Effects of late-Holocene fires on the carbon sequestration capacity of peatlands in the Sanjiang Plain

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Abstract. Peatland fires are frequent, but the effect of fire on soil organic carbon in peatlands is still currently variable. Especially at long time scales, it has not been clarified. In order to reveal the relationship between carbon accumulation patterns in peatlands at long time scales in response to local fire changes, high-resolution peat sediments from peatlands in the Three River Plain were selected and analysed for stratified charcoal debris and organic carbon in this paper. The results showed that the stronger carbon sequestration capacity in the periods of 0.6, 0.75, 1.25, 2.3, 2.75, 2.9, 3.6 and 5 ka BP corresponded to weaker fire intensity or even no fire. Late-Holocene fires in the Sanjiang Plain reduced the rate of carbon sequestration, suggesting that fires have been an important driver of the reduction in carbon sequestration capacity over the last 6000 years.

1 Introduction

In recent decades, frequent fires have been occurring in several countries as a result of global warming and the increasing impact of human activities. Frequent fires can significantly alter the global carbon balance by affecting vegetation community succession, soil structure and nutrient cycling. The long-term effects of fires on ecosystem-atmosphere carbon exchange depend mainly on biogeochemical processes such as accumulation and depletion in vegetation and soils after fires[1]. Of these, carbon emissions from biomass burning account for only a fraction of the overall fire emissions. Soil, as one of the largest carbon reservoirs on the Earth's surface, contributes 2,344 Pg of global carbon[2]. The accumulation of carbon-containing sediments in soils is the long-term result of an imbalance in the production and decomposition of vegetation biomass[3]. Wildfires, by burning vegetation, not only affect soil carbon content during combustion but also change the previous state of carbon accumulation long after combustion[4].

Most of the current studies only compare the changes in soil carbon content before and after a single fire, and there is a lack of long-term fire and soil carbon dynamics records, which can lead to uncertainty in the effects of fire on soil carbon sequestration. In addition, a large number of studies have attempted to reveal the effects of fire regimes on surface organic carbon. Some studies have shown that fire regimes have a significant negative impact on surface carbon sequestration, e.g. a study in the Sydney Basin, Australia, found a negative correlation between forest carbon "sinks", AGC, and frequent and severe wildfires, suggesting temperature-mediated reductions in forest carbon stocks under projections of future climate change[5]. In contrast, another subset of studies yielded little to no effect at millennial scales, e.g., peatlands in northern North American peatlands are likely to be less sensitive to burning, and the lack of a clear correlation between fire regimes and carbon accumulation suggests that fire regimes are not a driver of carbon sequestration at millennial time scales[6]. Even the opposite trend exists, as soil organic carbon (OC) content increased in the first two growing seasons after fire in the northeastern part of the Three Rivers Plain[7]. Similarly, these studies usually attribute the effect of fire on soil carbon accumulation to climate change and to changes in vegetation cover and soil water content in response to climate change. Therefore, it is crucial to select records of prolonged fire and soil organic carbon changes from climate-sensitive areas. The Sanjiang Plain is located in northeastern China and is sensitive to climate change due to its mid-to-high latitude and monsoon edge position[8]. In this study, we quantify the charcoal debris and soil organic carbon content based on peat sediments from the Sanjiang Plain, and then explore the effects of late Holocene fires on long-term changes in carbon accumulation.

2 Study region

The Sanjiang Plain (129°11′-135°05′ E, 43°49′-48°27′ N) is located in the northeastern Heilongjiang Province, China (Fig. 1). It is a huge alluvial plain crossed by three major rivers (Heilong River, Wusuli River and Songhua River), with a total area of 10.9×106 ha, an altitude of <200 m and a slope grade of <1:10,000. The present climate of the plain is temperate humid or sub-humid

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continental monsoonal. Until recent decades, fresh-water wetlands covered over 70% of the plain.

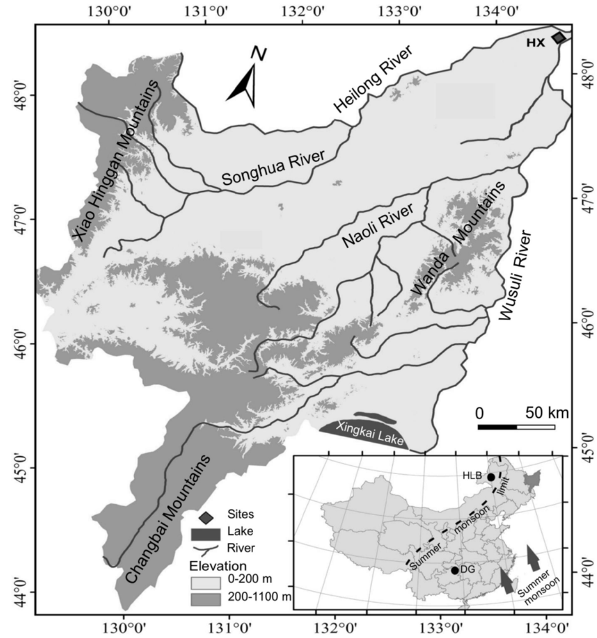

Fig. 1. Digital elevation model of the Sanjiang Plain.The solid diamond in black color indicates the sampling site[9].

3 Materials and research methods

The rock profile studied, HE (47° 35.096'N, 133° 30.006' E, 71 m a.s.l.), has a thickness of 148 cm, and all samples were collected at 1 cm thick intervals, for a total of 148 samples. As the results of sample collection and dating have been published in a separate article, they will not be repeated here[9](fig. 2). In addition, previous articles have conducted experiments related to the samples in this study, which provided charcoal debris and organic carbon data to support this study[9].

One hundred and forty-eight (148) 1 cm interval samples collected from cores were used for loss on ignition (LOI) and charcoal debris analyses. For LOI, samples with a volume of 2 cm^3 were sequentially burned in a muffle furnace at 500 °C and 900 °C to estimate organic matter and carbonate content. For carbon chip analysis samples were processed according to standard acetylation procedures. For each sub-sample with a volume of 2 cm^3 of air-dried sediment, 10 ml of 18% hydrochloric acid was added to remove carbonates. Then 10 ml of 10% NaOH was added and the solution was heated in a water bath at 90 °C for 30 min to remove organic matter. The residue was kept in 5 ml of 45% HF for 12 hours to remove silicates. After this treatment, the charcoal chips were separated from the macroscopic (> 125 μm) and microscopic (< 125 μm) fractions by means of a wet sieve and the charcoal and pollen pellets were concentrated using an ultrasonic cleaner and centrifuge. Slides were then prepared for mounting pollen and microscopic (< 125 μm) charcoal chips. Charcoal chips were identified and counted using an Olympus light microscope, and the total number of microscopic (< 125 μm) charcoal particles exceeded 300. All macroscopic charcoal particles (> 125 μm) from each sample were identified and counted under a stereomicroscope at 80x magnification. To calculate the charcoal concentration, a known number of exotic Staphylococcus spp. spores were added to each sample prior to pretreatment and the charcoal concentration of both fractions was calculated with the aid of Staphylococcus spp. spore counts.

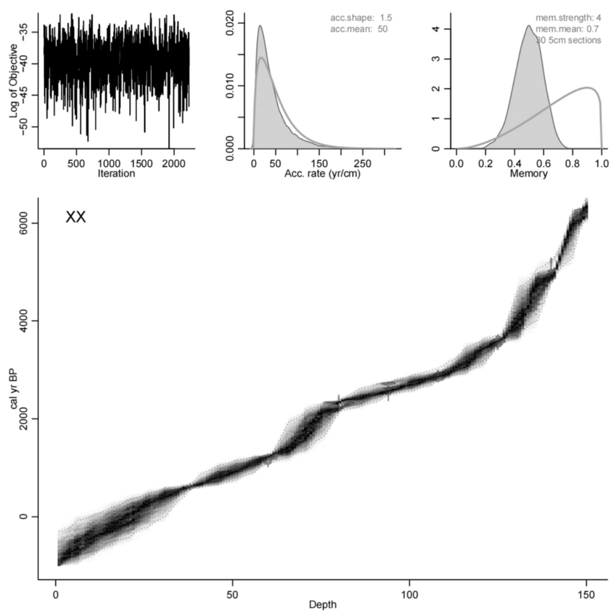

Fig. 2. Age-depth modelling of HE[9]

4 Discussion and analysis of results

The age-depth model shows that the sediment deposition process of HE is approximately 6000 years old. The charcoal debris in the sediments can indicate the scale and extent of fire occurrence, and the evolutionary history of fires during the geological history can be reconstructed by the different grain size contents of the charcoal debris. Typically, after a fire, a portion of the fine charcoal debris travelled downwind as the smoke rose into the air, while the coarse-grained charcoal debris was deposited in situ or in close proximity. In terms of propagation and deposition patterns, coarse-grained charcoal debris travelled shorter distances and was dispersed closer to the source area; in contrast, fine-grained charcoal debris was more easily transported over long distances by air currents, resulting in its dispersal in areas farther away from the source area. Therefore, the cumulative velocity of charcoal debris of different grain sizes in the depositional profile indicates different ranges of fire intensity[10](Fig. 3). Usually, the particle size of charcoal debris is divided by 125 μm, and it is believed that the large charcoal debris >125 μm is mostly deposited in the area of less than 3 km, which can reflect the local fire events, while the small charcoal debris <125 μm is transported by air currents over long distances, which can be indicative of the regional fire events. As shown in Fig. 3, the accumulation rates of large, small and total charcoal debris are generally similar. In addition, according to the trend of the accumulation rate of carbon debris of different grain sizes, the fire intensity can be classified as high or low, with stable changes in the periods of 6-5.7 and 3.7-1.5 ka BP, and lower fire intensity, and larger fluctuations in the periods of 5.7-3.7 and 1.5-0 ka BP, which resulted in higher fire intensity.

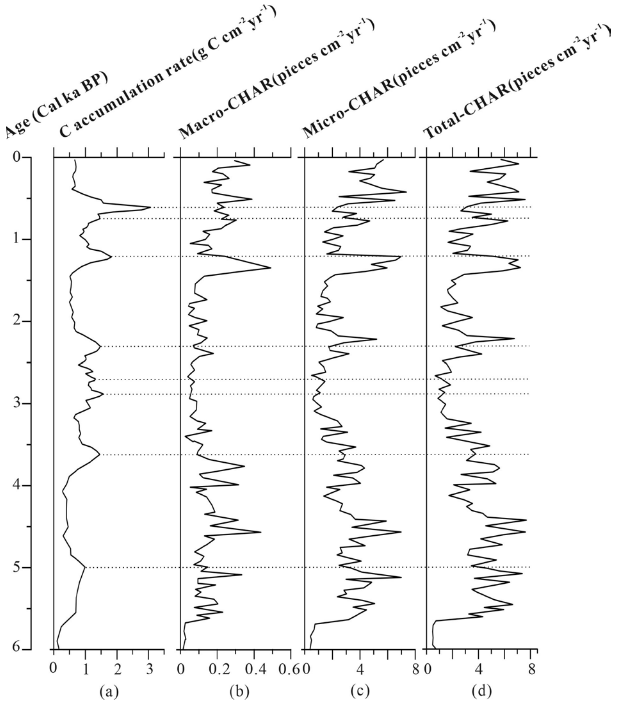

Fig. 3. C accumulation rate(a), charcoal analysis results(b,c and d) from the studied profile HE.

The apparent rate of organic carbon accumulation in the Late Holocene varied from 0.02 g C $cm^{-2}yr^{-1}$ to 3.07 g C $cm^{-2}yr^{-1}$, with an average accumulation rate of 0.95 g C $cm^{-2}yr^{-1}$. According to the rate of organic carbon deposition, it can be used as an indication of the strength of the soil's capacity to sequester organic carbon, and the rate of organic carbon sequestration in the periods of ~6-4, 2.2-1.25 ka BP tended to change steadily, with the capacity of sequestration being relatively weak, while that in the periods of 4-2.2, 1.5-0 ka BP fluctuated more, with the intensity of fire being generally lower. -2.2, 1.5-0 ka BP period changes are more dramatic, the overall carbon sequestration capacity is stronger. In the periods of 0.6, 0.75, 1.25, 2.3, 2.75, 2.9, 3.6, and 5 ka BP, the carbon sequestration capacity was strong, and the intensity of fires was weak or even did not occur. From this, we infer that the Late Holocene fire events in the Sanjiang Plain were unfavourable for organic carbon accumulation. It is widely believed that fires directly burned forest vegetation, causing the reduction of tree productivity and vegetation loss, which directly reduced the carbon sequestration capacity of vegetation in forest ecosystems[11]. At the same time, fire reduces the carbon pool of apoptosis and accelerates the decomposition of apoptosis by directly affecting the amount of apoptosis and indirectly affecting the decomposition rate of apoptosis. In addition, the effect of fire on forest soil carbon pools was manifested in the increase of soil organic matter decomposition, the increase of soil respiratory carbon release, the decrease of carbon input to the soil from above-ground vegetation, and the increase of black carbon as a carbon sink[12]. Therefore, we concluded that the occurrence of Late-Holocene fires in the Sanjiang Plain reduced soil carbon sequestration capacity.

The response of fire to carbon sequestration capacity varies across geography. It is generally accepted that fire depletes carbon sequestered at the surface through direct combustion and net post-fire emissions, but the effects of fire in marshy wetlands may be different. Due to the presence of a certain water table elevation in marshes, it is difficult for wildfires to penetrate the water table and cause damage to carbon stocks in the soil. Thus, the relatively low fire frequency in marshy wetlands, coupled with the dominance of surface fires, allows fire occurrence to play a special role in the long-term carbon accumulation process. In herbaceous-dominated wetland ecosystems, wildfires typically consume most of the biomass above the water table only through intensive, continuous surface fuel movement. Instead, dead plant roots remaining below the surface are decomposed by soil animals and incorporated into the soil. In addition, wildfires increase species diversity and the abundance of marsh soil formers, thereby increasing the amount of plant carbon accumulated on the surface of marsh soils by plant dieback. Thus due to fire-induced increases in surface biomass and subsurface carbon pools (from dead roots), more frequent and severe fires result in increased soil carbon content.

In addition to the direct effects of fire on the process of carbon accumulation in marshy wetland soils, large quantities of fire products (e.g., charcoal debris and charcoal black) can potentially affect carbon accumulation due to their physicochemical properties (e.g., recalcitrance and high surface area). Fire products in wetland soils not only act as the most stable portion of the wetland carbon pool, but medium to high levels of fire products can also promote plant growth and produce more carbohydrates from plant dieback residues in the soil. In addition, the high presence of carbon black in wetland soils makes it easier to retain stabilised carbon (e.g. aromatics) in the soil. And the high level of aromatic content means that the soil has higher stability. Therefore, we suggest that wetland fires not only promote the accumulation of soil carbon, but also the residual fire products increase the stability of soil carbon in marshy wetlands, which is very favourable for soil carbon sequestration on long time scales.

5 Conclusion

This study deepens our understanding of soil carbon sequestration in marshy wetlands as affected by fire. Based on the Late Holocene sedimentary charcoal debris and organic carbon records in the Sanjiang Plain, the studied aspects of fire conditions were linked to the rate of carbon accumulation in soils. The changes were more stable during the periods ~6-5.7, 3.7-1.5 ka BP its fire intensity was overall lower, and fluctuated more during the periods ~5.7-3.7, 1.5-0 ka BP, with an overall higher fire intensity. However, the change in the period of ~6-4, 2.2-1.25 ka BP tends to be stable with weaker carbon sequestration capacity, and the change in the period of 4-2.2, 1.5-0 ka BP is more drastic with overall stronger carbon sequestration capacity. In the periods of 0.6, 0.75, 1.25, 2.3, 2.75, 2.9, 3.6, and 5 ka BP, the carbon sequestration capacity was stronger, and the corresponding fire intensity was weaker or even no fire occurred. Thus, it can be demonstrated that fire in marshy wetlands greatly reduces long-term soil carbon sequestration.

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