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Forest Fires Effects on Carbon Stocks and Soil Chemistry in Central Yakutia, Eastern Siberia

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Abstract

This study was conducted to determine the impact of fire on the physical and chemical characteristics of soil as well as on the distribution of soil organic and black carbon stocks in ice-rich permafrost regions in eastern Siberia. Three intact and four burnt forest sites with different ignition years were selected. Volumetric water content did not increase in any of the burnt forests in the top soil layer but moisture accumulated at the bottom of the active layer of older burnt sites. Salt content increased in the active layer following forest fires, but a decade later, the salt increase disappeared, indicating the temporal characteristic of this change. The concentration of Na^+ and SO_4^{2-} in the active layer of the 4-year-old burnt forest site increased 70% and 49% respectively, while other salts (Mg^{2+} and Ca^{2+}) did not show any variation in the other burnt forest sites compared to the intact forest sites. The organic carbon stock in the top 200 cm of soil in the intact forest site (44.0 kg m^{-2}) was similar to that in burnt forest sites (41.4-43.7 kg m^{-2}). On average, 37% of organic carbon was found in the upper 30 cm of the soil profile for intact and burnt forests. The organic carbon distribution in the top 200 cm soil layer in Central Yakutia was higher than previously reported for other Siberian sites. The highest concentrations of black carbon were found in the upper soil layers (20-40 mg g^{-1} organic carbon) but concentrations of 10-20 mg g^{-1} organic carbon were also found in the permafrost (120-200 cm depth) of the intact and burnt forests. There was no variation in black carbon concentration among the sites. The presence of black carbon in the permafrost suggests that the active layer was deeper before and that black carbon accumulated because of fires that occurred at that time.

Key words: Black carbon, Forest fires, Permafrost, Soil chemistry, Soil organic carbon

Introduction

Boreal forests play an important role in the global carbon cycle, since they represent approximately 33% of all the Earth's forest (Prentice 2001). Nearly half of the global boreal forest is found in the continuous permafrost region of Siberia (Kolchuniga and Vinson, 1995). In boreal regions, vegetation and soil together contain approximately 300 Pg of carbon, of which approximately 85% is in soils (Dixon *et al*. 1994). These forests act as a modest atmospheric CO_2 sink (Lopez *et al*. 2008) that in the long-term maintains a positive carbon input despite carbon release caused by fire. Recent increases in air temperatures and precipitation variability have been observed in eastern Siberia (Iijima *et al*. 2010). These could lead to an increase in intensity and frequency of fire in Siberia (Kharuk *et al*. 2005) and a corresponding increase in burnt areas (Flannigan *et al*. 2009).

Depending on the intensity of fire, the organic layer can decrease or disappear entirely, and result in higher ground temperature and deepening of the active layer (Yoshikawa *et al*. 2002). The deepening of the active layer (the layer of soil that thaws in summer and freezes in winter) following fire events can release soluble salts formerly trapped in the permafrost layer into the water stream of the active layer. In the past, thawing of permafrost led to the formation of saline grasslands (Desyatkin 1993, Lopez *et al*. 2007) that at present show a different pattern of organic carbon accumulation compare to forests (Matsuura *et al.* 2005). It is not clear if changes in soil chemistry following fires cause physical changes in the soil that will alter carbon storage in the short-term (from several years to decades). According to Schulze *et al* (1999), forest fires enhance carbon sequestration in the long-term via charcoal (black carbon) formation that is transported to deeper layers via cryoturbation. The production of black carbon is estimated to account for approximately 0.2 Pg per year (Gonzales-Perez *et al*. 2004) and this accounts for reducing net CO_2 release caused by permanent deforestation by up to 18% (Kuhlbusch 1998). Even most recent estimates on carbon storage in permafrost soils suffer from limited data on carbon in the subsoil, which is the layer of soil under the topsoil (the outermost layer of soil, about the upper 20 cm) (Schuur *et al*. 2008).

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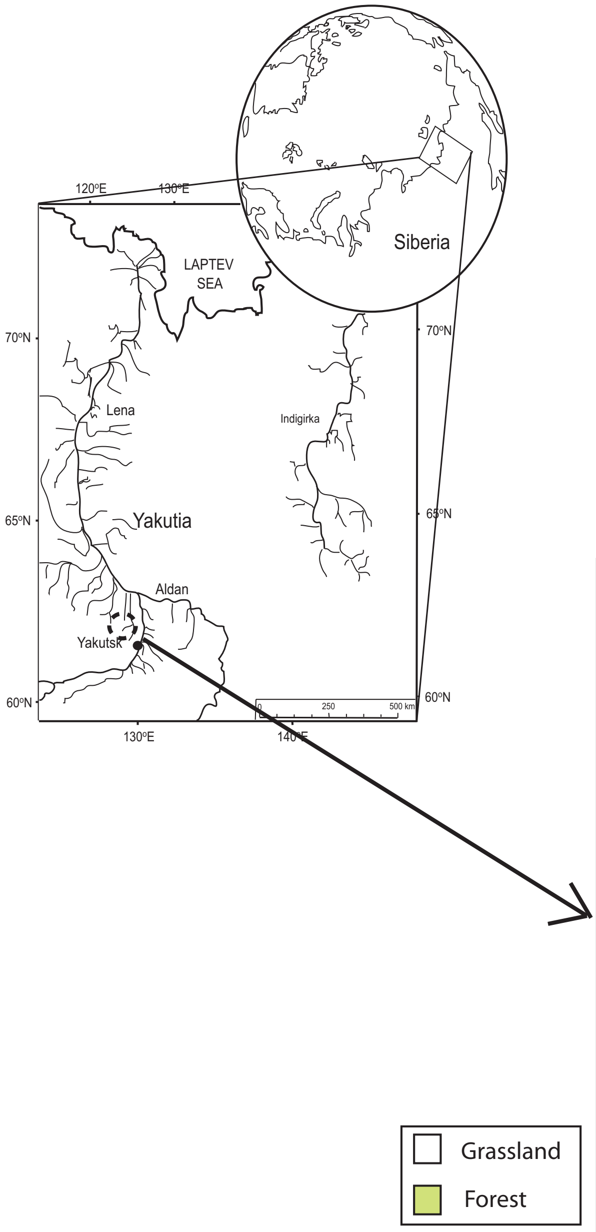
Measurements of soil carbon storage have largely been restricted to surface soil layers (Matsuura *et al.* 2005), or its description has fallen under large scale representative values of the active and upper permafrost layer (Stolbovoi 2002). Moreover, black carbon has not been studied following fires in eastern Siberia.

Thus, the aims of this study were as follows: 1) to determine the chemical and physical changes in the active layer and upper permafrost of the intact and chronologically burnt forests and 2) to determine the distribution of soil organic and black carbon.

2. Materials and Methods

2.1. Study site

This experiment was conducted in lowland Central Yakutia in the surroundings of the Yakutian Permafrost Institute experimental station (62º 19′N, 129º 30′E) (Fig. 1), located 30 km north-northwest from the city of Yakutsk. Mean annual temperature is -10.0°C to -11.8°C; amplitude of monthly temperatures is about 62.8°C, and annual mean precipitation is approximately 220 mm. In this region, the thickness of the continuous permafrost is up to 400-500 m, and soils are classified as Gelisols, having a silty-clay-loam (SiCL) to



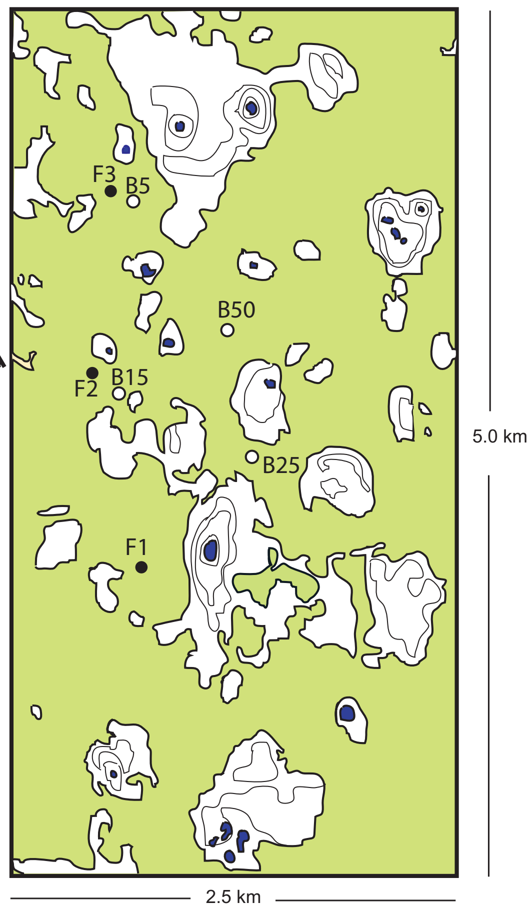


Fig. 1. Study site where the 3 intact forests sites (F1, F2, F3) and the 4 burnt forest sites (B4, B15, B25 and B50) where selected. Whight color indicates grasslands and dark gray indicates forest cover.

silty-clay (SiC) texture. All of the soil samples were taken in the year 2006 in an area encompassing 2.5 x 5.0 km.

The intact larch (*Larix cajanderi*) forest at the sampled sites was approximately 160 years old. Burnt forest sites were sampled based on the years elapsed after the fire event took place (vegetation characteristics at each site are described below):

B4 (2002, 4 years after fire): During the 4 years following the fire event the dominant vegetation consisted of several grasses and fireweed (*Chameneariom angustifolium*).

B15 (1991, 15 years after fire): Fireweed was the dominant vegetation, but after 7 to 8 years surface vegetation became more diverse (*Poa, Bromopsis pumpeliana, Artimisia conmutata, Sanguisorba officinalis, Vicia cracca, Salix bebbiana,* among others), and the presence of emergent birch was observed.

B25 (1981, 25 years after fire): Understory vegetation remained diverse, with some additional plants such as *Artemisia tanacetifolia, Cnidium cnidiifolium, Geranium pretense* and *Vicia amoena*, but the dominance of a taller birch stand and suppressed larch trees was the main characteristic.

B50 (1956, 50 years after fire): This site was characterized by low understory vegetation diversity, and larch stands are dominant.

2.2. Sampling

In early May 2006, three 2-m deep soil cores were sampled at three intact forest sites and four burnt forest sites (B4, B15, B25 and B50). The sampling protocol for soil carbon followed the design by Conant *et al.* (2003). Core samples were sectioned in 10-cm increments, logged, double-bagged, brought to the laboratory and air-dried for several days. The active layer depth was not measured in May because the soil profile was frozen making it difficult to distinguish the border between the active layer and the permafrost. Instead, it was measured (10 replications) at the end of September of the same year in all sites by pushing a graduated rod into the soil until it stuck to the frozen layer. In this study, the thickness of the upper permafrost was arbitrarily set from the bottom of the active layer to the depth of 200 cm.

2.3. Measurements

2.3.1. Volumetric water content and soluble salt analysis

Volumetric water content of the thawing soil layers was determined gravimetrically by drying the samples to a constant weight at 105ºC for 24 hours. For electric conductivity (*EC*) and pH measurements, samples were taken in 10-cm increments and were measured potentiometrically (EC meter: CM-30V, DKK-TOA, Tokyo, Japan and pH meter F51BW, Horiba, Kyoto Japan) in a 1:5 soil deionized water suspension. Electric conductivity of saturated paste EC_e, used to evaluate saline and alkaline soils, was estimated as five times the value of the measured *EC* of the soil water 1:5 suspension. For the analysis of dominating ions in the suspension, a composite of three mixed soil core samples per depth and per site were chosen. Concentrations of Na^+, Ca^{2+} and Mg^{2+} were measured by atomic absorption spectrophotometry (Z5010, Hitachi, Tokyo, Japan) and SO_4^{2-} was analyzed by ion-chromatograph (ICS-3000, Dionex, Tokyo, Japan).

2.3.2. Soil organic carbon measurements and calculations

All soil core samples (10-cm increment of each soil profile, 10 grams for each depth) were sieved (<2 mm), crushed and subsequently analyzed for total carbon (TC) by dry combustion (CHN 1000 analyzer, LECO, NSW, Australia). Total inorganic carbon (TIC) was measured by the HLC dissolution method and total organic carbon was calculated as the difference between total carbon and TIC. Since soil carbon density is a more reliable measure for comparison between different locations, bulk density was measured at each depth and taken into consideration using the following equation: *Soil carbon density* = C×V×H×S, where *C* is the carbon content in g kg^{-1}, *V* is the bulk density in kg m^{-3}, *H* is the thickness of the horizon in m and *S* is the correction coefficient on abundance (by soil volume) of rock fragments (S=1 in this study). Soil carbon density was divided into standard depths, 0-30, 0-50, 0-100, and 0-200 cm (Stolbovoi 2002) and considered separately for the active layer (0-120 cm) and upper permafrost (120-200 cm). Finally, the total carbon stock in larch forests in lowland Central Yakutia was estimated as the carbon content (kg m^{-2}) in the 0-200 cm soil layer multiplied by the total area of forests (2.1 million ha). The total amount is given in petagrams (Pg, 10^{15} g).

2.3.3. Soil black carbon measurements

Soil core samples (n=3) used for black carbon analysis corresponded to depths of 5, 15, 30, 85, 130 and 180 cm at all sites except for B4 (because of a lack of sampling amount). Only one forest site was chosen for black carbon analysis. Air-dried soil samples and freeze-dried water samples were analyzed for BC (black carbon) using the BPCA (benzenepolycarboxylic acid) method according to Glaser *et al*. (1998) and as modified by Brodowski *et al*. (2005). Briefly, metal elimination from soil was achieved by digestion with 4M trifluoroacetic acid. Then, the dried soil residue and approximately 0.1 g freeze-dried water sample, were oxidized into benzene polycarboxylic acids to with 65% HNO_3 in a high-pressure digestion apparatus. The solution was filtered through ash-less cellulose, cleaned using Dowex 50W X8, 200-400 mesh cation exchange resin, and freeze-dried. The benzene polycarboxylic acids were transformed to trimethylsilyl derivatives with N,O-Bis(trimethylsilyl) trifluoracetamide and analyzed with a gas chromatograph (GC 2010, Shimadzu Corp., Tokyo, Japan) equipped with a flame-ionization detector (FID) and a SPB-5 capillary column (30 m_0.25 mm i.d., 0.25 mm film thickness; Supelco, Deisenhofen, Germany).

2.4. Statistical analyses

Intact and burnt forests sites were analyzed by multiple comparisons using Tukey's HSD (Honestly Significant Difference). Results were considered significant at $P<0.05$. The statistical software *R* (R Core Development Team 2008) was used.

3. Results

3.1. Active layer depth and volumetric water content

In our experiments, the active layer depth in the three intact larch forests was 118.4 ± 9.4 cm. The active layer thickness in B4 (127.9 ± 6.8 cm) increased significantly after fire; however, in B15 (120.0 ± 4.8 cm) the active layer aggraded to a depth similar to the active layer of the intact forest sites. This was also observed in B25 (116.2 ± 11.3cm) and B50 (121.0 ± 6.5 cm).

Volumetric water content in the burnt sites was significantly lower than that in the intact forest sites in the upper 0-60 cm soil layer (Fig. 2). At B4 and B15, there was a decrease in soil water content that extends from 60 cm depth to the bottom of the active layer, while moisture in B25 and B50 sites increased sharply from 60 cm down to the base of the active layer, reaching values of 60%. The ice content in the upper permafrost (120-200 cm) was on average 40% for the intact forests sites and the B4 and B15 sites, while in B25 and B50 the ice content was nearly 50%.

3.2. Changes in soil chemistry

In the B4 site EC_e increased significantly in the active layer from 30-130 cm depth, in comparison to the active layer in the intact forest sites and also in comparison to the other burnt sites (B15, B25 and B50) (Fig. 3). In all sites, EC_e values tended to be low in the active layer and increased significantly once they crossed the boundary into the permafrost layer.

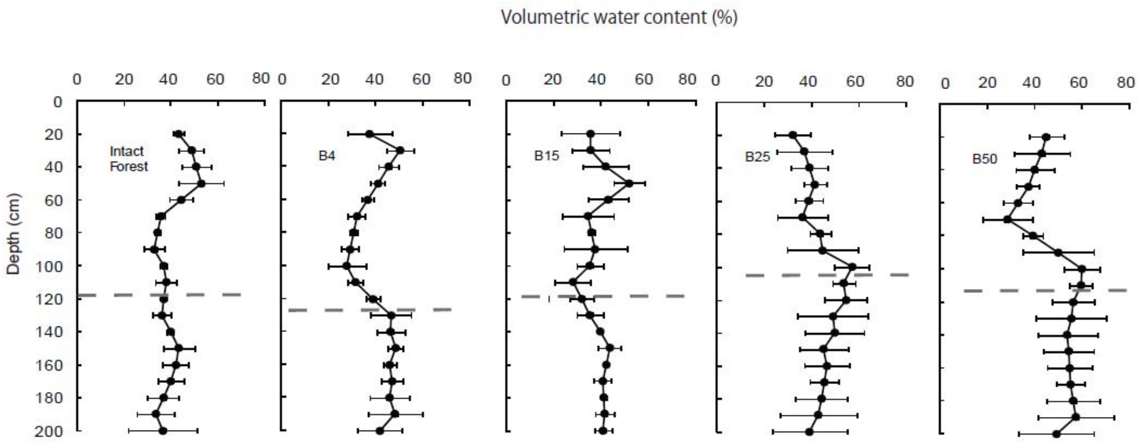


Fig. 2. Volumetric water content of the (a) intact forest sites and burnt forests sites, (b) B4; (c) B15 (d) B25 and (e) B50.

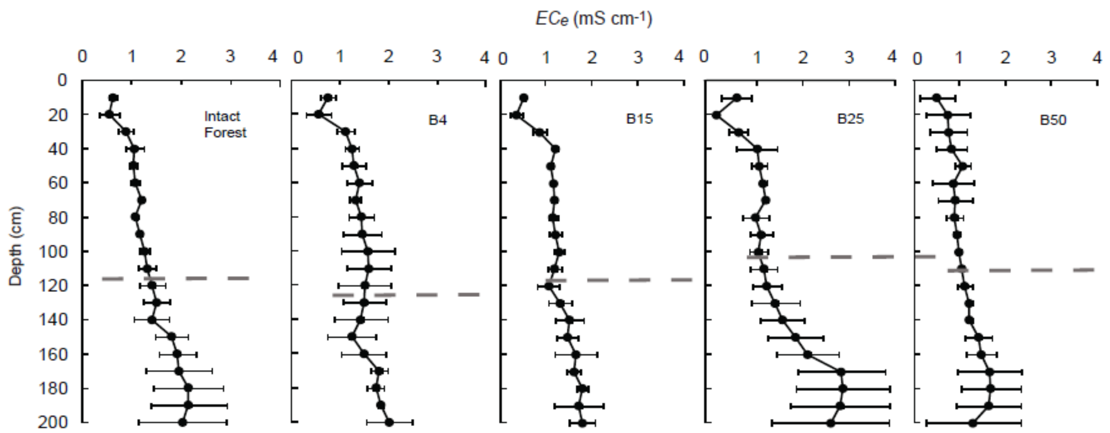


Fig. 3. (a) Electric conductivity of the intact forest sites (n=9) and burnt forests sites (b) B4; (c) B15; (d) B25 and (e) B50, (n=3) in 10-cm increments for a 0-200 cm soil profile.

Four years (B4) after the fire event, Na^+ and SO_4^{2-} concentrations exhibited an increase between 30-80 cm with a maximum value at 50 cm of 70% (Na^+) and 49% (SO_4^{2-}) in comparison to those at the same layer in the intact forests sites (Fig.4a). These peaks were also present at the same depth in B15 but in B25 the peak was at the bottom of the active layer while the profile of Na^+ and SO_4^{-2} concentrations for B50 were as low as the concentrations found in the intact forest sites. In contrast, Mg^{2+} and Ca^{2+} did not show any variation in the burnt forest sites (B4, B15, B25 and B50) in relation to the intact forest sites (Fig.4b).

3.3. Soil carbon density and black carbon

Organic carbon represented almost 99% of the total carbon in all soil profiles. Nearly 37% of soil carbon density is found in the upper 30 cm, with 16.6 ± 4.3 kg m^{-2} in the intact forest sites, while the soil carbon density at the same depth in the burnt sites (B4, B15, B25 and B50) was 13.3 ± 1.7 to 17.7 ± 3.9 kg m^{-2}. In the 200-cm depth layer the soil carbon density in the intact forest sites was 44±6.9 kg m^{-2}, while that in the burnt sites varied from 41.4 to 43.7 kg m^{-2} (Table 1). Soil carbon density did not show any significant differences between the intact forest sites (n=9) and

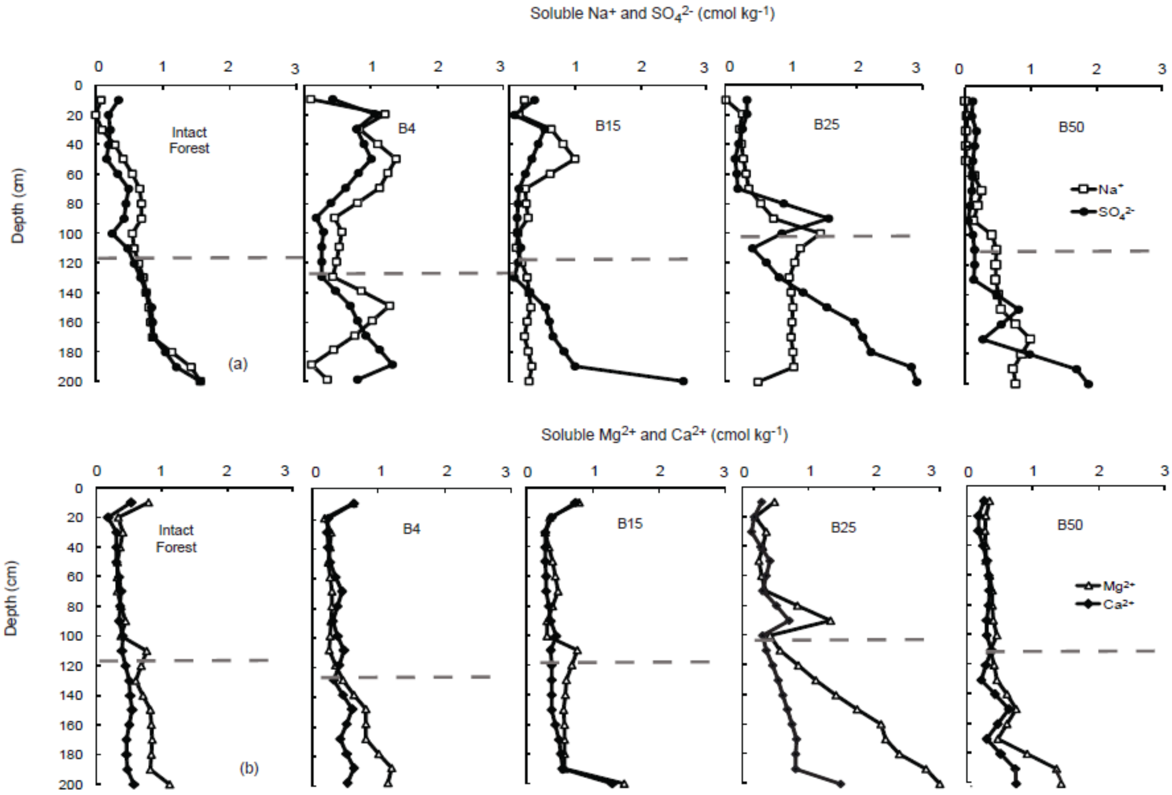


Fig. 4. (a) Na^+ and SO_4^{2-} distribution in the 0-200 cm soil profile in the intact and burnt forest sites and (b) Mg^{2+} and Ca^{2+} distribution in the 0-200 cm soil profile in the intact and burnt forest sites. Each point corresponds to a mixture of three samples taken at the same depth of the three profiles.

Table 1. Soil carbon density (kg m^{-2}) in the intact and burnt forest sites. The values from the second column to the right are cumulative values and their corresponding standard deviations

Soil carbon density (kg m^{-2})

Site	Layer			
	0-30	0-50	0-100	0-200
Intact Forest	16.6±4.3	22.0±5.1	30.9±4.5	44.0±6.9
B4	17.7±3.9	21.9±4.9	31.3±4.7	43.7±7.8
B15	13.3±1.7	19.0±2.7	27.3±1.8	41.4±5.1
B25	17.1±4.3	22.2±5.5	30.7±5.7	43.6±9.5
B50	13.5±6.2	18.4±7.8	26.0±7.0	43.3±9.9

each of the burnt sites in the upper 0-30 cm soil layer as well as in 0-200 cm soil layer, regardless of the time since the fire events (Tukey test; p>0.05). Soil carbon density in the 100 cm layer was on average 30.9 kg m^{-2} in the intact forest sites while the soil carbon density in the burnt forest sites ranged from 26.0 to 31.3 kg m^{-2}. In the intact forest sites, the SCD in the 100 cm upper soil layer was 70% of that of the 200-cm soil layer, while in the B4, B15, B25 and B50 sites the corresponding values were 71%, 66%, 70% and 60%.

The soil carbon density in the active layer (0-120 cm) of the intact forest sites was on average 33.6 kg m^{-2} (76% of the carbon content of the 200-cm soil profile) while in the burnt sites, the carbon density of the active layer ranged from 29.2 to 34.7 kg m^{-2}. In the permafrost layer (120-200 cm), the soil carbon density in the intact forest sites was 10.4 kg ± 5.1 kg m^{-2}, or 24% of the carbon content of the 200-cm soil profile, while in the burnt sites the accumulation of carbon in the upper permafrost layer (120-200 cm) varied from 9.8 to 14.1 kg m^{-2} (or 22%-32%). These values were obtained by adding the value of carbon density at each layer.

The highest content of black carbon was found in the upper 30-cm layer of the intact forest sites and the B50 site, with a content of 20-40 mg g^{-1} organic carbon. In the upper permafrost, black carbon ranged between 10-20 mg g^{-1} organic carbon in all the sites (intact and burnt) (Fig. 5).

4. Discussion

4.1 Movement of ions and volumetric water content in the active layer after fire

Siberian boreal forests are well adapted to fire since fire sustains the succession of forest ecosystems (Tsvetkov 2004). In contrast to a previous study, Mg^{2+} and Ca^{2+} did not increase in the active layer following the fire event and in our study they were one order lower than reported by that study in northern Mongolia (Krasnoshchekov 1994).

The processes that led to a salt build-up after forest fires occurred in summer and late autumn. In summer, thawing of the active layer released salts that were formerly trapped in the upper 30-40 cm of the upper permafrost layer. The soil thawing front reaches the bottom of the active layer in late July or early August when evapotranspiration demand is still high (Lopez *et al*. 2008), bringing salts upward together with water. Comparison of evapotranspiration from the intact forest site (F1) (Ohta *et al*. 2008) and from a 5-year-old burnt site (B5) in 2003 (unpublished data, eddy co-variance measurements) confirmed that for the period June-August, evapotranspiration was higher at the fireweed (after fire) covered surface (107.8 mm) than in the intact forest site (73.5 mm). Increases in evapotranspiration can also be explained by the significantly lower volumetric water content found in B4 compared to the volumetric water content profile in the active layer of the intact forest sites or the older burnt forest sites (B15, B25 and B50).

The second process that contributes to salt accumulation involves the bidirectional freezing – downward from the soil surface and upward from the bottom - of the active layer in late autumn. Along these two freezing fronts, salts migrate together with water (Murton and French 1994). The depth where the freezing fronts meet in the active layer underneath the larch forest in central Yakutia is generally in the range of 60-80 cm (Iwahana *et al*. 2005).

After vegetation and secondary forest (birch) appears, as was observed at all sites, the higher vegetation density decreases soil temperature and subsequently enables permafrost recovery. The salts at the bottom of the active layer are thus trapped again. The peak of salts observed at the bottom of the active layer suggests downward leaching, especially during extreme rain events (Lopez *et al*. 2010). This is evidenced by the

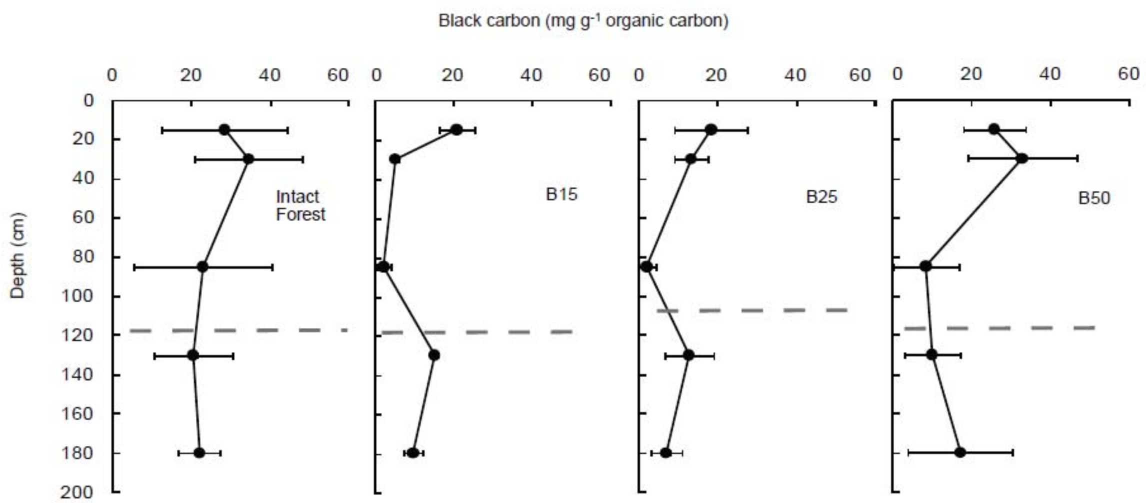


Fig. 5. Distribution of average black carbon in the 0-200 cm soil profile in (a) intact forest sites (n=9) and burnt forest sites (b) B4; (c) B15; (d) B25 and (e) B50, (n=3).

Table 2. Soil carbon density (kg m^{-2}) in the intact and burnt forest sites. The layers were separated into organic (0-20), mineral soil layer (20-120) and the upper permafrost (120-200 cm) layer

Soil carbon density (kg m^{-2})

Site	Layer		
	0-20	20-120	120-200
Intact Forest	14.3±3.8	19.3±2.5	10.4±5.1
B4	15.7±2.6	19.0±4.0	9.0±5.0
B15	11.7±1.9	18.2±1.7	11.5±2.9
B25	15.9±4.4	17.9±3.6	9.8±4.7
B50	10.0±4.8	19.2±2.4	14.1±4.7

high ice content at the base of the active layer with 0.55 ± 0.09% (B25) and 0.56 ± 0.11% (B50) that drained down as water after progressive decreases in evapotranspiration rates on the surface following the appearance of secondary forest. The richer ice layer, between the bottom of the active layer and the upper permafrost, prevents the active layer from deepening further (Shur *et al*. 2005).

4.2. Soil organic and black carbon stocks

In the present study, fires did not affect soil carbon density at the period and temporal resolution of investigation in the upper soil layer (0-30 cm). The average percentage of soil carbon density was 38% in the intact forest sites in the 0-30 cm upper soil layer in relation to the 200-cm layer, while the range in the burnt sites was between 31%-39%. These values are within the ranges found by Matsuura *et al.* (2005) but were lower than those found by Stolbovoi (2002) for eastern Siberia. Johnson and Curtis (2001) also reported that no decrease in soil carbon content was observed after fire. Short-term effects of fire on decreasing soil organic carbon were found by Fernandez *et al*. (1999) in temperate forests in Spain, but the lack of evaluation of long-term effects made it difficult to assess the real ecological role of fire. Lal (2005) has also suggested that natural or managed fire is an important disturbance that can affect soil organic carbon stocks in the long term.

Our estimation of carbon stock in the 0-200 cm layer (44 kg m^{-2}) in the forest soils of lowland central Yakutia (2.1 million ha) is approximately 0.9 Pg of C, which is about 0.4% of the total carbon stored in soils in Russia (Stolbovoi 2002). The carbon stocks in the soil of Central Yakutia are higher than those reported for any other region of Siberia (Stolbovoi 2002). According to Dutta *et al.* (2006), if 10% of the Siberian permafrost carbon pools are thawed, about 1 Pg C will be released from labile carbon, and increased respiration will follow for several decades. The accumulation of large amounts of soil organic carbon has also been reported in lowland central Yakutia in comparison to other regions in eastern Siberia (Matsuura 2006).

Our results agree with Schulze *et al.* (1999), in that black carbon shows higher concentrations in the upper soil layer (between 20-40 mg g^{-1} organic carbon). However there is also a considerable amount of black carbon in the permafrost. At present, in Central Yakutia wildfires cause active layer deepening of 30 to 40 cm as shown in this study. This has also been observed for disturbances such as clear-cutting in this region (Iwahana *et al*. 2005).This reflects black carbon accumulation from past fire events but also that in the past the active layer in the forests of Central Yakutia could have been deeper than what it is today, most probably during the Holocene optimum (5000-6000 years B.P.).

5. Conclusions

Temporal changes in the ion balance of the active layer were the apparent result of temporal changes in the water balance. At present, fires in the thermokarst-prone region of central Yakutia have a short-term (few years) impact on the chemical and physical characteristics of the active layer. As a result, soil organic carbon in the upper soil layers (0-30 cm) in the burnt forests did not experience any change due to fire for the time resolution in this study. The soil carbon content in the 0-200 cm soil layer was invariant at all sites and was on average 44 kg m^{-2}, higher than previously reported for this region. Black carbon was found in the active layer and in the permafrost reflecting past accumulations related to fire.

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