumulates in the soil C. pool after periods of high wildfire frequency (Marrs et al., 2018). In addition to the direct impact of wildfire on peat soils, pyrogenic carbon (PyC), one kinds of residual wildfire products, with high surface area and recalcitrance may also affect peatlands C. pools. PyC in the peatlands C. pool not only acts as the most stable C. store (Hammes et al., 2007; Wang et al., 2016), but also promotes decomposition of the native organic matter by changing microbial activities (Könönen et al., 2018; Noble et al., 2018). Due to rapid increases in human activity and climate change during the last century, the frequency and severity of wildfires has markedly increased, which has caused serious impacts on the peatlands C. pool (Marlon et al., 2009; Gao et al., 2014b; Gao et al., 2018).

The release of decomposition-inhibiting phenolic compounds from shrubs and high organic matter recalcitrance following the initial rapid decay of plant litter (Wright et al., 2011; Wang et al., 2015) were hypothesized as two major factors that have increased C. stability and have led to large peat deposits in warm environments. The existence of large peat deposits at low latitudes, where year-round warm temperatures exist, is surprising, (Knorr et al., 2005), and the cause of peat accumulation in this environment may provide potential methods for evaluating the stability of the C. pool for high-latitude peat under global warming (Hodgkins et al., 2018). With increasing carbohydrate contents in peat soils, incubation experiments found more dioxide of carbon (CO_2) production from peat C. decomposition (Leifeld et al., 2012). Hodgkins et al. (2018) found that the aromatic content in peat soils in low-latitude peatlands were significantly higher than those in mid-high latitude peatlands and that the carbohydrate contents were opposite. These results indicate that the aromatic and carbohydrate contents could be used as indicators to reflect the stability of the peatlands C. pool and that higher aromatic (lower carbohydrate) content in peat soils indicates that the peatlands C. pool is more stable.

The Great Khingan Mountains are located in the western region of Northeast China. The northern part of the Great Khingan Mountains is located in a permafrost region, and the temperature in this region has clearly increased during the last century (Novorotskii, 2007; Wang et al., 2010). Peatlands is one of the important ecosystem types in this region (Xing et al., 2015), and the peatlands C. pool is threatened by climate change. Peatlands, with slow decomposition rates under anaerobic conditions and continuous inputs by deposition (Martini et al., 2007), provide an ideal archive for reconstructing the historical variations in C. accumulation and composition (Loisel and Yu, 2013; Loisel et al., 2017). However, the impact of historical climate change on the C. stability of the peatlands C. pool in this permafrost region is still unclear. The northern Great Khingan Mountains have a high percentage of forest and a low mean annual precipitation (460–520 mm) (Fan et al., 2017). Due to low precipitation in spring and autumn, wildfires more frequently occur in this region than in other regions of China (Zhang, 2008). Wildfires not only directly influence the peatlands carbon pool in this region but also accelerate permafrost thawing and increase the depth of the active layer in permafrost peatlands (Zhao et al., 1994; Gao et al., 2018). Since 1895, people from other regions have been migrating (e.g., Southern China, Russia and Japan) Northeast China and have exploited its forest resources (Liu, 2001; Zhang et al., 2006). Since that time, this area has been exploited by humans without any forest protection policies, and the wildfire severities clearly increased until the 1980s, when the Chinese government began to implement forestry laws and establish forest wildfire monitoring stations and forest wildfire fighting brigades (Gao et al., 2018). Thus, the temperatures and wildfire severities have changed markedly in this region during the last 150 years. However, it is still unclear how the impacts of these changes affect the C. pools in these permafrost peatlands.

In this study, five peat cores from the northern Great Khingan Mountains, using the depth-age model reconstructed by ^{210}Pb data in previous studies, were selected for this study (Gao et al., 2018). Historical variations in C. accumulation rates (CARs) and the stability of the C. pool (indicated by the carbohydrate and aromatic contents) in these selected cores from the permafrost peatlands were reconstructed over the last 150 years. Based on this research, we first wanted to evaluate the stability of the peatlands C. pool in the northern Great Khingan Mountains; the second goal was to evaluate the wildfire frequency and wildfire residual products (e.g. PyC) and their impact on the stability of peatlands C. pool in the studied region; third, by comparing the wildfire and climate history with the CARs and C. pool stability, we expected to clarify the influence of climate change and wildfire frequency on the CARs and stability of the C. pool in the permafrost peatlands in the northern Great Khingan Mountains.

2. Materials and methods

2.1. Site description, sampling and data

The studied peatlands are located in the northern part of the Great Khingan Mountains in Northeast China (Fig. 1). The Great Khingan Mountains have a temperate continental monsoon climate with mean annual temperatures of −5–2 °C and a mean annual precipitation of 460–520 mm (Fick and Hijmans, 2017). Based on the monitoring data of fire statistics for the region, more than 1500 wildfires occurred from 1966 to 2005 and affected a region of more than 60,000 km^2 (Zhang, 2008). The northern part of the Great Khingan Mountains is located in the permafrost region, and the average active layer thickness in this region is approximately 60 cm. For evaluating the effects of wildfire and climate change on peatlands C. pool in studied region totally, five peat cores in different peatlands were collected from the permafrost peatlands of this region in September 2014 (Hongtu, HT, N 51.62°, E 124.24°, sampling depth 60 cm; Tuqiang TQ, N 52.88°, E 122.82°, sampling depth 37 cm; Mangui MG, N 52.02°, E 122.12°, sampling depth 35 cm; Genhe GH, N 50.86°, E 121.51°, sampling depth 35 cm; and Huyuan HY, N 51.94°, E 123.63°, sampling depth 40 cm) (Gao et al., 2018). Due to limitations in sampling methods, all peat cores were collected from the active layer of the permafrost peatlands before winter at September 2014. All of the selected sites are located in burned regions,

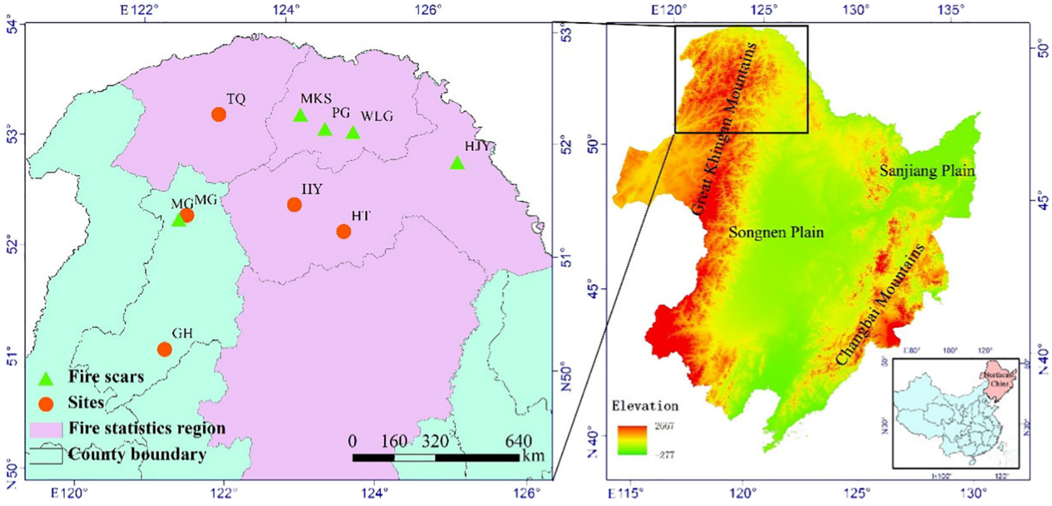

Fig. 1. Locations of the peat core sampling sites in the Great Khingan Mountains (red circles) and the fire scar research sites (green triangles) (Lu, 2012). TQ = Tuqiang, HY = Huyuan, HT = Hongtu, MG = Mangui, GH = Genhe, MKS = Mengkeshan, PG = Pangu, WLG = Walagan, and HJY = Hanjiayuan. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

while the regions with fire statistics do not cover all of the selected sites due to data limitations (Zhang, 2008). The numbers of fire scars (Fig. 1) were used to reflect the total frequency of wildfire in the northern part of the Great Khingan Mountains and calculated from several research sites in previous study (Lu, 2012). Due to limitations of climate data in the northern Great Khingan Mountains, long-term changes in annual temperatures and precipitation from a limited number of stations in the Amur River basin, integrated in a previous study, were selected as climate factors for the studied region from 1891 to 2004 (Novorotskii, 2007). Peat samples in this study could also reflected the stability of peatlands C. pools in studied region and used to compare other reference sites in previous study to evaluate the effect of climate on peatlands C. pools (Hodgkins et al., 2018). Meteorological data at the sampling sites or for reference sites from previous studies were collected from a dataset of global spatially interpolated monthly climate data (Fick and Hijmans, 2017). The average monthly temperature in July, annual precipitation, and solar radiation from April to October from 1970 to 2000 from this dataset were selected as the major meteorological parameters for further analysis.

The sampling sites were randomly selected and widely distributed in the northern part of the Great Khingan Mountains and were used to reflect the total C. accumulation history and the stability of the peatlands C. pool in this region. To decrease the difference of organic matter sources (i.e. types of plant litter) in each peatlands, the dominant plant species was *Vaccinium uliginosum* and was same in all five peatlands. The plant communities also consist of *Ledum palustre* var. *angustum*, *Carex schmidtii* and *Alnus hirsuta*. The location of each core was determined using a portable global positioning system (GPS) (Fig. 1). Samples were stored in polyethylene plastic bags and were subsequently brought to the laboratory for analysis. The samples were loosely disaggregated to facilitate air-drying at 20 °C.

2.2. Chronology

Peat cores were sectioned into 1 cm intervals with a stainless steel knife for ^{210}Pb dating and further analysis. The age-depth model was reconstructed based on a constant rate of supply (CRS) model and the ^{210}Pb data (Binford, 1990, Turetsky et al., 2004). Peat samples were analyzed for ^{210}Pb at 1 cm intervals by measuring the gamma ray emissions of the samples using a highly pure germanium semiconductor and a low-background gamma spectrometer (OTEC Instruments Ltd. USA) at the State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, CAS (Gao et al., 2016). The details of the age-depth model for each peat core are shown in previous studies (Gao et al., 2018).

2.3. FTIR analysis

For this study, Fourier transform infrared spectroscopy (FTIR) was applied to determine the abundances of the major polysaccharide moieties and to provide valuable information on the structural and functional properties of the organic matter molecules. The FTIR spectra of the peat samples were obtained using a Cary 670 FTIR spectrometer (Agilent, America; absorption mode, subsequent baseline subtraction) on KBr pellets (200 mg dried KBr and a 2 mg sample). Measurements were recorded from 4500 to 300 cm^{-1} using a resolution of 2 cm^{-1}. A total of 32 scans per sample were averaged. The absorption peaks indicative of the structural units in the organic matter were used as indicators for the peat chemical compositions. Peak 1720 (1715 to 1725 cm^{-1}) indicated the C=O stretching of COOH and COOR and is widely used to reflect peat humification (Cocozza et al., 2003; Broder et al., 2012). Peak 3437 indicates the O—H stretching of hydrogen-bonded O—H groups and is used to reflect the phenolic content in peat soils (Cocozza et al., 2003; Verchot et al., 2011). The ratios between the average heights of the 1720 cm^{-1} and 3437 cm^{-1} peaks for the following wavenumbers (given in cm^{-1}) with respect to polysaccharides (heights of 1030–1080 cm^{-1}) were calculated and labeled 1720 and 3437 and were used to evaluate the peat humification and the proportions of H bonded in the O—H groups of phenols in this study. Higher values for peak 1720 indicate greater degrees of peat humification or decomposition, and a high peak 3437 value reflects high proportions of phenol O—H groups in organic matter.

2.4. Aromatic and carbohydrate contents

The estimates of the carbohydrate and aromatic contents were based on a newly developed analysis technique for FTIR spectra, and details of this method were introduced in a previous study (Hodgkins et al., 2018). In brief, selected FTIR peaks were identified based on the minimum in the expected region of each peak's endpoint or were based on the maximum of the second derivative if there was no local minimum. Subtracting the absorbance below the baseline from each selected FTIR peak region (i.e., drawn between the endpoints of each peak) yielded the residual absorbance as the final peak (https://github.com/shodgkins/FTIRbaselines). The carbohydrate and aromatic peat contents were estimated based on their FTIR absorbance arising from carbohydrates (carb, ~1030 cm^{-1}) and aromatics (arom15, ~1510 cm^{-1} and arom16, ~1630 cm^{-1}) (Hodgkins et al., 2014). The peak heights were used as area-normalized and baseline-corrected peak heights, and the regression equations were calculated by using wet chemistry methods described in a previous study (Hodgkins et al., 2018). The regression equations for carbohydrates were estimated by the contents of cellulose + hemicellulose and carb height (carbohydrate contents = 49,204 ∗ carb − 1.7606), and the regression equations for the aromatics were estimated using the contents of Klason lignin and the heights of arom15 + arom16 (aromatic contents = 42,332 ∗ (arom15 + arom16) +7.3476) (Hodgkins et al., 2018).

2.5. Carbon accumulation rates

To determine bulk density and organic matter content, subsamples with fixed volumes were dried in an oven at 105 °C for 12 h (dry bulk density, DBD) and then burned at 550 °C for four hours (loss on ignition, LOI). The C. concentrations in the peat soils were calculated from the LOI (multiplying the organic matter content by 0.5) (Gao et al., 2014a). Based on the age-depth models, the measured DBDs, and the C. concentrations, the carbon accumulation rates (CARs) were calculated according to the following equation:

$$\text{CARs g m}^{-2}\text{ yr}^{-1} = \text{r cm yr}^{-1} \times \text{DBD g cm}^{-3} \times \text{C.mg g}^{-1} \times 10$$

where r is the rate of peat accumulation (cm yr^{-1}), calculated by age-depth model.

2.6. Statistical methods

According to the history of wildfire severities, pollution, human activities and settlement in the Great Khingan Mountains in Northeast China, the past 150 years were divided into four periods (e.g., before 1900, 1900 to 1950, 1950 to 1980, and after 1980). Before 1900, few people lived in this region and regional human activities were the lowest during the last 150 years. Since 1895, people began to migrate to or invade Northeast China and exploit its forest resources with no forest protection policies in place. Thus, human activities from 1900 to 1950 clearly increased and wildfire severities also increased. From 1950 to 1980, exploitation of forest resources continued, and wildfire severities were consistently higher than for other periods. After 1980, the Chinese government began to implement forestry laws, control the forest resources exploitation and forest fires. In this period, wildfire severities started to decrease and the impact of regional human activities on forests and peatlands were less than before. To evaluate the influence of regional human activities on peatlands C. accumulations and C. recalcitrance in the northern Great Khingan Mountains, CARs, FTIR peak 1720, FTIR peak 3437, carbohydrate and aromatic contents for each period in all five cores were regarded as the tested variables and were analyzed by one-way analysis of variance (one-way ANOVA using SPSS 20.0, IBM, Armonk, USA). Based on these data, we evaluated the impact of human activities in different periods on the C. accumulations and C. recalcitrance in each core. Furthermore, Tukey's honestly significant difference (Tukey-HSD) was used to evaluate significant differences among the means of the main factors and combinations of individual factors, which were grouped by different periods or sites for each factor. Significant differences are reported at the 0.05 probability level unless otherwise stated.

Linear regressions were performed for the peat chemicals (carbohydrate and aromatic content) and for the meteorological or latitude parameters (Origin 9.0, OriginLab Corporation, USA). For evaluating the impact of meteorological or latitude on peat chemicals in peatlands globally, the samples in this study and from a previous study (Hodgkins et al., 2018), which include peatlands peat chemicals data from tropical peatlands to northern peatlands, were integrated for linear regression analysis. The adjusted coefficient of determination (adj. R^2) is reported, which corresponds to adjustments made to the R^2 values based on the degrees of freedom of the respective model (adjusted for the number of regressors and the sample size). Except for the linear regression analyses, to evaluate the impact of wildfire frequency and residual PyC on the peatlands C. pools in the northern Great Khingan Mountains, non-linear regressions were performed for the CARs or peat chemicals (carbohydrate and aromatic content) and for the residual PyC (PyC contents) or PyC accumulation rates (PyCARs) which were collected from previous study (Gao et al., 2018) and were used to indicate wildfire frequencies in this study.

To evaluate historical variations in C. accumulation and recalcitrance in the studied region and to identify their potential influencing factors, the results of the CARs and the carbohydrate and aromatic contents from each core were aggregated for further comparable research. First, historical variations in CARs, carbohydrate content and aromatic content in each core were predicted for 1-year intervals through the 'spline' model using the 'interpSpline' function in the R environment for statistical computing using the 'splines' package (R Core Team, 2017). Second, the average and standard deviations of the selected parameters in each year were calculated based on the results of these parameters for all five peat cores.

3. Results

3.1. FTIR ratios for different periods

Peak 1720 and peak 3437 were selected as two typical FTIR ratios to reflect the organic matter properties of peat soils, and the historical variations for these two selected peaks are shown in Table 1 and Fig. 2. Over the past 150 years, the average values of peak 1720 and peak 3437 in the five peat cores were 0.33 ± 0.13–0.44 ± 0.04 and 0.58 ± 0.18–0.92 ± 0.05, respectively. In the GH peat core, both peak 1720 and peak 3437 showed the lowest values and were significantly different from the other four peat cores. There were no significant differences for peak 1720 in the other four peat cores, while peak 3437 in HT was clearly higher than for the other cores, which showed values of approximately 0.72. From 1880 to present, most of the highest values for peaks 1720 and 3437 occurred after 1950, and there were no significant differences between 1950 and 1980 and after 1980 in several peat cores (e.g. HT, MG). Only in the GH peat core, the highest values of peak 1720 (0.44 ± 0.10) and peak 3437 (0.72 ± 0.13) both appeared in 1900–1950 and were significantly higher than in other periods.

3.2. Impact of environmental factors on carbohydrate and aromatic contents

The carbohydrate contents in the peat soils in the northern Great Khingan Mountains were between 35.7 ± 3.1% and 43.5 ± 10.7%, and the aromatic contents were between 26.0 ± 1.9% and 27.8 ± 0.7% (Table 1). Linear regression analyses between peat carbohydrate or aromatic contents and latitude or selected meteorological parameters were used to reflect the impacts of location and regional climate on the carbohydrate and aromatic contents, and the results are shown in Fig. 3. Similar to other northern peatlands, the results also showed higher carbohydrate contents and lower aromatic contents in peatlands in the northern Great Khingan Mountains than those in low latitude peatlands (Fig. 3a, e). The carbohydrate and aromatic contents in the peat soils in the northern Great Khingan Mountains were similar to those peat soils where the annual precipitation was approximately 500 mm. With annual precipitation increasing from 500 to 3000 mm, the carbohydrate contents decreased ($R^2 = 0.16$) and the aromatic contents increased ($R^2 = 0.16$) (Fig. 3c, g). With increasing solar radiation, the carbohydrate contents decreased and the aromatic contents increased (Fig. 3d, h). The R^2 values for carbohydrates and aromatics were similar and were approximately 0.5 (e.g. 0.46 for carbohydrates and 0.50 for aromatics). The impact of the mean July temperatures on

Table 1
Average and standard deviations of the carbon accumulation rates (CAR); carbohydrate contents; aromatic contents; FTIR peak 1720; and FTIR peak 3437 for five typical peat sites during four different periods (before 1900, 1900–1950, 1950–1980 and after 1980) in the northern Great Khingan Mountains.

Sites	Periods	CAR g m^{-2} yr^{-1}	Carbohydrate %	Aromatic %	Peak 1720	Peak 3437
GH	Before 1900 *n* = 3	78.0 ± 24.3a	60.3 ± 0.7b	24.3 ± 0.3a	0.18 ± 0.00a	0.38 ± 0.01a
	1900–1950 *n* = 9	136.5 ± 60.6ab	36.2 ± 9.1a	27.7 ± 1.2b	0.44 ± 0.10b	0.72 ± 0.13b
	1950–1980 n = 9	185.0 ± 71.7ab	45.4 ± 9.4a	25.8 ± 1.6ab	0.31 ± 0.13ab	0.52 ± 0.17ab
	After 1980 *n* = 5	190.4 ± 72.3b	43.2 ± 5.9a	24.2 ± 1.3a	0.28 ± 0.06ab	0.58 ± 0.17ab
	Total *n* = 26	156.9 ± 71.5AB	43.5 ± 10.7B	26.0 ± 1.9A	0.33 ± 0.13A	0.58 ± 0.18A
HT	Before 1900 *n* = 6	35.5 ± 26.1a	36.0 ± 0.9a	28.1 ± 0.3a	0.43 ± 0.02b	0.95 ± 0.03a
	1900–1950 *n* = 8	64.0 ± 46.9ab	40.2 ± 3.5b	28.1 ± 0.6a	0.38 ± 0.05a	0.89 ± 0.03a
	1950–1980 *n* = 13	168.2 ± 70.7c	34.1 ± 1.9a	27.6 ± 0.5a	0.47 ± 0.03b	0.90 ± 0.05a
	After 1980 *n* = 15	106.4 ± 28.6b	34.7 ± 1.7a	27.8 ± 0.9a	0.45 ± 0.02b	0.94 ± 0.07a
	Total *n* = 42	107.3 ± 67.1A	35.7 ± 3.1A	27.8 ± 0.7C	0.44 ± 0.04B	0.92 ± 0.05C
HY	Before 1900 n = 3	22.7 ± 8.2a	48.5 ± 3.2c	26.6 ± 0.4b	0.30 ± 0.03a	0.68 ± 0.05a
	1900–1950 n = 9	148.6 ± 74.9b	45.3 ± 3.4c	25.5 ± 0.5a	0.33 ± 0.03a	0.63 ± 0.04a
	1950–1980 *n* = 11	210.1 ± 51.2b	38.5 ± 3.9b	25.9 ± 0.6ab	0.41 ± 0.06b	0.70 ± 0.09a
	After 1980 *n* = 12	139.3 ± 50.2b	33.5 ± 1.9a	26.8 ± 1.0b	0.45 ± 0.04b	0.80 ± 0.05b
	Total *n* = 35	154.0 ± 74.4AB	39.4 ± 6.2AB	26.2 ± 0.9AB	0.40 ± 0.07AB	0.71 ± 0.09B
MG	Before 1900 n = 2	19.9 ± 4.2a	72.1 ± 0.9c	17.0 ± 0.4a	0.09 ± 0.00a	0.22 ± 0.00a
	1900–1950 n = 6	133.7 ± 66.3b	44.6 ± 6.8b	24.6 ± 2.0b	0.33 ± 0.09b	0.53 ± 0.13b
	1950–1980 *n* = 10	210.3 ± 51.8b	31.3 ± 3.4a	27.2 ± 1.2c	0.50 ± 0.06c	0.85 ± 0.09c
	After 1980 n = 13	199.7 ± 53.2b	31.6 ± 2.2a	27.1 ± 1.2c	0.48 ± 0.06c	0.84 ± 0.06c
	Total *n* = 31	178.7 ± 72.7B	36.6 ± 11.4A	26.0 ± 2. 9A	0.43 ± 0.13B	0.74 ± 0.20B
TQ	Before 1900 n = 4	33.0 ± 5.3a	48.7 ± 9.5b	26.4 ± 0.9a	0.33 ± 0.10a	0.58 ± 0.10a
	1900–1950 n = 5	73.86 ± 20.34a	46.7 ± 6.9ab	26.7 ± 1.2a	0.35 ± 0.10a	0.64 ± 0.15ab
	1950–1980 n = 10	204.2 ± 48.6b	37.7 ± 6.2a	27.8 ± 0.7a	0.47 ± 0.09b	0.79 ± 0.13b
	After 1980 *n* = 14	208.9 ± 57.0b	38.5 ± 4.6a	27.2 ± 1.0a	0.42 ± 0.05ab	0.73 ± 0.10ab
	Total *n* = 33	165.7 ± 82.7B	40.8 ± 7.2AB	27.2 ± 1.0BC	0.42 ± 0.09B	0.72 ± 0.13B

a, b, c: groups of four periods in each site were divided by one-way ANOVA analysis and Tukey's honestly significant difference (Tukey-HSD) test.
A, B, C: groups of five sites were divided by one-way ANOVA analysis and Tukey's honestly significant difference (Tukey-HSD) test.

carbohydrate and aromatic contents was more obvious than for the other factors with high R^2 values, for which the R^2 values were 0.72 for carbohydrate content and 0.74 for aromatic content (Fig. 3b, f).

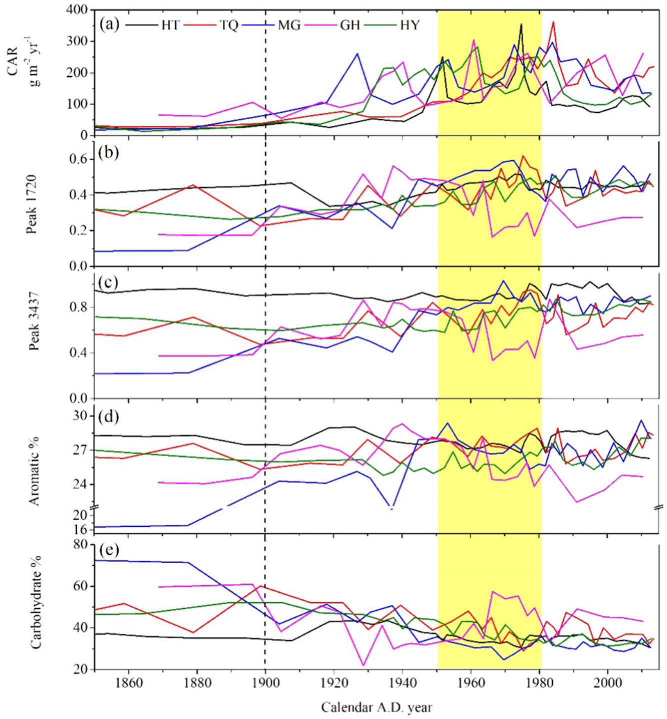

Fig. 2. Chronology of carbon accumulation rates (CAR); FTIR peak 1720; FTIR peak 3437; aromatic contents; and carbohydrate contents for five typical peat sites in the northern Great Khingan Mountains. TQ = Tuqiang, HY = Huyuan, HT = Hongtu, MG = Mangui, and GH = Genhe. The dash line and color shading is used to divide the past 150 years into four periods; dash line represents 1900, and the yellow shading represents the period from 1950 to 1980. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

With increases in mean July temperatures, the carbohydrate contents decreased and the aromatic contents increased.

3.3. Impact of PyC concentrations and PyC accumulation rates on peatlands carbon pool

Integrated trend lines calculated by non-linear regression analyses of CARs, carbohydrate, aromatic contents vs. PyC concentrations or PyCARs are shown in Fig. 4. As the PyCARs increased from 2 to 10 g m^{-2} yr^{-1}, the CARs increased from 20 to 200 g m^{-2} yr^{-1}. However, there was no obvious increasing trend as the PyCARs increased from 10 to 25 g m^{-2} yr^{-1}(Fig. 4a). When comparing the carbohydrate and aromatic contents with the PyCARs levels, there was no obvious trend between the aromatic contents and PyCARs. While, with increasing PyCARs, the carbohydrate contents clearly decreased (Fig. 4c, e). Unlike the case that there was no obvious relationship between PyC concentrations and CARs, as the PyC concentrations increased from 1 to 10 mg/g, the aromatic contents increased and the carbohydrate contents decreased (Fig. 4d, f). While, with PyC concentrations increasing from 10 to 40 mg/g, there was no obvious change in carbohydrate content. As the PyC concentrations increased from 1 to 40 mg/g, the aromatic contents increased from 26.5 to 28% in total.

3.4. Historical variation of carbohydrate and aromatic contents in peat soils

The overall trend for the carbohydrate content decreased from 50% in 1850 to 30% in recent years, and the aromatic contents increased slightly (Fig. 2). The highest carbohydrate content in all five peat cores for different periods was 72.1 ± 0.9% in the MG peat core before 1900, and the lowest carbohydrate content was also in the MG peat core and was 31.3 ± 3.4% in 1950–1980. Except for the HY peat core, there were no significant differences in the carbohydrate contents for 1950–1980 and after 1980. The carbohydrate contents in these two periods were definitely lower than those in nearby periods within the same peat core. In TQ and HT, there were no significant differences in the aromatic content in different periods, and they were approximately 27% and 28%, respectively. Low aromatic contents in the GH peat core

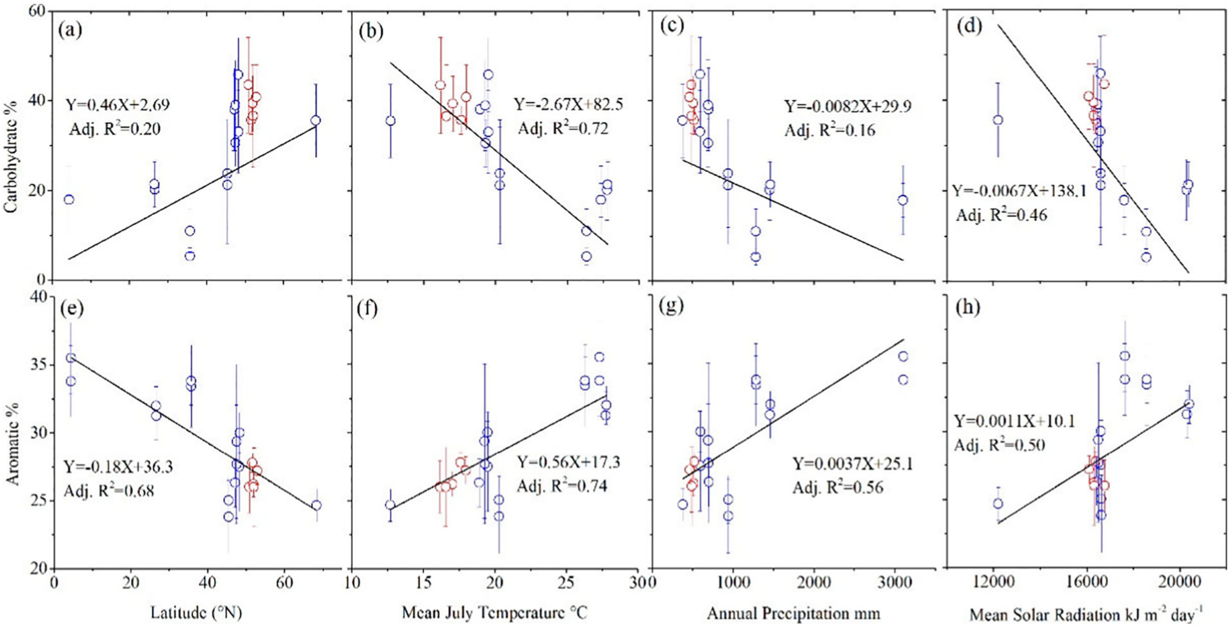

Fig. 3. Relation between estimated carbohydrate (a–d) and aromatic (e–h) contents with latitude, mean July temperature, annual precipitation, and mean solar radiation from April to October. Each point represents the average ± one standard deviation of the peat sites in the northern Great Khingan Mountains (red circles) and the values for other peat sites around the world, obtained from previous studies (blue circles, Hodgkins et al., 2018). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

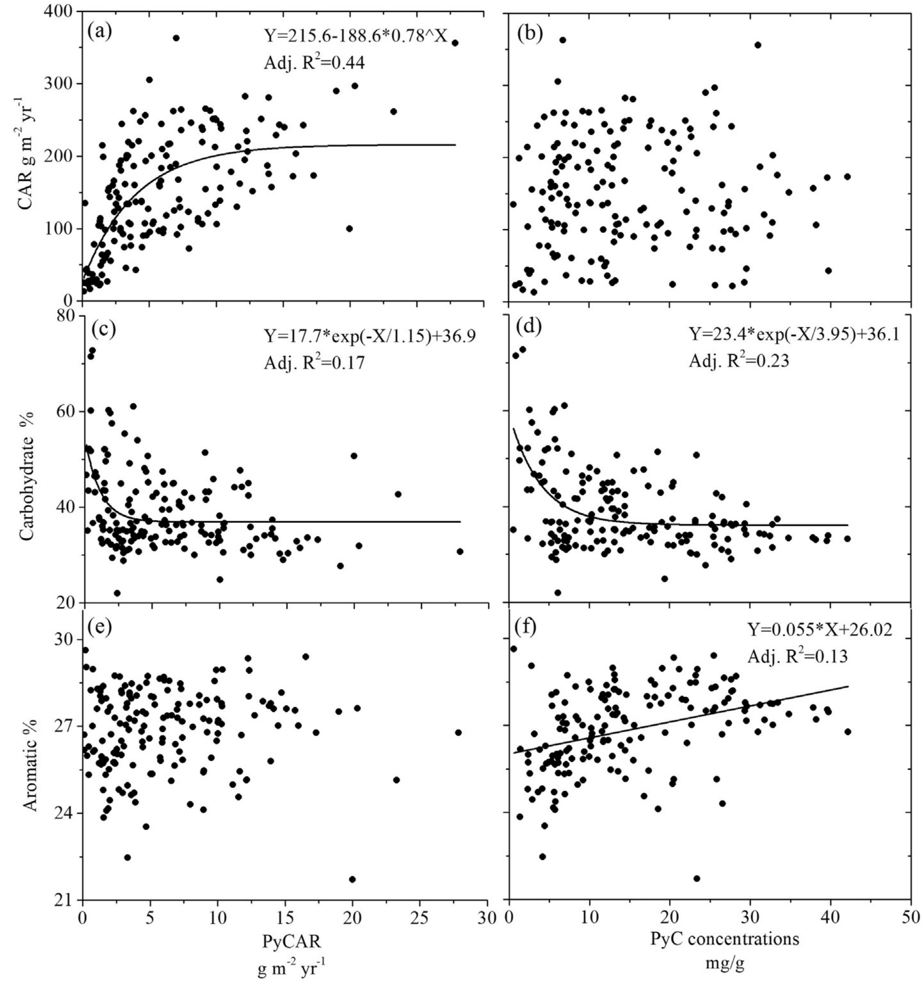

Fig. 4. Carbon accumulation rates, carbohydrate contents and aromatic contents versus the PyC accumulation rates (PyC AR, left) and PyC concentrations (right) for five peatlands sites in the northern Great Khingan Mountains. The fitting functions show the overall trends of the combined data.

appeared before 1900 and after 1980, while high aromatic contents in the HY peat core appeared in these two periods.

3.5. Historical variation of carbon accumulation rates

The CARs in the five peatlands in the northern Great Khingan Mountains during different periods are shown in Table 1 and Fig. 2. Each data point in Fig. 2 shows the CAR for each 1 cm section of the peat core. Over the past 150 years, the average CARs in the five peat cores were between 107.3 ± 67.1 g m^{-2} yr^{-1} in HT and 178.7 ± 72.7 g m^{-2} yr^{-1} in MG. The average CARs in HT were the smallest of all five peat cores and were significantly different from the other four peat cores. The average CARs in MG and TQ were 178.7 ± 72.7 g m^{-2} yr^{-1} and 165.7 ± 82.7 g m^{-2} yr^{-1}, respectively, which were similar to and noticeably higher than for the other samples. Over the past 150 years, the lowest CARs in the five peat cores always occurred before 1900 and were between 19.9 ± 4.2 g m^{-2} yr^{-1} in MG and 78.0 ± 24.3 g m^{-2} yr^{-1} in GH. High CARs in the five peat cores occurred after 1950, and there were no significant differences in the CARs in 1950–1980 and after 1980 in most of the peat cores (except for the HT peat core). In the HT peat core, the CARs were 168.2 ± 70.7 g m^{-2} yr^{-1} from 1950 to 1980 and were significantly higher than after 1980, which showed a value of only 106.4 ± 28.6 g m^{-2} yr^{-1}.

4. Discussion

4.1. Stability of peatlands carbon pools in the northern Great Khingan Mountains

To evaluate the stability of the peatlands C. pools in the northern Great Khingan Mountains and whether high wildfire frequency leads to stability of the peatlands C. pools in the studied region that is different from other peatlands, the carbohydrate and aromatic contents at other sites around the world as reported in a previous study (Hodgkins et al., 2018) were used in this study. Although meteorological data were collected from a dataset of global spatially interpolated monthly climate data, same source of meteorological data for all sites make the meteorological parameters in different sites were unify and comparable (Fig. 3).

The carbohydrate contents in the northern Great Khingan Mountains were similar to those seen for Minnesota (47°N—49°N) and were approximately 40%. In contrast, the carbohydrate contents in the northern Great Khingan Mountains and Minnesota (47—53°N) were slightly higher than those in northern Sweden (68°N) and Mer Bleue (45°N), for which the carbohydrate contents were approximately 35% and 22%, respectively (Hodgkins et al., 2018). Due to the high carbohydrate contents in Minnesota and in the northern Great Khingan Mountains or the low carbohydrate contents in Sweden, the R^2 value in this linear model was only 0.20, which indicates that the relationship between carbohydrate content and latitude is weak (Fig. 3a). Unlike carbohydrate content vs. latitude (Fig. 3a), the R^2 value in the linear model of aromatic content vs. latitude was 0.68, indicating that the impact of latitude on aromatic contents in peat soils was stronger than for carbohydrate contents. Aromatic contents in leaves in low latitude peatlands are marked lower than those in mid-high latitude peatlands, especially in shrubs and trees (Wang et al., 2015). From tropical peatlands to northern peatlands with increasing latitude, the decreasing of aromatic contents in leaves was speculated as major factor that lead the aromatic contents in the peat soils also clearly decreased. Additionally, the aromatic contents in the peatlands in the northern Great Khingan Mountains (approximately 27%) were lower than those in Minnesota (approximately 29%) and higher than those in northern Sweden (approximately 24%). Thus, the peatlands locations strongly affect the aromatic content in peat soils and weakly affect the carbohydrate content.

Climate factors, such as temperature, precipitation, and solar radiation, are key factors that influence C. accumulation and the decomposition process in peatlands (Gallego-Sala and Prentice, 2013; Wang et al., 2014; Xing et al., 2015). For example, high temperatures and low precipitation reduce the peat CARs (Bragazza et al., 2016). High precipitation increases the moisture levels in peatlands, and sufficient moisture delays the decomposition processes in peat soils (Laiho, 2006). As sufficient moisture also decreases local plant growth, high moisture levels do not promote higher CARs (Gallego-Sala et al., 2018). A more definite decreasing trend for carbohydrate contents occurred as the precipitation increased from 500 to 1500 mm. There were no obvious changes in carbohydrate content as the precipitation increased from 1500 to 3000 mm, which means that high precipitation also does not change the carbohydrate content. Furthermore, the C. stabilities in peatlands were mainly influenced by the variations in aromatic content under the high-precipitation environment. Similar to latitude, the impacts of precipitation on the aromatic content were stronger than those on the carbohydrate content. Solar radiation mainly influenced C. accumulations and stability through the net primary productivity (NPP) of local plants. The photosynthetically active radiation summed over the growing season is the best explanatory variable of all the bioclimatic variables that were statistically fitted to the C. accumulations in the peatlands across different latitude regions (Gallego-Sala et al., 2018). The impacts of solar radiation on the contents of these two types of chemical compounds were similar, due to similar R^2 values for carbohydrates and aromatics. Interestingly, the impacts of solar radiation on these two chemical compounds mainly occurred as the solar radiation increased from 15,000 to 20,000 kJ m^{-2} day^{-1}, and no obvious change occurred if the solar radiation was below 15,000 kJ m^{-2} day^{-1}.

Both chemical compounds in peat soils from the northern Great Khingan Mountains were close to the linear regression functions and were similar to those that were located in regions with similar mean July temperatures around the world (Hodgkins et al., 2018). With increasing temperature, more aromatics and less carbohydrates were available in peat soils, leading to a more stable C. pool. The variations in growing season temperature also served as a trigger for peatlands initiation (Morris et al., 2018). High growing season temperatures not only promoted the NPP of local plants but also increased the decomposition rates of surface plant litter due to an increase in microbial activities. Peat soils with high carbohydrate/low aromatic contents were more easily decomposed than those with low carbohydrate/high aromatic contents (Leifeld et al., 2012; Wang et al., 2015). This indicates more C. inputs in the high temperature environments, and more unstable C. compounds were decomposed by high microbial activity under the warm environment (Liu et al., 2019). Finally, the high amounts of stable C. compounds, such as the aromatics, were more readily preserved in peatlands. Thus, the warm environment promote more stable C. compounds residues in peatlands and cause the peatlands C. pool to be more recalcitrance.

The stabilities of the peatlands C. pool in the northern Great Khingan Mountains were similar to other peatlands located at sites with similar climate condition around the world (Hodgkins et al., 2018). The mean July temperature was the most important climate factor for C. stability in the peatlands C. pool. With increases in mean July temperatures, more aromatics and fewer carbohydrate residuals were seen for peat soils and the C. stability for the peatlands carbon pools notably increased. Except for the mean July temperatures, increases in annual precipitation and decreases in latitude also produced more available aromatics in peat soils and increased the stability of the peatlands C. pool.

4.2. Wildfire influence on peatlands carbon pools in the northern Great Khingan Mountains

As highlighted in previous studies, for the wildfire impacts on C. dynamics in northern peatlands (Gao et al., 2016; Heinemeyer et al., 2018; Leifeld et al., 2018; Marrs et al., 2018), historical research on C. stability and PyCARs has provided novel insights into the potential impact of wildfire on the stability and accumulation of C. in permafrost peatlands. Due to low fossil fuel consumption in this region, the major source of PyC in the northern Great Khingan Mountains was wildfire (Gao et al., 2018). The PyC concentrations were used to evaluate the amounts of wildfire residual products in this study. Because the PyCARs levels were calculated based on the peat accumulation rates, PyCARs reflected the deposition of wildfire residual products by year, and thus could be used to reflect historical wildfire frequency and severity.

The relationship between PyCARs and CARs indicates that low wildfire frequencies promoted more C. accumulation in peatlands; in contrast, high wildfires frequencies may burn up the peat soils on the surfaces of peatlands and decrease the CARs in peatlands. Field experiments in previous studies have demonstrated that high wildfire frequencies caused the CARs in peatlands to significantly decrease, and each additional burning episode reduced the ARs by 4.9 g m^{-2} yr^{-1} (peat) and by 1.9 g C m^{-2} yr^{-1} directly (Marrs et al., 2018). Low carbohydrate contents with high PyCARs levels indicate high wildfire frequency that accelerated the decomposition of unstable C. compounds, and carbohydrates were more easily destroyed by wildfire. With PyCARs values increasing from 5 to 25 g m^{-2} yr^{-1}, the carbohydrate contents remained stable and were approximately 37%. Wildfire increased species diversity and the abundance of peat-forming species, which increased the plant C. that accumulated on the peatlands surfaces as plant litter (Zhao et al., 2012). High amounts of carbohydrates from plants were able to maintain the carbohydrate content at approximately 37% in peat soils. High wildfire frequency increased the amounts of PyC residues in peat soils that contained high amounts of aromatics and were stable (Hammes et al., 2007; Leifeld et al., 2018). While, due to the low PyC contents (5–13%) in the total peatlands C. pool, the increasing of PyCARs were not sufficient to directly and markedly increase the aromatic contents in peat soils (Gao et al., 2016; Leifeld et al., 2018). So, although PyC is one type of aromatic-rich carbon material, the lack of a clear relationship between aromatic contents and PyCARs levels indicates that increases in aromatic contents did not all come from PyC. Part of aromatic contents in peat soils might came from surface plants, such as shrubs. Thus, the CARs and carbohydrate contents in peat soils were sensitive to low levels of wildfire frequency, which was associated with PyCARs levels below 10 g m^{-2} yr^{-1}. Further, there were no obvious changes in CARs and carbohydrate contents in peat soils under high frequency wildfire conditions (PyCARs higher than 10 g m^{-2} yr^{-1}).

Except for the direct impact of wildfire on the C. accumulation process and the C. stability in peat soils, the residual wildfire products (PyC) may exert potential influences on peatlands C. pools due to their physico-chemical characteristics (e.g. recalcitrance and high surface area). PyC in the peatlands C. pool not only acts as the most stable C. store in the peatlands C. pool (Hammes et al., 2007; Wang et al., 2016), but can also impact biogeochemical cycles in burned peatlands, via, for example, changes in microbial activity and promoting the decomposition of native organic matter (Könönen et al., 2018; Noble et al., 2018). Increases in microbial activity promoted the decomposition of weakly stable C. compounds and was speculated as the major factor that notably decreased carbohydrate contents (Singh et al., 2017). While, high levels of PyC in peat soils also could promote plant growth and produce more carbohydrate compounds from plant litter residues in peat soils. These results indicated the different impacts of different PyC amounts that affected microbial activities and carbohydrate sources (Fig. 4d). Compared to the unstable C. compounds, the stable C. compounds, such as the aromatics, more readily remained in peat soils if there were high amounts of PyC. Thus, with increasing PyC concentrations, more aromatics, not only from PyC but also from plant sources that were residues in peat soils, definitely increased the aromatic contents. Additionally, the impact of the PyC on the aromatic contents was more obvious than the direct wildfire effects on the aromatic contents.

With increases in wildfire frequency, more C. with low carbohydrate content and high aromatic content can accumulate in peatlands, which means that peatlands carbon pools accumulated under the high wildfire frequency were more stable. Variations in wildfire within a low level (e.g. PyCARs below 10 g m^{-2} yr^{-1}) more clearly showed the impact of fire frequency on the stability of the peatlands carbon pool. Not only the direct effects of wildfire on the peatlands C. pool, but the residual PyC also influenced the stability of the peatlands C. pool. Increasing PyC content decreased the carbohydrate content and increased the aromatic content, thus increasing the stability of the peatlands C. pool.

4.3. Historical impacts of anthropogenic and climate factors on the peatlands carbon pool

As there are other permafrost peatlands with warm spring seasons and low precipitations, the northern Great Khingan Mountains are threatened by high wildfire frequency due to their warm spring seasons and low precipitation. More than 1500 wildfire events occurred in the northern Great Khingan Mountains from 1966 to 2005 and affected more than 60,000 km^2 (Zhang, 2008). Serious variations in wildfire frequency are one of the important factors affecting the C. accumulation history and C. stability in the permafrost peatlands in this region. Due to rapid increases in regional human activities, wildfire frequency is the most direct indicator for reflecting the impact of anthropogenic factors in this region (Gao et al., 2018). For evaluating the impact of wildfire on C. accumulation and stability, the PyCARs levels and wildfire scars recorded by tree rings in previous studies were selected as indicators to indicate the frequency of wildfires in the studied region (Gao et al., 2018). Combined with wildfire and climate data (Novorotskii, 2007), historical variations of CARs, carbohydrate content and aromatic content, and their potential influencing factors in the northern Great Khingan Mountains are shown in Fig. 5.

Before 1900, the average CARs in the northern Great Khingan Mountains were low at approximately 50 g m^{-2} yr^{-1}. In this period, the carbohydrate contents in peat soils were higher than the blue trend lines, and the aromatic contents were low (Fig. 5b, c). In general, the CARs in this period were low and the C. stability was weak. During this period, few humans lived in the northern Great Khingan Mountains, and wildfires were mainly caused by natural factors such as lightning. The few wildfire scars recorded by tree rings and the low PyCARs in this region indicated that the wildfire frequency was lower and that the burn areas were smaller (Lu, 2012; Gao et al., 2018). Climate data indicated that the climate conditions were cool and dry before 1900 (Novorotskii, 2007). Based on the previous discussion, the C. stability, which accumulated under low temperatures and a dry environment, was weaker than those accumulations that formed under high temperatures and wet environments (Fig. 3). There were also no obvious wildfire events detected and this promoted the accumulation of more stable C. compounds in the peatlands during this period. Thus, low wildfire frequency and cold/dry climate conditions in the northern Great Khingan Mountains were the major factors that led to lower CARs and weaker stability of the C. pool in this period than for nearby periods (e.g., 1900–1950).

After 1895, increasing population and increasing intensities of forest resource exploitation led to increases in the frequency of wildfire events, as indicated by the increasing numbers of wildfire scars and by the PyCARs (Lu, 2012; Gao et al., 2018). From the 1900s to the 1970s, the forest resources of the Great Khingan Mountains were exploited without constraints. With the increases in wildfire frequency and a warmer and wetter climate from 1900 to 1950, the carbohydrate contents decreased, while the aromatic contents and CARs increased. The increasing aromatic contents indicate that the stability of the permafrost peatlands C. pool in the northern Great Khingan Mountains changed to a more stable state, especially after 1940, when high wildfire

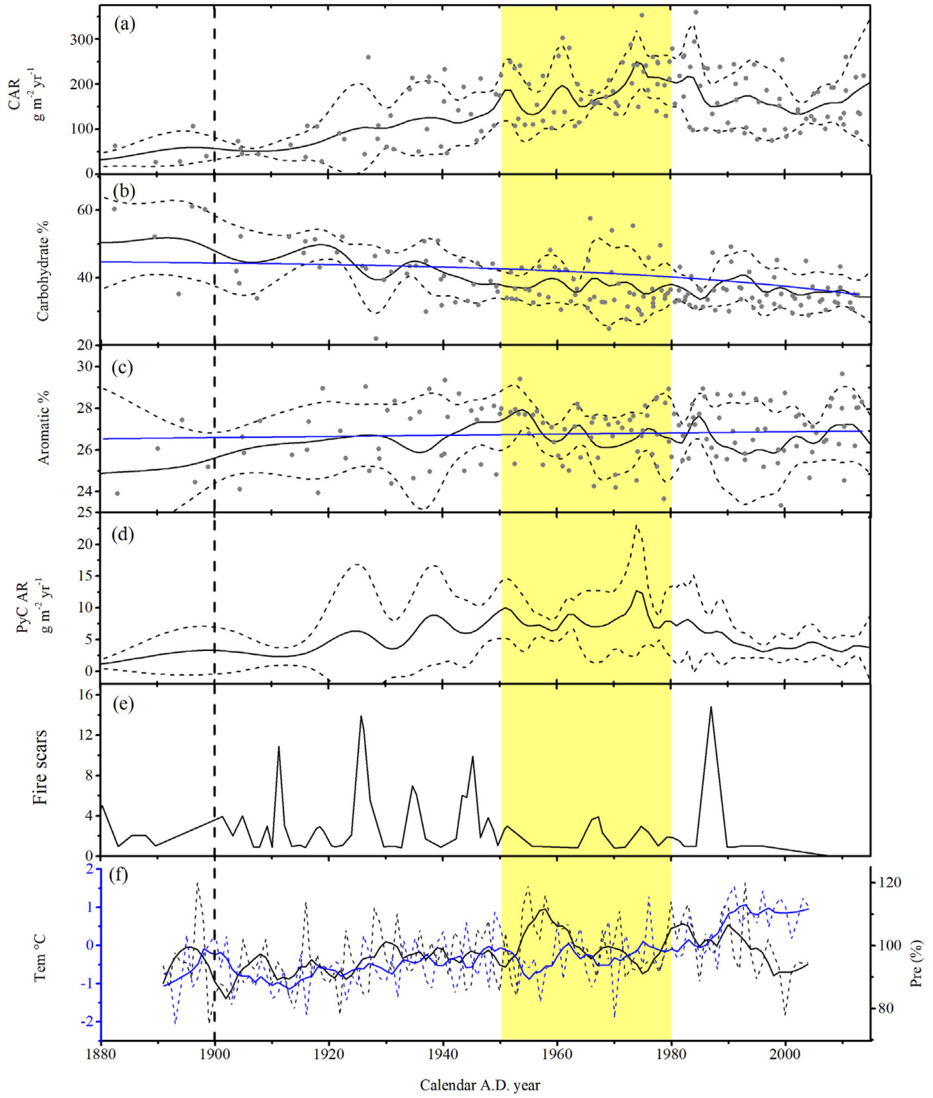

Fig. 5. (a) Averages (solid black) ± standard deviation (black dashes) of the carbon accumulation rates at five peatlands sites in the Northern Great Khingan Mountains (dots indicate original CARs); (b) Average ± standard deviation and fitted lines (blue) of the carbohydrate contents at five peatlands sites in the Northern Great Khingan Mountains (dots indicate original carbohydrate contents); (c) Average ± standard deviation and fitted lines (blue) of the aromatic contents at five peatlands sites in the Northern Great Khingan Mountains (dots indicate original aromatic contents); (d) Average ± standard deviation of the PyC accumulation rates (PyC AR) at five peatlands sites in the Northern Great Khingan Mountains (Gao et al., 2018); (e) Numbers of fire scars in the northern part of the Great Khingan Mountains (Lu, 2012); (f) Annual mean air temperature anomalies (°C) and the long-period changes in total annual precipitation (%, the ratio to the mean for 1961–1990) in the Amur River basin from 1891 to 2004 (Novorotskii, 2007). The dash line and color shading is used to divide the past 150 years into four periods; dash line represents 1900, and the yellow shading represents the period from 1950 to 1980. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

frequencies occurred in this region. Increases in regional human activities were the major factors that caused the wildfire frequencies and severities to increase markedly in this period. High wildfire frequency promotes the accumulation of more stable C. compounds in the peatlands in the northern Great Khingan Mountains. Thus, the high wildfire frequencies led to more stable C. accumulations in the peatlands and the C. pool that accumulated in this period was more stable than for nearby periods.

After the founding of the People's Republic of China in 1949, forest resource exploitation continued in the Great Khingan Mountains until the 1980s (Gao et al., 2018). The high wildfire frequencies were similar to the period in 1900–1950, while the climate characteristics in this period were definitely different from those in 1900–1950. Low temperatures and high precipitation were the main characteristics in 1950–1980. During this period, the CARs continued to increase from 100 to 200 g m^{-2} yr^{-1}, and the highest CARs in the studied region occurred in the middle of the 1970s. However, the peatlands C. pool stability fluctuated and the aromatic contents decreased when the climate properties were cold/wet in the 1950s and around 1970. Low temperatures and high precipitation may have decreased the aromatic contents and increased the carbohydrate contents in the northern Great Khingan Mountains. Similar with 1900–1950, high wildfire frequency from 1950 to 1980 caused more C. to be accumulated in the peatlands of the northern Great Khingan mountains. While, the climate fluctuations (especially high precipitation and low temperature) in 1950–1980 caused the peatlands C. pool to be less stable than in 1900–1950.

After ending of this period of resource exploitation, the government began to monitor and control wildfires, especially anthropogenic fires, in the Great Khingan Mountains in 1977. As a result, the wildfire frequencies and burn areas in the Great Khingan Mountains clearly decreased after 1980, and especially after 1987 (Gao et al., 2018). After 1980, the average annual temperatures gradually increased, while the annual precipitation decreased (Novorotskii, 2007). Due to the decreased wildfire frequency, the CARs and aromatic contents clearly declined in this period, most notably from 1980 to 2000. The decrease in wildfire frequency decreased the amount of stable C. compounds that accumulated in the peatlands and also stopped promoting plant growth, thus, the CARs and C. stability began to decrease in this period. In contrast, with increasing temperatures (especially after 2000), the warm/dry climate conditions lowered the peatlands water tables. With this change, the abundance of plants, and especially the diversity of shrubs increased markedly (Murphy et al., 2009). More stable C. compounds (e.g. lignin) from shrub litter accumulated in the peatlands, which is speculated as the major factor that caused the aromatic contents to increase starting from 2000 to the present. Except for the aromatic contents, the increasing plant growth promoted the accumulation of more C. in peatlands and the CARs also began to increase after 2000.

The historical variations in CARs and C. stability in the permafrost peatlands in the northern Great Khingan Mountains during the last 150 years were mainly controlled by climate change and also by regional wildfire frequency, which was mainly influenced by regional human activities. High wildfire frequencies increased the CARs and the stability of the C. pool in the peatlands in this region from 1900 to 1980. The effects of climate factors on the C. pool were more obvious after the local wildfire frequency was controlled by environmentally friendly policies in the 1980s. In particular, after 2000, the increasing temperatures and decreasing precipitation promoted the accumulation of more C. with high aromatic content in the peatlands, and ultimately led to high CARs and a more stable peatlands C. pool in this period.

5. Conclusions

This is the first study to evaluate the historical stability of the C. pool in a permafrost peatlands in relation to different anthropogenic and climate factors and to interpret the effects of wildfire. Compared with other peatlands around the world, the stability of the peatlands in the northern Great Khingan Mountains is similar to those at sites located at similar latitudes and with similar climate conditions, and the mean July temperature is the most important climate factor for C. stability in the peatlands C. pool. As the local wildfire frequency remained at low levels (recorded by PyCARs levels below 10 g m^{-2} yr^{-1}), the CARs and carbohydrate contents were sensitive to wildfires. The increasing wildfire frequency caused more C. with low carbohydrate contents from plants and wildfire residual products accumulated in peatlands, and increased the stability of the peatlands C. pool. Regional human activities caused high wildfire frequencies from 1900 to 1980 and increased the CARs and stability of the C. pool in the peatlands of the northern Great Khingan Mountains. After 1980, the wildfire frequency decreased due to environmentally friendly policies that reduced wildfire frequencies and climate conditions started to influence the stability of the C. pool in the studied region. Especially after 2000, the increasing temperatures and decreasing precipitation caused both the CARs and the stability of the peatlands C. pool in the northern Great Khingan Mountains to markedly increase.

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