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Black carbon deposition and storage in peat soils of the Changbai Mountain, China

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ABSTRACT

Black carbon (BC) is produced by incomplete combustion of fossil fuels and biomass and emissions are influenced by human activities. Due to its refractory nature and long half-life times, BC contributes to carbon sequestration in soils. Here, we investigated BC concentrations and storage in peatlands of the Changbai Mountains (Northeast China) and reconstructed historical trends of deposition fluxes from four peat cores. Results showed that there were no significant differences of BC deposition fluxes in different cores sampled at similar altitudes, but BC deposition fluxes at low altitudes were stronger influenced by human activities than those at high altitudes. During the last 150 years, more BC was emitted by increasing anthropogenic sources, and therefore the BC deposition fluxes accordingly increased. Total BC storage in peat soils of the Changbai Mountains was estimated to 1.61 Tg (5.13 Gg C km^{-2}) and a deposition flux of 3.30 Gg yr^{-1} of BC was calculated. The high BC deposition fluxes the fact that about 5% of carbon storage in peatland could be regarded as BC support that BC represents an important fraction of carbon storage in peatland ecosystems.

1. Introduction

Black carbon (BC) is produced by the incomplete combustion of fossil fuels or biomass. It is ubiquitous in the environment and influences biogeochemical processes in ecosystems (Hammes et al., 2007). The global BC emission was estimated to 50–385 Tg C yr^{-1} by vegetation fire and 4.4 Tg C yr^{-1} (2000 A.D.) by fossil fuel combustion, respectively (Kuhlbusch and Crutzen, 1995; Bond et al., 2007; Santín et al., 2016). BC is co-emitted with persistent organic pollutants (POPs) and enhances their transport into the atmosphere (Lohmann and Lammel, 2004; Elmquist et al., 2007; Nam et al., 2008). As an important component of atmospheric aerosols, BC is the second dominant factor besides CO_2 that contributes to climate change (Ramanathan and Carmichael, 2008). After few days of retention in the atmosphere (Streets et al., 2001), BC is deposited in the soil and can be stored in the soil carbon pool for millennia (Preston and Schmidt, 2006). Previous studies have thus focused on investigating the BC concentrations and historical deposition fluxes, e.g. in loess (Wang et al., 2005), forest soils (Cordeiro et al., 2002; Soucémarianadin et al., 2014), paddy soils (Lehndorff et al., 2014), marine sediments (Liu et al., 2011), or lake sediments (Wang et al., 2013). However, few studies have so far been conducted in peatland ecosystems. Peatlands, with slow rates of decomposition under anaerobic conditions but continuous inputs by deposition (Martini et al., 2007; Olid et al., 2010), should provide ideal archives for stocks of BC and for reconstructing the BC deposition history. Global peatlands were estimated to hold 540 Pg of carbon within only 3–4% of the world's land area, thus representing about 1.5% of the total estimated global carbon storage and about 25–30% of that stored in terrestrial vegetation and soils (Millennium Ecosystem Assessment, 2005). Investigating BC storage in peatland systems may thus help to improve the understanding of peatlands for global carbon cycles and soil carbon stocks.

The Changbai Mountain range is a well-known mountain range in northeast China, bordering the Korean Peninsula in the south (Bao et al., 2010). The total area of peatlands in this region was estimated to 314 km^2, with an estimated peat storage of 93.8 Tg (Yin, 1991). Peatlands in the Changbai Mountains are located at different altitudes, spanning a range of >1000 m (Bao et al., 2010). Previous studies in lake sediments showed that BC deposition fluxes at different altitudes are different (Han et al., 2010; Cong et al., 2013). It could therefore be expected that the BC deposition fluxes to peatlands of the Changbai Mountain would also differ with respect to the altitude.

Since 1895, an increasing number of people migrated to northeastern China, and the population in northeastern China (i.e. Heilongjiang, Jilin, Liaoning provinces) increased from 15.88 million in 1911 to 108.15

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million in 2011 (Zhang et al., 2006; China Statistical Database, 2014). Population growth caused more BC production and emission by anthropogenic sources (e.g. residential, industry) and presumably increased also the deposition fluxes of BC (Qin and Xie, 2012). The Changbai Mountain range is an ideal area for BC deposition studies, as there is a distinct height gradient and a high historical emission of BC from anthropogenic sources.

In this study, we thus aimed at investigating ranges of BC concentrations in peatlands in the Changbai Mountains and at elucidating the effect of elevation and deposition history on BC fluxes and inventories. Deposition periods and sites were regarded as two factors in a two-way ANOVA to evaluate deposition history and elevation as separate factors for BC deposition fluxes and inventories. By further meta-analysis of our data we aimed at comparing data from this study with BC fluxes available for China, Europe and the former USSR (Cottenie, 2005; Bond et al., 2007; Viechtbauer, 2010). We further aggregated our BC deposition data to provide average BC deposition fluxes for the Changbai Mountain area and to assess the impact of human activities on BC deposition at the different altitudes.

To address these research questions, we analyzed BC concentrations from four peat cores (Ch, Yc, Ha, and Jc) of two different altitudes in the Changbai Mountains, northeastern China, and used previously published rates of carbon accumulation (Bao et al., 2010). To our knowledge, this study thereby provides the first data on BC fluxes in the Changbai Mountain area. Besides being one of the rare studies on BC conducted in peatlands, an evaluation of BC deposition in the Changbai Mountain area provides information about the impact of increasing emissions from China compared to long-range atmospheric transport to this remote area.

2. Materials and methods

2.1. Site description and sampling

The Changbai Mountain range, named after a dormant volcano in its central part and with an elevation range of 400–2740 m above sea level, is situated at the boundary between northeastern China and North Korea. Its topography is diversified, including valleys, basins, hills, and steep slopes. The area has a temperate continental monsoon climate with mean annual temperatures of −7 to +3 °C and mean annual precipitation of 700–1400 mm, depending on the elevation. Also depending on elevation, the vegetation is dominated by mixed forests (600–1100 m), coniferous forests (1100–1800 m), sub-alpine *Betula ermanii* forests (1800–2000 m), or alpine tundra vegetation above 2000 m. Peatlands are mostly found in the mixed forests and coniferous forest ranges. Detailed information is provided elsewhere (Bao et al., 2010; Wang et al., 2014; Zhang et al., 2007). Four peat cores (Ch, Yc-1, Jc and Ha) were collected in September 2005 in the Changbai Mountains, each profile covering about 150 years (Bao et al., 2010), using a Wardenaar peat corer (Wardenaar, 1987). The Chichi site (Ch), dominated by *Carex lasiocarpa* and various *Sphagnum* species, has 42 cm of peat accumulation, of which the upper 24 cm were sampled for BC analysis, pH at the site is around 5–6; the Yuanchi site (Yc-1) is mainly overgrown by *C. lasiocarpa*, has 46 cm of peat accumulation, of which 29 cm were sampled, pH is about 4–6; the Jinchuan site (Jc) is also dominated by *C. lasiocarpa*, has 88 cm peat depth, of which 31 cm were sampled, pH was not determined; at the site Haerbaling (Ha), dominated by *C. lasiocarpa* and various *Sphagnum* species, 72 cm of peat has accumulated, of which we sampled 26 cm, pH was not determined (Bao et al., 2010). Sites Ch, Yc-1, and Jc developed from small shallow lakes, in case of Ch and Yc-1 volcanic lakes; site Ha is situated in a valley and has developed from a riparian wetland, thus here some minerotrophic influence cannot be fully excluded. Ch, Yc-1, and Jc appear to be ombrotrophic, but may have received substantial dust deposition from the nearby bare soils at high elevations around the volcano, and from the steppe of inner Mongolia stretching west of the Manchuria plain west of the mountain forelands. The location of each core was determined using a portable global positioning system (GPS) (Fig. 1).

The peat cores were sectioned into 1 cm intervals with a stainless steel knife for ^{210}Pb dating and determination of loss on ignition (LOI). Samples were stored in polyethylene plastic bags, and subsequently brought to the laboratory for analysis. Prior to further processing all visible roots were removed manually. In this study, we analyzed the BC concentrations at the sites Yc-1, Jc, and Ha in 1 cm depth intervals, at the site Ch only every second sample was analyzed (2 cm intervals). Samples were loosely disaggregated to facilitate air-drying at 20 °C.

2.2. Methods

2.2.1. Physicochemical analysis

Chronology, bulk density and carbon concentrations, and carbon accumulation rates were taken from Bao et al. (2010). Briefly, peat accumulation rates were calculated from ^{210}Pb data and bulk density of the peat, applying a constant rate of supply (CRS) model to determine dates based on ^{210}Pb counts (Binford, 1990; Turetsky et al., 2004). Bulk density was determined by oven drying at 105 °C for 12 h. The carbon (C) concentration was calculated from loss on ignition (LOI) at 550 °C (multiplying the organic matter concentration by 0.5) (Bao et al., 2010; Lamarre et al., 2012).

To determine BC concentrations in the peat samples, we used the dichromate oxidation method (Lim and Cachier, 1996; Song et al., 2002). First inorganic carbon was removed, treating 1 g of sample in centrifuge tubes for 20 h with 10 mL 1 mol L^{-1} HCl. After centrifugation and decanting the supernatant, 10 mL of a mixture of HCl (3 mol L^{-1}) + HF (22 mol L^{-1}), volumetric ratio 1:2, was added and allowed to react for another 20 h. After further centrifugation and after decanting of the HCl/HF, the residual sample was soaked in 1 mol L^{-1} HCl (10 mL) for 10 h. To remove non-pyrogenic organic carbon, 30 mL of 0.1 mol L^{-1} of NaOH was used to extract humic acids. Deviating from the original protocol, we increased the number of extraction steps here from one to two (each 12 h reaction time) to improve humic acid removal from the peat. Thereafter, kerogens were removed by stepwise addition of a mixture of $K_2Cr_2O_7$ (0.1 mol L^{-1}) and H_2SO_4 (2 mol L^{-1}) (10 mL per step, 60 h reaction time, repeated 2–3 times until solution remained yellow). All steps were carried out in a water bath at 55 °C (Lim and Cachier, 1996; Wang et al., 2013). The residual carbon after this treatment was then termed as black carbon and quantified using an EA (Flash 2000 series, Thermo Fischer, Waltham, USA) at the Analysis and Test Center of Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences. References of known carbon concentrations (IRMS certified reference: BN/132357) were used for calibration. Black carbon reference material (charred wood) produced at the Department of Geography, University of Zurich (Hammes et al., 2006), was used to verify our method and to ensure that increasing the number of NaOH extraction steps from one to two did not affect the recovery of BC (two steps NaOH: 48.7–50.2%, n = 3; one step NaOH: 48.4–55.8%, n = 4).

Based on published carbon accumulation rates of 124.2 to 292.8 g C m^{-2} a^{-1} and total carbon concentrations (Bao et al., 2010), BC deposition fluxes were obtained using the determined mass fraction of BC (Eq. (1)):

$$\text{BC deposition flux} = \frac{\text{BC}}{\text{TOC}} \times \text{C accumulation rate} \quad (1)$$

In which the C accumulation rates were obtained from total C concentrations, peat density and the respective time intervals obtained from ^{210}Pb dating. BC deposition fluxes were finally obtained by multiplying the BC/TOC mass fraction (expressed in %) by the C accumulation rates.