forests

MDPI

Article

Effects of Fire Severity and Topography on Soil Black Carbon Accumulation in Boreal Forest of Northeast China

Wentao Huang [1,2], Yuanman Hu [1], Yu Chang [1,*], Miao Liu [1], Yuehui Li [1], Baihui Ren [1,2] and Sixue Shi [1,2]

1 CAS Key Laboratory of Forest Ecology and Management, Institute of Applied Ecology, Chinese Academy of Science, Shenyang 110016, China; huangwentao14@mails.ucas.ac.cn (W.H.); huym@iae.ac.cn (Y.H.); lium@iae.ac.cn (M.L.); liyh@iae.ac.cn (Y.L.); renbaihui1004@126.com (B.R.); ssx_ssx@126.com (S.S.)

2 University of Chinese Academy of Science, Beijing 100049, China

* Correspondence: changyu@iae.ac.cn; Tel.: +86-024-8397-0350

Received: 23 May 2018; Accepted: 3 July 2018; Published: 6 July 2018

Abstract: Black carbon (BC) from incomplete combustion of biomass and fossil fuel is widespread in sediments and soils because of its high stability in nature and is considered an important component of the global carbon sink. However, knowledge of BC stocks and influencing factors in forest ecosystems is currently limited. We investigated soil BC contents in burned boreal forests of the Great Khingan Mountains, northeast China. We collected soil samples from 14 sites with different fire severities, slope positions and aspects. The samples were analyzed by the chemo-thermal oxidation method to obtain their BC concentrations. The BC concentrations of the studied soils ranged from 0.03 to 36.91 mg C g^{-1}, with a mean of 1.44 ± 0.11 mg C g^{-1}. BC concentrations gradually decline with depth, and that was significantly less in the 20–30 cm layer compared to all shallower layers. Forests burned by moderate-severity fires had the highest soil BC, the shady aspect had higher soil BC than the sunny aspect. Our results provide some basic data for evaluating the soil BC sink in boreal forests, which is a useful amendment to current carbon budget and carbon cycle in boreal forest ecosystems.

Keywords: black carbon; the Great Khingan Mountains; fire severity; topography; boreal forests

1. Introduction

Black carbon (BC), alternatively termed pyrogenic carbon, char, charcoal, or biochar depending on different points of focus [1–3], is the residue production from incomplete combustion of biomass and fossil fuel [4–6]. It can resist a high level of degradation and be stored for centuries to millennia in the natural environment [7]. BC is widespread in sediments and soils because of its refractory nature and the common occurrence of combustion [8–10]. Some studies have shown that much of BC is stored in boreal forest soils [11–14]. In addition, fire frequency will increase in boreal forest ecosystems with the climatic warming [15] and this trend could be further enhanced by the end of this century [16]. Therefore, the production of BC from wildfires in boreal forests will probably increase, resulting in more BC being stored in soils. Although the BC is considered an important carbon sink and may play an important role in alleviating climate change [17,18], it is largely neglected in current studies in carbon cycling and carbon budget of forest ecosystems. Therefore, estimation of the BC stock and determination of its influencing factors are crucial for understanding carbon cycling and carbon stocks of boreal forest ecosystems under future climate change. Researchers have demonstrated the need for taking into account soil BC in the inventories of global carbon pools [19,20].

There are few quantitative reports of BC stocks in boreal forest soils, particularly in boreal forests of China [21]. Soil BC was 0.2 (± 0.1) kg C m^{-2} in Quebec black spruce forests [13] and 0.6 ± 0.3 kg C m^{-2} in black spruce forest floors from eastern Canada [22] and 0.072 kg C m^{-2} on the forest floor of Siberian Scots pine forests [23]. Average BC in surface mineral soils of black spruce forests at different landscape positions in Alaska, USA was 0.34 ± 0.09 kg C m^{-2} [24] and 0.02–3.40 kg C·m^{-2} in the forest tundra ecotone in Northern Siberia [25]. These results show large differences, which could be attributed to different methods of sampling and measuring [26,27]. Many factors may influence soil BC [28] and forest fire severity is a major contributing factor to soil BC retention. For example, a previous study showed that less BC stocked in the forest floor was burned by high-severity fires than by low-to-moderate severity fires [29]. In contrast, a previous study reported that BC tended to increase in areas subjected to low-severity burning [30]. There has been no agreement on the influences of forest fire severity on soil black carbon stocks in recent years. In addition, topographic condition may be another crucial control on soil BC stocks. Some reports have indicated that south-facing aspects had more BC than north-facing aspects [24,31] and BC was highest at hill bottoms [32]. However, it remains unclear how fire severities and topography affect soil BC stocks in boreal forests [33].

The area of boreal forests of the world is nearly 16.6 million km^2, comprising about one third of the world's forest cover [34]. About 5–20 million ha of boreal forests are burnt annually [35]. Boreal forests are subjected to frequent fire disturbances resulting in the accumulation of BC in forest soils, which could be a potential carbon sink given the extensive distribution of boreal forests [5]. Estimation of BC stocks is crucial for evaluating the BC sink to further inform current forest carbon budget and carbon cycling. Therefore, investigation of BC storage in boreal forest soils may thus help to understand the role of boreal forests in global carbon cycles and soil carbon stocks.

The Great Khingan Range is a well-known mountain range in northeast China, bordering the Russian Far East in the north (49°22′57″ N, 123°09′24″ E) [36,37]. The area has a large expanse of hills with an elevation of 1200–1300 m a.s.l., and it belongs to the cold temperate zone continental monsoon climate. There are 16.5 million ha of boreal forests in the range and the forest coverage rate is 76.4% [38]. The forest fire regime in the Great Khingan Range is characterized by low frequency and high-severity fire [39]. On 6 May 1987, a catastrophic fire occurred, which lasted almost a month. The fire covered about 10,000 km^2, of which 6500 km^2 was forestry [40], providing an ideal location for estimating BC stocks and exploring the factors affecting BC storage.

Therefore, in this paper, taking Tuqiang Forest Bureau on the eastern slopes of Great Khingan Ranges, we aim to (1) investigate BC contents in boreal forest soils in the Great Khingan Range, and (2) elucidate the effect of fire severity and different topography on BC content. We initially hypothesized that (1) the soil BC content is higher on sunny slopes than shady slopes as sunny slopes are subjected to frequent fires; and that (2) the soil BC content is high in forests burned by moderate-severity fires owing to low burning efficiency at low-severity and complete burning at high-severity. We measured the concentration of BC in boreal forest soils and assessed the effects of different wildfire severities and topography on BC storage in the Great Khingan Mountains.

2. Materials and Methods

2.1. Study Area

The study was conducted in the Tuqiang Forest Bureau (from 52°15′55″ to 53°33′40″ N, and 122°18′05″ to 123°29′00″ E) with an area of ~4000 km^2, located in Mohe county, the northernmost county of China (Figure 1). The study area has a cold, continental climate, with an average annual temperature of −5 °C. Monthly mean temperature ranges from −47.2 °C in January to 31.4 °C in July. The average annual precipitation is 432 mm, with great inter-annual variations, and 75% of the rainfall occurs between June and August. Uplands and small hills characterize this region, though it possesses a relatively smooth topography. Slopes are generally less than 15°, the maximum slope is less than 45°. Hills undulate throughout this area, and mountain ranges mostly run in north and south directions.

Elevations range from 270 to 1210 m a.s.l., with the mean elevation of 500 m. Brown coniferous forest soil is representative in the Bureau. Vegetation is dominated by larch (*Larix gmelinii* Rupr.) forests. White birch (*Betula platyphylla* var. *japonica*) is the major broad-leaved species in the region. In addition to larch and white birch, the tree species include Mongolian Scotch Pine (*Pinus sylvestris* var. *mongolica*), spruce (*Picea koraiensis* Nakai), aspen-D (*Poulus davidiana* Dode), black birch (*Betula davurica* Pall.), aspen-S (*Populus suaveolens* Fisch), and willow (*Salix matsudana* Koidz.) [41].

On 6 May 1987, a catastrophic forest fire of 1.33×10^4 km^2 took place in the Great Khingan Mountains. The burned area covered 2.31×10^3 km^2 in the Tuqiang Forest Bureau, and the severely burned area covered roughly 900 km^2. The conflagration destroyed an extensive amount vegetation, during which a considerable amount of BC was produced.

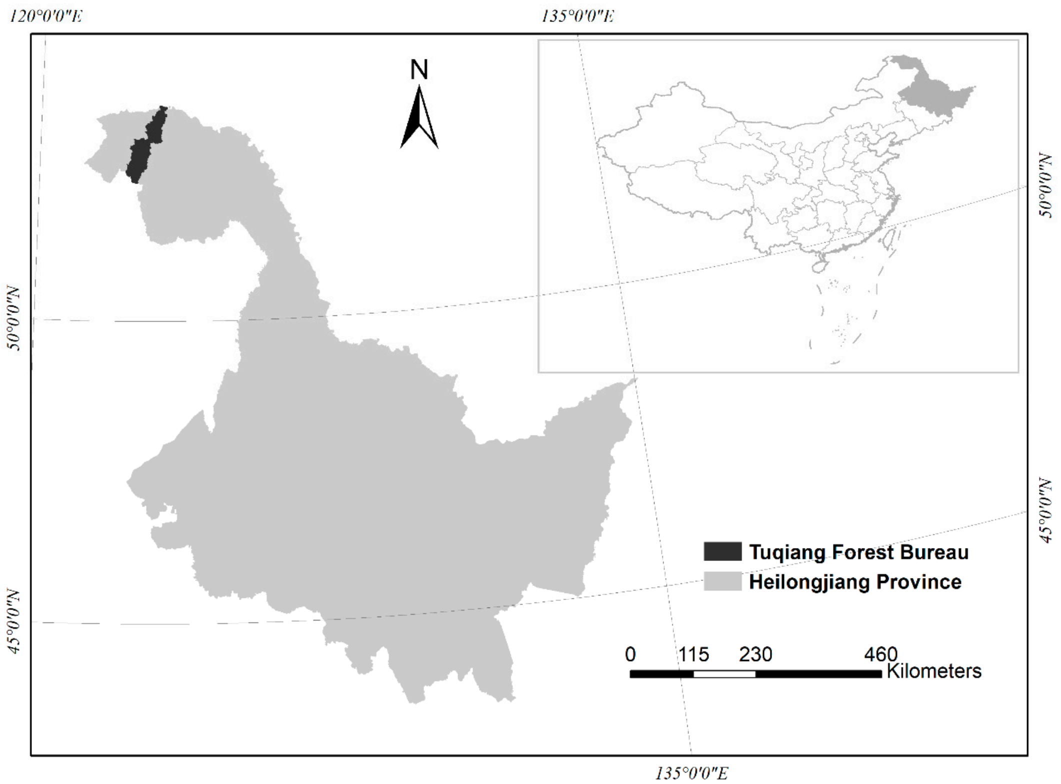

Figure 1. Location of the Tuqiang Forest Bureau study site in Heilongjiang province, China.

2.2. Sampling

Samples were collected from 29 July to 3 August 2016. Fourteen sites were chosen across the burned areas with different severities of the Tuqiang Forest Bureau in 1987 (Figure 2). At each site, three plots (20 × 20 m) were established, ~20 m apart from each other. The location of each plot was determined using a portable global positioning system. We recorded the severity of forest fires, aspect, slope position, altitude, and forest type for each plot (Table 1). For each plot, we randomly chose three sub-plots. At each sub-plot, four samples each at different depths (0–5, 5–10, 10–20 and 20–30 cm) were collected with cutting rings in pits. On our study sites, wildfires happened nearly 30 years ago, so that there were no apparently organic layers. Actually, the organic layer is part of our top soil layer (0–5 cm). Each sample was stored in an aluminum box, and subsequently brought to the laboratory for analysis. Prior to further processing all visible roots and rocks were removed manually.

Table 1. Details of the selected sampling sites.

Site	Number of Samples	Coordinate	Fire Severity	Slope Position	Aspect	Dominant Specie
1	32	122.7514 E, 52.8045 N	High	Lower	Shady	*Larix gmelinii* Rupr.
2	35	122.7526 E, 52.8043 N	High	Lower	Shady	*Betula platyphylla* var. *japonica*
3	36	122.5676 E, 52.8860 N	Moderate	Flat	Flat	*Larix gmelinii*
4	28	122.5828 E, 52.8577 N	High	Upper	Sunny	*Populus davidiana* Dode
5	26	122.5815 E, 52.8573 N	Low	Middle	Sunny	*Pinus sylvestris* var. *mongolica*.
6	33	122.5808 E, 52.8579 N	Low	Lower	Sunny	*Pinus sylvestris* var. *mongolica*.
7	35	122.6474 E, 52.6998 N	Unburned	Middle	Shady	*Larix gmelinii*
8	35	122.6466 E, 52.7010 N	Unburned	Bottom	Shady	*Larix gmelinii*
9	36	122.6513 E, 52.7115 N	Unburned	Middle	Sunny	*Pinus sylvestris* var. *mongolica*.
10	36	122.6514 E, 52.7111 N	Unburned	Bottom	Sunny	*Pinus sylvestris* var. *mongolica*.
11	36	122.6554 E, 52.7437 N	Moderate	Lower	Shady	*Larix gmelinii*
12	33	122.6804 E, 52.7436 N	Low	Upper	Shady	*Pinus sylvestris* var. *mongolica*
13	36	122.6803 E, 52.7435 N	Low	Middle	Shady	*Pinus sylvestris* var. *mongolica*
14	36	122.6797 E, 52.7436 N	Low	Lower	Shady	*Pinus sylvestris* var. *mongolica*

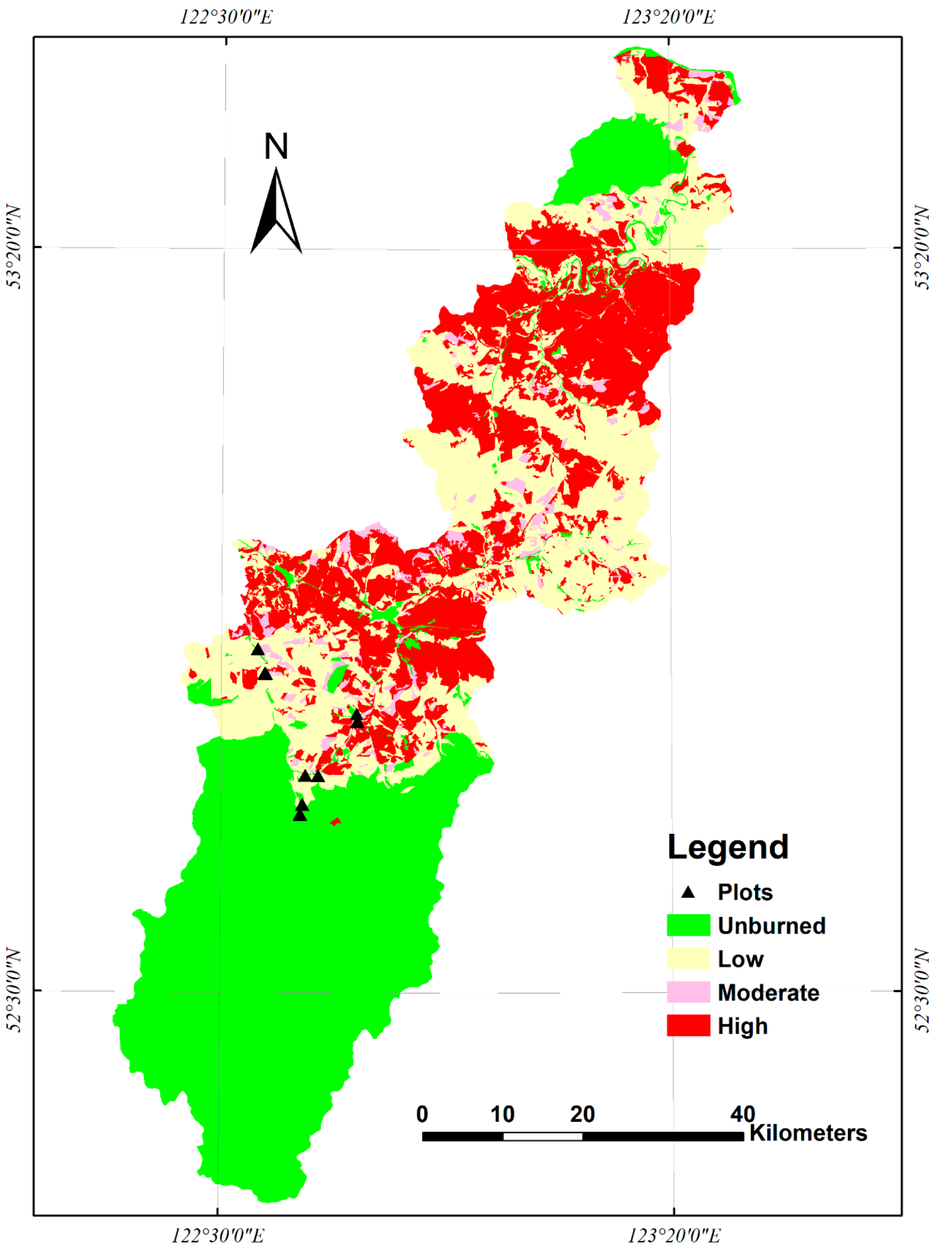

Figure 2. Distribution of forest fire severity and locations of sample plots.

2.3. Measurements of Bulk Density and Determination of BC

Bulk density was determined by oven drying at 105 °C for 12 h. Soil samples were ground and subsequently sieved through 100 mesh (diameter: 0.150 mm). To determine BC concentrations in the samples, we used the chemo-thermal oxidation method (CTO-375). This method considers differences in chemical and thermal stability between BC and other forms of carbon, and thus only measures the most refractory fraction of BC and has the lowest bias [42–44]. First non-pyrogenic organic carbon was removed by thermal oxidation of 1.00 g soil at 375 °C for 16 h under air flow conditions. To remove inorganic carbon, the residual samples were transferred into centrifuge tubes and soaked in 1 mol L^{-1} HCl (10 mL) for 1 h. After decarbonation, we added 50% NaOH to adjust the pH to 7. To avoid possible causticity of Cl^{-} on the elemental analyzer, after centrifugation and decanting the supernatant, 10 mL deionized water was added to wash the residues and repeated three times until Cl^{-} of residues was removed. The residues were dried at 100 °C. The residual carbon after these treatments was then termed as BC and quantified using an elemental analyzer (Vario MACRO Cube, Elementar, Hanau, Germany) at the Agricultural Product Safety and Environmental Quality Testing Center of Institute of Applied Ecology, Chinese Academy of Sciences. References of known carbon (D-Phenylalanine, $C_9H_{11}NO_2$, 99%) concentrations were used for calibration. Soil BC stocks were calculated using the BC concentration and bulk density data.

2.4. Statistical Analysis

Statistical analyses were performed with the software IBM SPSS Statistics 24. We examined whether there was a significant difference of soil BC content among various soil depths, fire severities, aspects, slope positions, and by single factor analysis of variance or an independent-samples *t*-test. The tests of normality of data were assessed using the Shapiro-Wilk test and the equality of variances was assessed using Levene's homoscedasticity test. In the cases where differences in arithmetic mean BC content among classes were statistically significant and variances of BC content for those classes were equal, the post-hoc Duncan's multiple range test was performed to identify classes with significantly different means. In the cases of unequal variance, the post-hoc Tamhane's T2 test was performed instead of Duncan's. The level of significance used for all the tests was 5% (i.e., $\alpha = 0.05$). We used a general linear model to test potential interactions between fire severity and topographic features. More information about statistical analysis can be found in the Supplement 1.

3. Results

3.1. Soil BC Concentration at Different Depths

The BC concentration in different layers of forest soils of the Great Khingan Mountains ranged from 0.03 to 36.91 mg C g^{-1}, with a mean of 1.44 ± 0.11 mg C g^{-1}. The maximum was observed in the 0–5 cm layer and the minimum in the 20–30 cm layer. Soil BC concentration decreased with depth (Figure 3). In the 0–5 cm layer, the mean value of soil BC concentration was 2.38 ± 0.37 mg C g^{-1}, the highest of the studied soil depth, followed by 1.44 ± 0.14 mg C g^{-1} at 5–10 cm, 1.02 ± 0.08 mg C g^{-1} at 10–20 cm layer, and 0.76 ± 0.03 mg C g^{-1} at 20–30 cm soil depth. Significant differences in BC concentration were observed between layers; soil BC concentration at 0–5 cm soil depth was significantly higher than that at 10–20 cm ($p < 0.05$). The soil BC concentration at 20–30 soil depth was significantly lower than that at 10–20 cm ($p < 0.05$).

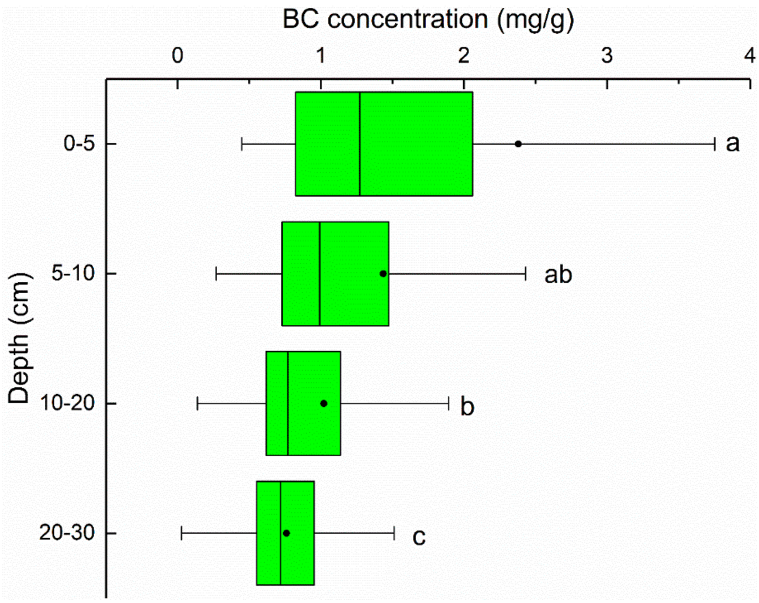

Figure 3. Vertical distribution of BC in soils on burned areas in the Great Khingan Mountains. The black points in the box plots were mean values of BC.

3.2. Soil BC Concentration among Different Topography and Various Fire Severities

At 0–5, 5–10, and 10–20 cm soil depth, the shady aspect had a higher BC concentration than the sunny aspect and flat terrain, whereas at 20–30 cm soil depth, the flat terrain had the highest BC concentration (Figure 4a). The soil BC concentration was significantly higher ($p < 0.05$) on the shady slope than on the sunny slope at 0–5 and 5–10 cm soil depth, whereas there was no significant difference ($p > 0.05$) in soil BC concentration on the shady aspect and the sunny terrain at 10–20 and 20–30 cm soil depth.

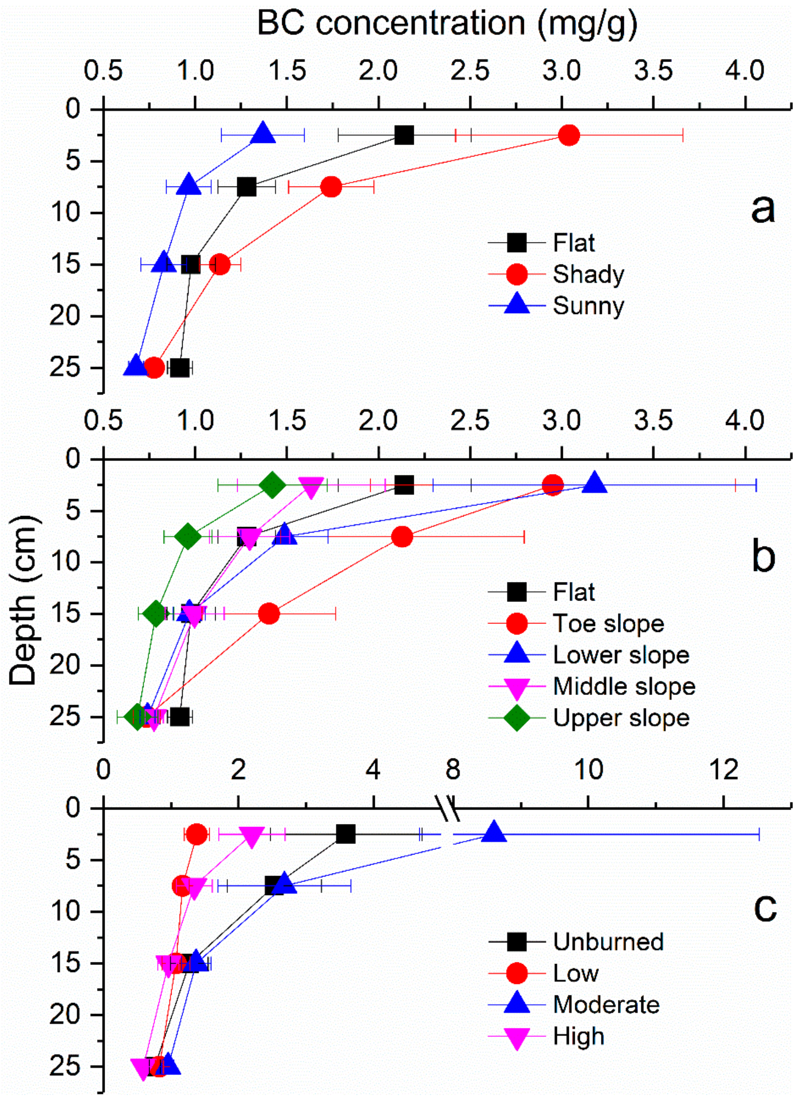

Figure 4. Soil BC concentrations on different aspects (**a**), on different slope positions (**b**) and of various fire severities (**c**) in the Great Khingan Mountains. Error bars indicate standard errors.

With regard to slope position, we found that soil BC concentration was the highest on toe slopes, except at 0–5 cm depth on the lower slopes and 20–30 cm depth on flat positions. Soil BC concentration at each soil depth was lowest on the upper slopes at each depth. Statistical analysis showed that there was no significant difference ($p > 0.05$) in soil BC concentration on all slopes at any depth (Figure 4b).

We found that forest burned by moderate-severity fires had the highest soil BC concentration at each soil depth. The lowest soil BC concentration occurred in forests burned by low-severity fires at 0–5 and 5–10 cm soil depth, and by high-severity fires at depth of 10–20 and 20–30 cm soil depth (Figure 4c). Statistical analysis showed that, for each of the four layers, there was no significant difference ($p > 0.05$)

in soil BC concentration of plots burned by different fire severities except at 20–30 cm soil depth, where soil BC concentration in forests burned by high-severity fires was significantly lower ($p < 0.05$) than fires at other severities.

3.3. Soil BC Stocks among Different Topography and Various Fire Severities

We calculated soil BC stocks in our sites using the soil bulk density and BC concentration data (Supplement 2). Soil BC stocks ranged from 0.12 to 0.59 kg C m^{-2}, with a mean of 0.26 ± 0.02 kg C m^{-2}. Forests burned by moderate-severity fires had the highest soil BC stocks (Figure 5A). For aspect, soil BC stocks in flat and shady plots were higher than those in sunny plots (Figure 5B). With regard to slope position, soil BC stocks were highest on toe slopes, followed by flat, lower, slopes and upper slopes (Figure 5C). A significant difference ($p < 0.05$) was only found between soil BC stocks on plots burned by moderate-severity fires and soil BC stocks on all other plots. In addition, we found that there was no significant correlation ($p < 0.05$) between effects of fire severity on BC stocks and that of aspect or slope position.

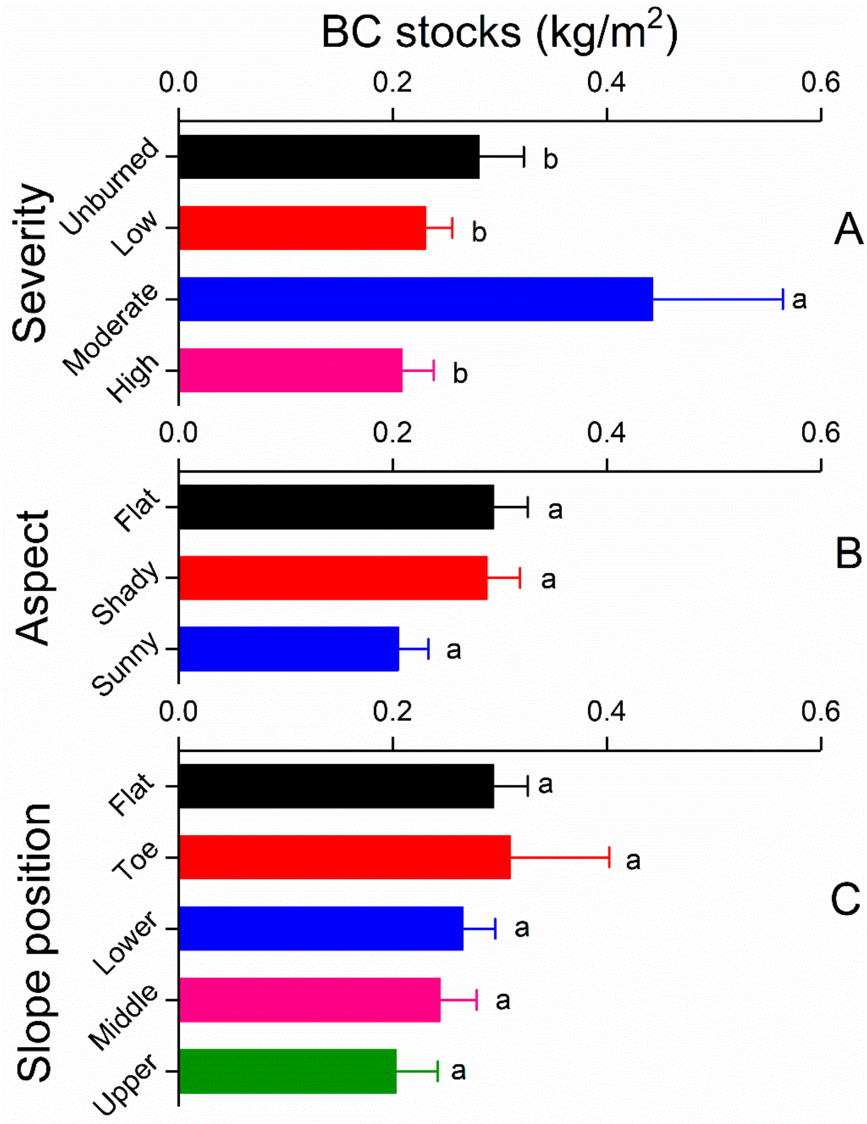

Figure 5. Soil BC stocks of various fire severities (**A**), on different aspects (**B**) and on different slope positions (**C**) in the Great Khingan Mountains. Error bars indicate standard errors.

4. Discussion

4.1. Soil Content in Forests of the Great Khingan Mountains

Our findings are the first estimation of soil BC in the Great Khingan Mountains as affected by fire severity and topography. Our results indicated that BC concentration ranged from 0.03 to 36.91 mg C g^{-1}, with mean of 1.44 ± 0.11 mg C g^{-1}, a 10th percentile of 0.53 mg C g^{-1}, and 90th percentile of 2.23 mg C g^{-1}. Our results are comparable to previous reports, such as 0.57–7.15 mg C g^{-1} from Australian soils [45]; 0.27–5.62 mg C g^{-1} from Australian agricultural, pastoral, bushland, and parkland soil [9]; and 0.28–2.7 mg C g^{-1} in soils around France [44]. Moreover, the soil BC concentration in our study area was much lower than that in top peat soils in Changbai Mountains, China ranging from 0.25 to 50.7 mg C g^{-1} with a mean of 17.2 mg C g^{-1} [46] and in a swamp in Australia, which ranged from 1 to 32 mg C g^{-1} [47]. This is because peat soils typically exhibit a lack of oxygen, which is unfavorable for degradation of BC [46]. In contrast, we measured soil BC concentration by the CTO-375 method, which could only quantify highly condensed BC. Therefore, the soil BC concentration was substantially below that measured by the dichromate oxidation method [46] and benzene polycarboxylic acids method [42,47].

Soil BC concentration in our study sites decreased with depth. This is similar to the findings in the Amazon basin forest soils [48] and in the Amazon seasonal forest soils [19]. This similarity may be because there are few disturbances along the direction of gravity in the Great Khingan Mountains and BC degrade slowly in soils [49]. Thus, the pyrogenic carbon/total organic carbon ratio in the Amazon basin forest soils increases with depth [19]. This indicates that BC will degrade distinctly slower in deep soils compared with other types of organic carbon. In addition, we only collected soil samples up to 0–30 cm depth rather than 0–100 m depth or more [19,48,50]. This was because the thickness of soils in our plots was nearly 30 cm below which was only hard rocks. Nonetheless, we found that soil BC was mainly distributed in top soils (0–20 cm), accounting for 80.2%, and only a small portion of BC was therefore present within deeper soils (20–30 cm). On our study sites, the top soil layer (0–5 cm) includes the organic layer, this is in line with a previous report that most BC stores in the organic layer and deep mineral soil contains very little BC in the boreal forests [23]. Hence, the soil BC data we obtained could be part of database that used to estimate the total BC sink in the Great Khingan Mountains and other regions that contain a similar boreal forest condition.

4.2. Factors Affecting Soil BC Distribution

Forest fire severity coupled with topographic conditions may impact the formation and content of BC in soils [24,29]. We found soil BC stocks on flat and shady slopes was higher than those on sunny slopes. This result rejects our first hypothesis that the soil BC stocks are higher on sunny slopes than that on shady ones. Our results are consistent with a previous report that more soil BC on north-facing aspects was founded than on south-facing aspects in burned boreal forests in Alaska [31]. This is understandable as flat and shady slopes are generally more humid than sunny slopes. Once forests on shady slopes are burned, the humid environmental conditions are more conductive to the incomplete combustion of forest fuels, thus increasing BC [31,51]. In addition, the soil temperature of flat and shady slopes is lower than that of sunny slopes because of the lower amount of incoming solar radiation. Warmer conditions on sunny slopes are suitable for the growth and reproduction of microbes that can decompose BC [52], resulting in the degradation of BC. Our results showed that flat and shady slopes had similar amounts of soil BC stocks. This might be related to the increased amount of available fuels and warmer conditions on flat plots than in shady plots.

Our results also showed that more soil BC was generated by moderate-severity fires. This result supports our second hypothesis that the soil BC content is high in forests burned by moderate-severity fires. Our result supports the finding that the pyrogenic carbon in soils was higher after moderate forest fire disturbances in California, USA [29]. This is because fuel is exposed to high temperatures during high-severity fires, resulting in more complete combustion than in moderate-severity fires and thus reduced production of BC [23,53]. In contrast, less fuel is consumed during low-severity fires [54] leading to some BC remaining in soils. However, we found that the unburned plots had more (not significantly) soil BC than both low- and high-severity fire plots. The soil BC in unburned plots may be caused by historical forest fires. Repeated fires could consume a portion of soil BC previously accumulated [14]. In addition, wildfires may result in soil erosion which could deliver soil BC to rivers [55] and to the mountain hill foot [56].

Besides aspects and fire severities, slope position may also affect soil BC contents, for example, a greater accumulation of organic material on lower slope positions [22,31]. Our results suggest that soil BC content on lower slopes is higher than on middle and upper slopes. Our results are inconsistent with previous findings [22,24]. This might be attributed to runoff and soil erosion [57] on post-fire terrain, which carry soil BC to lower places. The runoff and soil erosion are common following heavy rainfall events after burning of steep terrain [57], resulting in the accumulation of BC on lower slopes. However, the runoff and soil erosion processes are highly complicated and understanding of the influence of soil erosion on the movement of soil BC downwards remains quite limited and requires further exploration [57,58].

4.3. Other Possible Factors Affecting Soil BC Distribution and Prospects

Although we found that fire severity did significantly affect BC stocks and topography could affect BC stocks as well, our statistical analysis indicates that there was no significant difference between the effects of fire severity on BC stocks and that of topography. However, this result was based on only a few sites. Actually, fires of high severity tend to occur more often on eastern and southern aspects than that on other aspects in Northeast China [59]. The interaction between topographic features and fire severity might affects soil BC stocks in boreal forests, which should be taken into account in further studies. Regarding vegetation types, our findings showed that no correlation between dominant tree species and soil BC content. However, fires of high severity are more likely burn within coniferous forests [59,60], and thus vegetation species may affect soil BC stocks. Therefore, further studies needed to design to determine the effects of vegetations on soil BC stocks and the interaction between fire severity and vegetation types. In addition, other possible factors such as wind, soil types, and water erosion require further study in the future.

5. Conclusions

Soil BC was mainly distributed at 0–20 cm, accounting for 80.2% of total BC. Soil BC contents were affected by fire severity, slope position, and aspect, leading to heterogeneous patterns. Forests burned by moderate-severity fires had the highest soil BC, probably because of the increased production of BC in moderate wildfires. The flat and shady aspect had higher soil BC than the sunny aspect probably because of improper conditions for BC production and accumulation; and soil BC on lower slopes was higher than that on middle and upper slopes. Therefore, boreal forests burned with moderate-severity wildfires on lower shady slopes are most conducive to soil BC accumulation in the Great Khingan Mountains. Our results could provide some basic data for evaluating the soil black carbon sink in boreal forests, which is a useful amendment to the current carbon budget and carbon cycle in boreal forest ecosystems.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/9/7/408/s1.

Author Contributions: Methodology, W.H.; Software, W.H. and B.R.; Formal Analysis, Y.C. and W.H.; Investigation, Y.C., W.H., Y.L. and S.S.; Resources, M.L.; Writing—Original Draft Preparation, W.H.; Writing—Review & Editing, Y.C., Y.H.; Supervision, Y.C., Y.H.; Project Administration, Y.C. and M.L.; Funding Acquisition, Y.C.

Funding: This research was funded by National Natural Science Foundation of China (grant number: 31470516).

Acknowledgments: The authors acknowledge the assistance of the Test Center of Agricultural Product and Environmental Quality of Institute of Applied Ecology, Chinese Academy of Sciences. We thank Zaiping Xiong, Long Chen, Zhen Li, Changmeng Zhang, Hongxin Zhang, Changhe Hu and Baoqi Zhang for helping to collect samples and to the field guide. We thank Alex Boon, from Liwen Bianji, Edanz Editing China (www.liwenbianji.cn/ac), for editing the English text of a draft of this manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Bird, M.I.; Ascough, P.L. Isotopes in pyrogenic carbon: A review. *Org. Geochem.* **2012**, *42*, 1529–1539. [CrossRef]
2. Zimmermann, M.; Bird, M.I.; Wurster, C.; Saiz, G.; Goodrick, I.; Barta, J.; Capek, P.; Santruckova, H.; Smernik, R. Rapid degradation of pyrogenic carbon. *Glob. Chang. Biol.* **2012**, *18*, 3306–3316. [CrossRef]
3. Chiapini, M.; Schellekens, J.; Calegari, M.R.; de Almeida, J.A.; Buurman, P.; de Camargo, P.B.; Vidal-Torrado, P. Formation of black carbon rich 'sombric' horizons in the subsoil—A case study from subtropical Brazil. *Geoderma* **2018**, *314*, 232–244. [CrossRef]
4. Goldberg, E.D. *Black Carbon in the Environment: Properties and Distribution*; John Wiley & Sons Inc.: Hoboken, NJ, USA, 1985; p. 798.
5. Bird, M.I.; Wynn, J.G.; Saiz, G.; Wurster, C.M.; McBeath, A. The Pyrogenic Carbon Cycle. *Annu. Rev. Earth Planet. Sci.* **2015**, *43*, 273–298. [CrossRef]
6. Mastrolonardo, G.; Hudspith, V.A.; Francioso, O.; Rumpel, C.; Montecchio, D.; Doerr, S.H.; Certini, G. Size fractionation as a tool for separating charcoal of different fuel source and recalcitrance in the wildfire ash layer. *Sci. Total Environ.* **2017**, *595*, 461–471. [CrossRef] [PubMed]
7. Singh, N.; Abiven, S.; Torn, M.S.; Schmidt, M.W.I. Fire–derived organic carbon in soil turns over on a centennial scale. *Biogeosciences* **2012**, *9*, 2847–2857. [CrossRef]
8. Jauss, V.; Sullivan, P.J.; Sanderman, J.; Smith, D.B.; Lehmann, J. Pyrogenic carbon distribution in mineral topsoils of the northeastern United States. *Geoderma* **2017**, *296*, 69–78. [CrossRef]
9. Qi, F.; Naidu, R.; Bolan, N.S.; Dong, Z.; Yan, Y.; Lamb, D.; Bucheli, T.D.; Choppala, G.; Duan, L.; Semple, K.T. Pyrogenic carbon in Australian soils. *Sci. Total Environ.* **2017**, *586*, 849–857. [CrossRef] [PubMed]
10. Reisser, M.; Purves, R.S.; Schmidt, M.W.I.; Abiven, S. Pyrogenic Carbon in Soils: A Literature–Based Inventory and a Global Estimation of Its Content in Soil Organic Carbon and Stocks. *Front. Earth Sci.* **2016**, *4*. [CrossRef]
11. Ohlson, M.; Dahlberg, B.; Okland, T.; Brown, K.J.; Halvorsen, R. The charcoal carbon pool in boreal forest soils. *Nat. Geosci.* **2009**, *2*, 692–695. [CrossRef]
12. Hart, S.; Luckai, N. Charcoal function and management in boreal ecosystems. *J. Appl. Ecol.* **2013**, *50*, 1197–1206. [CrossRef]
13. Soucémarianadin, L.N.; Quideau, S.A.; MacKenzie, M.D. Pyrogenic carbon stocks and storage mechanisms in podzolic soils of fire–affected Quebec black spruce forests. *Geoderma* **2014**, *217–218*, 118–128. [CrossRef]
14. Kasin, I.; Ellingsen, V.M.; Asplund, J.; Ohlson, M. Spatial and temporal dynamics of the soil charcoal pool in relation to fire history in a boreal forest landscape. *Can. J. For. Res.* **2016**, *47*, 28–35. [CrossRef]
15. Kelly, R.; Chipman, M.L.; Higuera, P.E.; Stefanova, I.; Brubaker, L.B.; Hu, F.S. Recent burning of boreal forests exceeds fire regime limits of the past 10,000 years. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 13055–13060. [CrossRef] [PubMed]
16. Heon, J.; Arseneault, D.; Parisien, M.A. Resistance of the boreal forest to high burn rates. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 13888–13893. [CrossRef] [PubMed]
17. Santin, C.; Doerr, S.H.; Preston, C.M.; Gonzalez–Rodriguez, G. Pyrogenic organic matter production from wildfires: A missing sink in the global carbon cycle. *Glob. Chang. Biol.* **2015**, *21*, 1621–1633. [CrossRef] [PubMed]
18. Landry, J.-S.; Matthews, H.D. The global pyrogenic carbon cycle and its impact on the level of atmospheric CO2 over past and future centuries. *Glob. Chang. Biol.* **2017**, *23*, 3205–3218. [CrossRef] [PubMed]
19. Turcios, M.M.; Jaramillo, M.M.; do Vale, J.F., Jr.; Fearnside, P.M.; Barbosa, R.I. Soil charcoal as long–term pyrogenic carbon storage in Amazonian seasonal forests. *Glob. Chang. Biol.* **2016**, *22*, 190–197. [CrossRef] [PubMed]
20. Mastrolonardo, G.; Francioso, O.; Certini, G. Relic charcoal hearth soils: A neglected carbon reservoir. Case study at Marsiliana forest, Central Italy. *Geoderma* **2018**, *315*, 88–95. [CrossRef]

21. Preston, C.M.; Schmidt, M.W.I. Black (pyrogenic) carbon: a synthesis of current knowledge and uncertainties with special consideration of boreal regions. *Biogeosciences* **2006**, *3*, 397–420. [CrossRef]
22. Soucemarianadin, L.N.; Quideau, S.A.; MacKenzie, M.D.; Munson, A.D.; Boiffin, J.; Bernard, G.M.; Wasylishen, R.E. Total and pyrogenic carbon stocks in black spruce forest floors from eastern Canada. *Org. Geochem.* **2015**, *82*, 1–11. [CrossRef]
23. Czimczik, C.I.; Schmidt, M.W.I.; Schulze, E.D. Effects of increasing fire frequency on black carbon and organic matter in Podzols of Siberian Scots pine forests. *Eur. J. Soil Sci.* **2005**, *56*, 417–428. [CrossRef]
24. Kane, E.S.; Hockaday, W.C.; Turetsky, M.R.; Masiello, C.A.; Valentine, D.W.; Finney, B.P.; Baldock, J.A. Topographic controls on black carbon accumulation in Alaskan black spruce forest soils: implications for organic matter dynamics. *Biogeochemistry* **2010**, *100*, 39–56. [CrossRef]
25. Guggenberger, G.; Rodionov, A.; Shibistova, O.; Grabe, M.; Kasansky, O.A.; Fuchs, H.; Mikheyeva, N.; Zrazhevskaya, G.; Flessa, H. Storage and mobility of black carbon in permafrost soils of the forest tundra ecotone in Northern Siberia. *Glob. Chang. Biol.* **2008**, *14*, 1367–1381. [CrossRef]
26. Hiederer, R.; Köchy, M. *Global Soil Organic Carbon Estimates and the Harmonized World Soil Database*; Publications Office of the European Union: Luxembourg, 2011; pp. 308–309.
27. Gross, C.D.; Harrison, R.B. Quantifying and comparing soil carbon stocks: Underestimation with the core sampling method. *Soil Sci. Soc. Am. J.* **2018**, accepted. [CrossRef]
28. Czimczik, C.I.; Masiello, C.A. Controls on black carbon storage in soils. *Glob. Biogeochem. Cycles* **2007**, *21*. [CrossRef]
29. Maestrini, B.; Alvey, E.C.; Hurteau, M.D.; Safford, H.; Miesel, J.R. Fire severity alters the distribution of pyrogenic carbon stocks across ecosystem pools in a Californian mixed–conifer forest. *J. Geophys. Res. Biogeosci.* **2017**, *122*, 2338–2355. [CrossRef]
30. Galanter, A.; Cadol, D.; Lohse, K. Geomorphic influences on the distribution and accumulation of pyrogenic carbon (PyC) following a low severity wildfire in northern New Mexico: Distribution and accumulation of pyrogenic black carbon. *Earth Surf. Process. Landf.* **2018**, accepted. [CrossRef]
31. Kane, E.S.; Kasischke, E.S.; Valentine, D.W.; Turetsky, M.R.; Mcguire, A.D. Topography influences on wildfire consumption of soil organic carbon in interior Alaska. *J. Geophys. Res. Biogeosci.* **2007**, *112*. [CrossRef]
32. Ahmed, Z.U.; Woodbury, P.B.; Sanderman, J.; Hawke, B.; Jauss, V.; Solomon, D.; Lehmann, J. Assessing soil carbon vulnerability in the Western USA by geospatial modeling of pyrogenic and particulate carbon stocks. *J. Geophys. Res. Biogeosci.* **2017**, *122*, 354–369. [CrossRef]
33. Santin, C.; Doerr, S.; Preston, C. Carbon sequestration from boreal wildfires via Pyrogenic Carbon production. In Proceedings of the EGU General Assembly Conference, Vienna, Austria, 27 April–2 May 2014.
34. Fyles, I.H.; Shaw, C.H.; Apps, M.J.; Karjalainen, T.; Stocks, B.J.; Running, S.W.; Kurz, W.A.; Weyerhaeuser, G.; Jarvis, P.G. The role of boreal forests and forestry in the global carbon budget: A synthesis. In Proceedings of the IBFRA 2000 Conference, Edmonton, AB, Canada, 8–12 May 2000.
35. Flannigan, M.; Stocks, B.; Turetsky, M.; Wotton, M. Impacts of climate change on fire activity and fire management in the circumboreal forest. *Glob. Chang. Biol.* **2009**, *15*, 549–560. [CrossRef]
36. Liu, Z.H.; Chang, Y.; Hu, Y.M.; Li, Y.H.; Wang, J.H.; Jing, G.Z.; Zhang, H.X.; Zhang, C.M. Comparasion of storage of coarse woody debris between Huzhong Forest Bureau and Huzhong Natrural Reserve in Da Hinggan Mountains, China. *Chin. J. Plant Ecol.* **2009**, *33*, 1075–1083. [CrossRef]
37. Wu, W.; Li, Y.; Hu, Y.; Xiu, C.; Yan, X. Impacts of Changing Forest Management Areas on Forest Landscapes and Habitat Patterns in Northeastern China. *Sustainability* **2018**, *10*, 1211. [CrossRef]
38. Zhao, X.Q.; Ma, Y.E. Dynamic gray prediction of Da xing'an Mountains forest. *J. Northeast For. Univ.* **2015**, 98–100. [CrossRef]
39. Jin, S.; Hu, H.Q. Study on forest fire regime of Heilongjiang province, forest fire spatial and temporal dynamics and statistical distribution. *Sci. Silvae Sin.* **2002**, *38*, 88–94.
40. Sun, L.; Zhang, Y.; Guo, Q.; Hu, H. Carbon emission and dynamic of NPP post forest fires in 1987 in Daxing'an Mountains. *Sci. Silvae Sin.* **2009**, *45*, 100–104. [CrossRef]
41. Hu, H.Q.; Luo, B.Z.; Wei, S.J.; Wei, S.W.; Wen, Z.M.; Sun, L.; Luo, S.S.; Wang, L.M.; Ma, H.B. Estimating biological carbon storage of five typical forest types in the Daxing' anling Mountains, Heilongjiang, China. *Acta Ecol. Sin.* **2015**, *35*, 5745–5760. [CrossRef]

42. Hammes, K.; Schmidt, M.W.I.; Smernik, R.J.; Currie, L.A.; Ball, W.P.; Nguyen, T.H.; Louchouarn, P.; Houel, S.; Gustafsson, O.; Elmquist, M.; et al. Comparison of quantification methods to measure fire–derived (black/elemental) carbon in soils and sediments using reference materials from soil, water, sediment and the atmosphere. *Glob. Biogeochem. Cycles* **2007**, *21*. [CrossRef]
43. Poot, A.; Quik, J.T.K.; Veld, H.; Koelmans, A.A. Quantification methods of Black Carbon: Comparison of Rock–Eval analysis with traditional methods. *J. Chromatogr. A* **2009**, *1216*, 613–622. [CrossRef] [PubMed]
44. Caria, G.; Arrouays, D.; Dubromel, E.; Jolivet, C.; Ratie, C.; Bernoux, M.; Barthes, B.G.; Brunet, D.; Grinand, C. Black carbon estimation in French calcareous soils using chemo–thermal oxidation method. *Soil Use Manag.* **2011**, *27*, 333–339. [CrossRef]
45. Schmidt, M.W.I.; Skjemstad, J.O.; Czimczik, C.I.; Glaser, B.; Prentice, K.M.; Gelinas, Y.; Kuhlbusch, T.A.J. Comparative analysis of black carbon in soils. *Glob. Biogeochem. Cycles* **2001**, *15*, 163–167. [CrossRef]
46. Gao, C.; Knorr, K.-H.; Yu, Z.; He, J.; Zhang, S.; Lu, X.; Wang, G. Black carbon deposition and storage in peat soils of the Changbai Mountain, China. *Geoderma* **2016**, *273*, 98–105. [CrossRef]
47. Wiedemeier, D.B.; Hilf, M.D.; Smittenberg, R.H.; Haberle, S.G.; Schmidt, M.W.I. Improved assessment of pyrogenic carbon quantity and quality in environmental samples by high–performance liquid chromatography. *J. Chromatogr. A* **2013**, *1304*, 246–250. [CrossRef] [PubMed]
48. Koele, N.; Bird, M.; Haig, J.; Marimon-Junior, B.H.; Marimon, B.S.; Phillips, O.L.; de Oliveira, E.A.; Quesada, C.A.; Feldpausch, T.R. Amazon Basin forest pyrogenic carbon stocks: First estimate of deep storage. *Geoderma* **2017**, *306*, 237–243. [CrossRef]
49. Kasin, I.; Blanck, Y.L.; Storaunet, K.O.; Rolstad, J.; Ohlson, M. The charcoal record in peat and mineral soil across a boreal landscape and possible linkages to climate change and recent fire history. *Holocene* **2013**, *23*, 1052–1065. [CrossRef]
50. Pagano, M.C.; Ribeiro-Soares, J.; Cancado, L.G.; Falcao, N.P.S.; Goncalves, V.N.; Rosa, L.H.; Takahashi, J.A.; Achete, C.A.; Jorio, A. Depth dependence of black carbon structure, elemental and microbiological composition in anthropic Amazonian dark soil. *Soil Till. Res.* **2016**, *155*, 298–307. [CrossRef]
51. Wickland, K.P.; Neff, J.C. Decomposition of soil organic matter from boreal black spruce forest: Environmental and chemical controls. *Biogeochemistry* **2008**, *87*, 29–47. [CrossRef]
52. Kuzyakov, Y.; Bogomolova, I.; Glaser, B. Biochar stability in soil: Decomposition during eight years and transformation as assessed by compound–specific C–14 analysis. *Soil Biol. Biochem.* **2014**, *70*, 229–236. [CrossRef]
53. Carvalho, E.O.; Kobziar, L.N.; Putz, F.E. Fire ignition patterns affect production of charcoal in southern forests. *Int. J. Wildland Fire* **2011**, *20*, 474–477. [CrossRef]
54. Krishnaraj, S.J.; Baker, T.G.; Polglase, P.J.; Volkova, L.; Weston, C.J. Prescribed fire increases pyrogenic carbon in litter and surface soil in lowland Eucalyptus forests of south–eastern Australia. *For. Ecol. Manag.* **2016**, *366*, 98–105. [CrossRef]
55. Cotrufo, M.F.; Boot, C.M.; Kampf, S.; Nelson, P.A.; Brogan, D.J.; Covino, T.; Haddix, M.L.; Macdonald, L.H.; Rathburn, S.; Ryan-Bukett, S. Redistribution of pyrogenic carbon from hillslopes to stream corridors following a large montane wildfire. *Glob. Biogeochem. Cycles* **2016**, *30*, 1348–1355. [CrossRef]
56. Asefaw Berhe, A.; Abney, R.; Hockaday, W.; Fogel, M.; Kuhn, T. Role of erosional redistribution following wildfires in determining fate of pyrogenic carbon in the soil system. In Proceedings of the EGU General Assembly Conference, Vienna, Austria, 17–22 April 2016.
57. Moody, J.A.; Shakesby, R.A.; Robichaud, P.R.; Cannon, S.H.; Martin, D.A. Current research issues related to post–wildfire runoff and erosion processes. *Earth-Sci. Rev.* **2013**, *122*, 10–37. [CrossRef]
58. Cerda, A. Post–fire dynamics of erosional processes under Mediterranean climatic conditions. *Z. Geomorphol.* **1998**, *42*, 373–398.
59. Chang, Y.; Zhu, Z.; Feng, Y.; Li, Y.; Bu, R.; Hu, Y. The spatial variation in forest burn severity in Heilongjiang Province, China. *Nat. Hazards* **2016**, *81*, 981–1001. [CrossRef]
60. Epting, J.; Verbyla, D.; Sorbel, B. Evaluation of remotely sensed indices for assessing burn severity in interior Alaska using Landsat TM and ETM+. *Remote Sens. Environ.* **2005**, *96*, 328–339. [CrossRef]