

Effects of increasing fire frequency on black carbon and organic matter in Podzols of Siberian Scots pine forests

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Summary

Fires in boreal forests frequently convert organic matter in the organic layer to black carbon, but we know little of how changing fire frequency alters the amount, composition and distribution of black carbon and organic matter within soils, or affects podzolization. We compared black carbon and organic matter (organic carbon and nitrogen) in soils of three Siberian Scots pine forests with frequent, moderately frequent and infrequent fires.

Black carbon did not significantly contribute to the storage of organic matter, most likely because it is consumed by intense fires. We found 99% of black carbon in the organic layer; maximum stocks were 72 g m⁻². Less intense fires consumed only parts of the organic layer and converted some organic matter to black carbon (> 5 g m⁻²), whereas more intense fires consumed almost the entire organic layer. In the upper 0.25 m of the mineral soil, black carbon stocks were 0.1 g m⁻² in the infrequent fire regime.

After fire, organic carbon and nitrogen in the organic layer accumulated with an estimated rate of 14.4 g C m⁻² year⁻¹ or 0.241 g N m⁻² year⁻¹. Maximum stocks 140 years after fire were 2190 g organic C m⁻² and 40 g N m⁻², with no differences among fire regimes. With increasing fire frequency, stocks of organic carbon increased from 600 to 1100 g m⁻² (0–0.25 m). Stocks of nitrogen in the mineral soil were similar among the regimes (0.04 g m⁻²). We found that greater intensities of fire reduce amounts of organic matter in the organic layer but that the greater frequencies may slightly increase amounts in the mineral soil.

Introduction

Boreal forests cover 9% (13.7 × 10⁶ km²) of the land between 45° and 70° north. Fire, windthrow and outbreaks of insects and pathogens are frequent in them. We know little of how much such disturbances affect the stocks of organic matter beneath them, and we should because the soil contains roughly 22% (338–471 Pg C) of global soil carbon (IPCC, 2001).

Fire is the most important disturbance in boreal regions, and is caused by lightning during summer droughts. This is especially true for Siberian Scots pine (*Pinus sylvestris*) and larch (*Larix gmelinii* and *L. cajanderi*) forests (Conard & Ivanova, 1997) and the western boreal, subarctic, and mountain regions of Canada (Kurz & Apps, 1999). There are some indications that fires will be more frequent in the future (Flannigan *et al.*, 2001), partly as a result of global warming, and partly caused by an increasing anthropogenic activity in the boreal region.

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In the last 20 years, the area of boreal forest burned in northern America doubled, and a similar trend is thought to apply for Russia (Chapin *et al.*, 2000).

Fire reduces the amount of organic matter in the soil and alters its composition. In Russian Scots pine and larch forests, surface fires are the most frequent; they affect mainly the organic layer, and kill seedlings and trees in lower canopies (Wirth *et al.*, 1999). Vegetation and soil organic matter can be distilled, oxidized, or charred. Most of the products are instantaneously released. Organic carbon is converted to CO₂, CO, and CH₄, nitrogen to NO_x and N₂, and sulphur to SO₂, all of which are lost into the atmosphere. Auclair & Carter (1993) estimated losses of carbon to be 0.13 Pg C year⁻¹ between 1977 and 1990 for the northern hemisphere. Harden *et al.* (2000) reckon that 25% of the annual net primary production of Canadian jack pine (*Pinus banksiana*) forests is lost in this way, and Wirth *et al.* (2002a) estimate that 35% of net primary production of Siberian Scots pine forests is lost. However, during burning, a small fraction of carbon (0.7–8%, Czimczik *et al.*, 2003) is converted to black carbon. The term black

carbon describes a continuum of aromatic carbon with highly condensed structures from partly charred plant material through charcoal to soot with no general agreement on clear-cut boundaries (Schmidt *et al.*, 2001). Although some studies suggest that black carbon can be degraded by microorganisms (Haumaier & Zech, 1995; Baldock & Smernik, 2002), it accumulates in soils of some ecosystems where fires are frequent, and can account for 10–45% of all the organic carbon (Skjemstad *et al.*, 1996; Glaser, 1999; Schmidt *et al.*, 1999).

As far as we know no one has studied the fate of black carbon in boreal soils, and little is known about the accumulation of organic matter in soils following fire, especially in Russia. In Siberian Scots pine forests which dominate in western Siberia we tried to answer the following question: How does increasing frequency of fire affect the amounts of black carbon and organic matter in the soils?

Materials and methods

Sites

Our study area is about 40 km west of the river Yenisey at the eastern edge of the West Siberian Plain (60°43–45'N, 89°08–83'E, 50–100 m above sea level). The climate is continental with a monthly average air temperature of 18°C in July and –24°C in January, and an annual precipitation of 560 mm (225 mm as snow) (Tchebakova *et al.*, 2002).

The vegetation consists of pristine monotypic Siberian Scots pine forests (*Pinus sylvestris* ssp. *sibirica* Lebed.) with an understorey dominated by reindeer lichens, surrounded by string-type sphagnum bogs and small rivers. The trees regenerate from seeds after their crowns have been destroyed by fires. Also, stands are frequently damaged by surface fires. Fires are frequent during the entire growing season (March to September) after long periods of drought, ignited by both lightning and people. Sites are fragmented by wetland. Apart from fire frequency, all sites have soils of similar quality, as indicated by the lichen that dominates the understorey and the similar growth pattern of the trees.

We investigated the soils of three forests with three distinct fire regimes described earlier by Wirth *et al.* (1999). The least frequent fire regime consisted of four dense forests which had not experienced surface fires since the last crown fire. The medium frequency regime consisted of seven closed forest stands with a homogeneous stand structure and a mean surface fire return interval of 43 years. The most frequent fire regime consisted of seven open forest stands (woodlands) with a mean surface fire return interval of 25 years. The latter included two stands that had not experienced a surface fire since the last crown fire, because their stand structure resembled that of the other stands of this regime, and the recent fire history could be reconstructed.

Soils are Gleyic, Cambic, or Haplic Podzols. All show a clear albic E horizon of 0.02–0.18 m thickness, with pH < 4.5 except shortly after a fire. In the upper part of the underlying

spodic B horizon, a subhorizon < 2 cm is enriched in organic matter and is darker. In some places, this subhorizon is absent. As a representative example, pH, cation exchange capacity, and Fe concentrations are shown for the regime with least frequent fire (Figure 1). The soils are developed on glacio-fluvial sediments. The texture of all mineral soils (< 2 mm) is very similar and dominated by sand (98–99 mass %) of a diameter between 250 and 500 μm . Below 1 m depth, some soils have a discontinuous horizon containing more clay (clay lenses). The soils are currently not affected by permafrost.

Sampling

The soils were sampled from three pine forests that differed in the frequency of recurring surface fires (infrequent, intermediate, and frequent) (Table 1). We chose sampling sites in topographically similar situations to represent a typical part of the stands and kept the distance to neighbouring trees constant (about 2 m). Soil organic layers were sampled from one 0.3 m \times 0.3 m area per site, with the sampling depth adjusted to coincide with the upper boundary of the mineral soil. We excluded coarse woody debris (diameter > 2 cm), and living biomass (roots, ericaceous shrubs, and grasses).

Organic layers (organic matter content > 30% by mass) were divided into three sublayers: fresh litter (L), partly decomposed litter (Of), and highly decomposed organic matter (Oh). However, reindeer lichens dominate the ground vegetation, forming a more or less continuous layer on the Of layer, and are difficult to separate from the organic matter. This is because at the top of the lichen layer, fresh litter is incorporated into the growing lichen. At the bottom, dead lichen that is often still connected to the living lichen is incorporated into the Of layer. In 1999, organic layers were distinguished into L on top of the lichen layer, the lichen layer which was easily separated from the underlying soil organic layer (Of + living lichens), and the underlying layers (Of + Oh). In 2000, we separated living lichens from the Of horizon by picking them out after wetting them with distilled water. The organic layers in young forest stand (0–16 years since the last fire) consisted of black hardened material which we could not separate into sublayers.

We calculated stocks of black carbon, organic carbon, and nitrogen in the organic layers using the samples from 2000 which did not include the fractions stored in the lichen layer. Only for two samples from 1999 did we calculate stocks by assuming a similar contribution of the lichen layer as in 2000 (see Figure 2).

Mineral soil was sampled from one soil pit per site (2 m \times 2 m to the upper boundary of parent material or groundwater). The average thickness of the E horizon was measured along the pit walls. The lengths of E-horizon fingers into the B horizon were measured separately. Samples for each horizon were taken from a freshly cut part of a wall with a 100-cm³ metal cylinder for bulk density. Samples for chemical

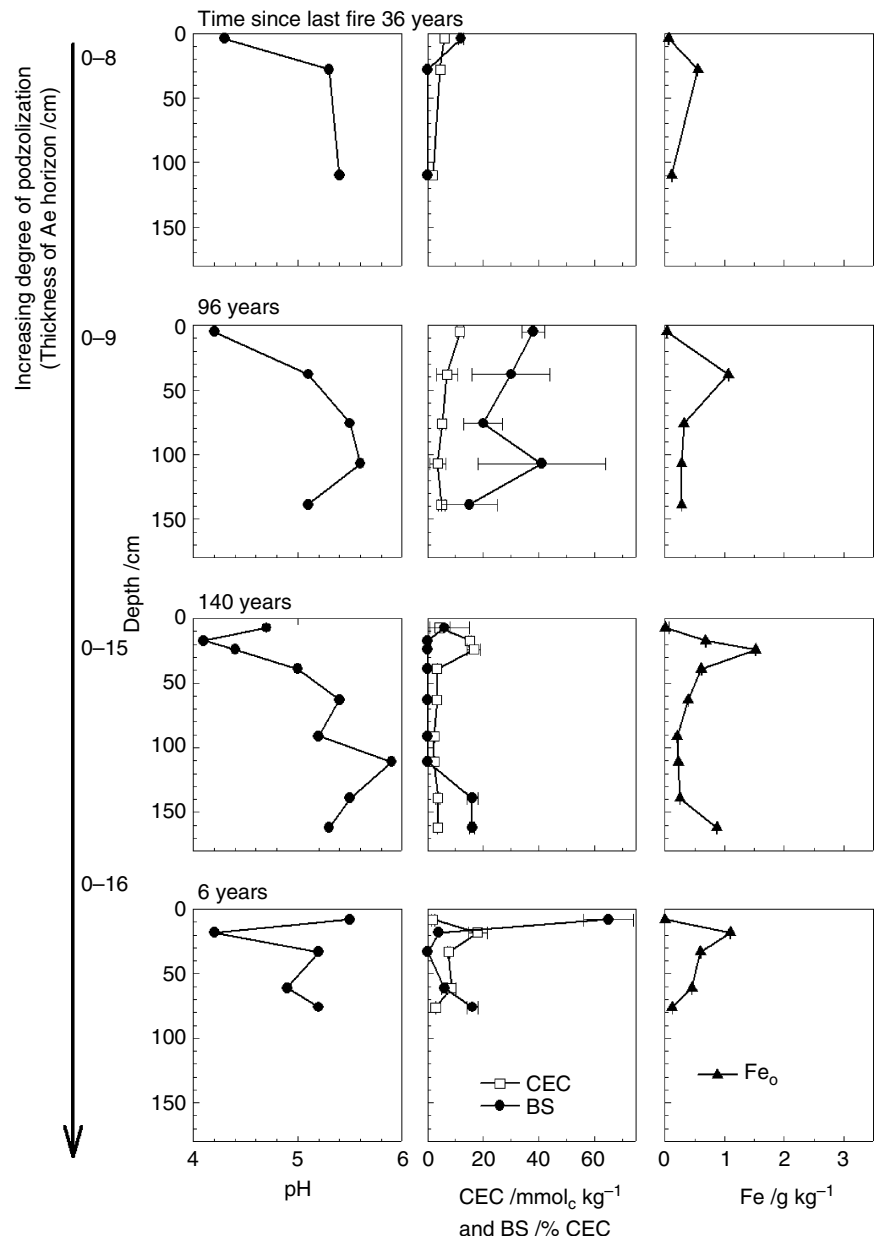


Figure 1 Podzolization indices of the mineral soils of the infrequent fire regime. Note the different scales of the abscissae. CEC, cation exchange capacity; BS, base saturation.

analyses were taken as mixed samples across the pit walls from soil horizons which we distinguished by colour, density, and texture.

Soil analysis

Samples were dried to constant weight at 60°C, and mineral soil samples were dry-sieved (< 2 mm). We calculated the density of organic samples after drying them at 60°C and of mineral soil samples after drying at 110°C.

To characterize the degree of podzolization, we measured (i) the pH of all mineral soil samples (except for replicate samples of the same site, see Table 1), (ii) cation exchange capacities

(CEC), (iii) concentrations of extractable Fe of all mineral soil samples of the infrequent fire regime, and (iv) the thickness of the albic E horizon of all soil profiles. We determined the pH with a pH electrode after having shaken each mineral soil sample (10 g) in 25 ml distilled water for 1 hour and letting the suspension settle for another hour. We quantified the CEC (sum of extractable Ca^{2+} , K^{+} , Mg^{2+} , Na^{+} , Al^{3+} , Fe^{3+} , Mn^{4+} , and H^{+}) after pre-extracting bulk mineral soil samples (2.5 g) with 3 ml 1 M NH_4Cl overnight, and percolating the samples with 90 ml 1 M NH_4Cl (approximately 0.375 ml per minute), and adjusting the volume to 100 ml. Concentrations of extractable basic cations except H^{+} were quantified via inductively coupled plasma optical emission spectroscopy

Table 1 Location and fire history of soil sampling sites

Name of forest stand ^a	Location		Time since last fire /years	Stand age ^b /years	Year of last surface fires since last stand-replacing fire	Year of sampling
	N	E				
Low fire frequency						
2 _{lu}	ND	ND	6	6	–	1999
	ND	ND				1999
28 _{lu}	60°43.491'	89°08.943'	36	36	–	2000
95 _{lu}	60°45.303'	89°23.957'	96	96	–	1999
	60°45.304'	89°23.950'				1999
			97			2000 ^c
–	ND	ND	140	140	–	1999 ^d
Medium fire frequency						
67 _{lm}	60°43.348'	89°08.460'	36	72	1964	2000
138 _{lm}	60°43.357'	89°08.129'	36	143	1964, 1939, 1923, 1885	2000
204 _{lm}	60°43.393'	89°09.010'	36	209	1964, 1939, 1850	2000
383 _{lm}	60°43.500'	89°83.260'	36	388	1964, 1850, 1790	2000
–	60°44.080'	89°20.890'	39	100	1960	1999
			40			2000 ^{c,d}
–	60°45.065'	89°23.138'	50	201	1949, 1898, 1871, 1824	1999 ^d
	60°45.011'	89°23.370'	51	201		2000
200 _{lm}	60°45.016'	89°23.435'	102	202	1898, 1871, 1824	2000
High fire frequency						
–	60°44.968'	89°04.064'	0	250	2000, (+ ?)	2000 ^{c,d}
235 _{lh}	ND	ND	9	239	1990, 1979	1999
14 _{lh}	60°44.680'	89°26.320'	15	15	–	1999
26 _{lh}	60°44.690'	89°26.300'	27	27	1982	1999
244 _{lh}	60°43.487'	89°08.502'	17	249	1982, 1980, 1964, 1912, 1848, 1838, 1790	1999
–	60°43.175'	89°08.092'	25	71	1974/1975, 1939	2000 ^d
–	ND	ND	59	199	1940	1999 ^d

^aFire history reconstructed by Wirth *et al.* (1999).

^bTime since last stand-replacing fire.

^cOnly organic layers sampled.

^dFire history reconstructed by C. Wirth (tree core or slice, and stand density; unpublished data).

ND, not determined.

(ICP, Optima 3300 DV, Perkin-Elmer, USA). We estimated concentrations of protons by measuring the pH of the extract relative to the pH of the 1 M NH₄Cl solution and corrected for hydrolysed Al:

$$[\text{H}^+]_{\text{extractable}} = [\text{H}^+] - [\text{H}^+]_{\text{hydrolysed Al}}$$

with

$$[\text{H}^+] = 10^{-\text{pH soil extract}} - 10^{-\text{pH NH}_4\text{Cl}/\alpha}$$

in which α (the activity coefficient of H⁺ in 1 M NH₄Cl) = 0.88, and

$$[\text{H}^+]_{\text{hydrolysed Al}} = \frac{[\text{Al}]}{(1 + 10^{-\text{pH soil extract}/10^{5.85}})}$$

Base saturation (BS) was calculated as the sum of extractable Ca²⁺, K⁺, Mg²⁺, and Na⁺ divided by CEC, and expressed as a

percentage. We extracted amorphous iron oxides (Fe_o, mainly non- or poorly crystalline oxides such as ferrihydrite) from 0.5 g ground soil by shaking it in 30 ml of acid ammonium oxalate in darkness for 2 hours (SSSA, 1996). The Fe was quantified by ICP after filtration. We prepared the ammonium oxalate solution by combining 24.87 g (NH₄)₂C₂O₄·H₂O, 12.61 g H₂C₂O₄·H₂O and 800 ml water. We adjusted the pH of the solution to 3.0, and the volume to 1 l.

Soil organic matter

To characterize the soil organic matter, we quantified the following.

1 Concentrations of black carbon in all organic layer samples, and of the mineral soil samples of the regime with infrequent fires, and of one soil profile with frequent fires.

2 Concentrations of organic carbon and nitrogen in all organic layer and mineral soil samples.

3 The concentration of ^{14}C in the organic layer and mineral topsoil (E to spodic B horizons) of the regime with least frequent fires, and of various individual charcoal pieces found in organic layers or mineral soils.

We quantified the amount of black carbon in the bulk soil samples using benzenepolycarboxylic acids (hemimellitic, trimellitic, trimesic, pyromellitic, prehnitic, mellophanic, benzene-pentacarboxylic, and mellitic acid) as molecular markers (Glaser *et al.*, 1998). We removed the major fraction of polyvalent cations from the mineral soil samples by hydrolysing 0.5 g ground soil sample in 2 ml 32% (v/v) HCl at 170°C for 4 hours under pressure, filtering them on ashless cellulose filters, rinsing with deionized water and drying them at 40°C. The hydrolysis was omitted for organic layer samples on the advice of B. Glaser (personal communication) because of much smaller cation concentrations. After the analysis Glaser & Amelung (2003) showed that hydrolysis with HCl can form black carbon as an artefact and result in overestimation of its concentrations, and HCl should therefore be replaced with trifluoroacetic acid. However, this potential formation of artefacts does not apply to our organic layers, because they were not treated with HCl. For the mineral soil samples HCl was used, but black carbon concentrations were uniformly very small. Our results show that stocks of black carbon in organic horizons dominated by far over those in the mineral soils. So we conclude that if the analysis of mineral soils produced artefacts the outcome of our study would not have been affected greatly.

Fifty-milligram samples of ground organic layer and pre-hydrolysed mineral soil samples were oxidized in 2 ml 65% (v/v) HNO_3 at 170°C for 8 hours under pressure, filtered into 10-ml flasks through ashless cellulose filter, rinsed with deionized water, and filled up to 10 ml. Remaining polyvalent cations were removed from the samples by cation exchange resin (Biorad, München, AG 50 WX8, 200–400 mesh). Resin columns were conditioned with 18 ml 2 M HCl, and subsequently rinsed with water until the solution was neutral. Two millilitres of sample and 100 μl of internal standard (25 mg citric acid in 50 ml water) were applied to the column and collected in 100-ml flasks. Columns were rinsed twice with 18 ml water, then once with 9 ml water. Combined solutions were freeze-dried. The dried samples were transferred into 3-ml Teflon-lined screw-cap vials using four times 750 μl methanol and dried again under N_2 . Samples were derivatized with 100 μl dried pyridine and 100 μl *N*, *O*-bis(trimethylsilyl)-trifluoroacetamide at 80°C for 2 hours. Derivatized oxidation products were separated by gas chromatography (carrier gas: He, capillary column HP-5 ms: 34 m \times 250 μm , 0.25 μm film thickness), and detected by an atom emission detector (Hewlett Packard 19091S-433, Böblingen, Germany). After injection (2 μl , split ratio 2.5–10:1), the temperature programme was the following: 110°C for 1 minute, 110–200°C at 10°C per minute, 200–250°C

at 5°C per minute, 250–300°C at 20°C per minute, and 300°C for 5 minutes.

Individual benzenepolycarboxylic acids (BCAs) were quantified by comparison of their retention times with those of commercially available ones (external standards), and response factors were calculated with citric acid as internal standard and external standards in three concentrations. The response factor for pyromellitic acid was used to quantify prehnitic and mellophanic acid, which were not available commercially. We calculated black carbon concentrations by dividing the sum of BCAs by 0.441 as obtained from a set of black carbon standard materials by Glaser (1999). Organic carbon and nitrogen were quantified by dry combustion in an elemental analyser (Vario EL, Hanau) after we had ground the samples in a ball mill.

^{14}C analysis

To estimate the stability of black carbon in the soils, we compared the average radiocarbon (^{14}C) age of individual charcoal pieces found in different horizons within the study area with that of the bulk soil horizons from the sites with low fire frequency. The ^{14}C analysis charcoal pieces were cleaned from recognizable non-charcoal particles. Bulk organic samples and mineral soil were treated similarly to avoid differences in ^{14}C concentration caused by the preparation technique. Twenty grams of bulk organic layer (without lichens) and mineral samples freed of recognizable plant, root, or fauna fragments were ground in a ball mill. Then, the organic layer samples were suspended in 200 ml water and mineral soils in 150 ml water, shaken for 10 minutes and stored overnight at 7°C. The next day the solutions were dispersed by ultrasonification (Branson 250, Danbury, USA) at 55 W for 44 s per 1 g soil. Then, organic layer samples were freeze-dried, while mineral soils were freeze-dried after wet-sieving through a < 63- μm aperture mesh to remove fine roots.

The organic carbon in the samples was combusted to CO_2 in an elemental analyser (NA 1110 with AS 128, CE Instruments, Milano) coupled to an isotope-ratio mass spectrometer (Delta^{plus}, ThermoFinnigan, Bremen). The CO_2 was reduced to graphite by H_2 with Fe as a catalyst at 600°C (MPI BGC, Jena). The ^{14}C concentration of the graphite was measured by accelerator mass spectroscopy (Rafter Laboratory, Lower Hutt, New Zealand). The ^{14}C concentrations are given in percent modern (pM), defined by Mook & van der Plicht (1999) as

$$\text{pM} = \frac{{}^{14}A}{{}^{14}A_{\text{NOX}}} \times \frac{1}{0.7459} \times \left(\frac{1 + {}^{13}\delta_{\text{NOX}}}{1 + {}^{13}\delta} \right)^2,$$

in which ^{14}A is the concentration of ^{14}C in the sample, ${}^{14}A_{\text{NOX}}$ is the concentration of ^{14}C in the standard (new oxalic acid standard NBS SRM 4990C), ${}^{13}\delta$ and ${}^{13}\delta_{\text{NOX}}$ represent the fractionation of the sample and of the standard, respectively, and 0.7459 is constant for the standard.

Results and discussion

In the following we focus on the stocks of black carbon and organic matter. Concentrations, bulk densities, and other data can be found in Czimczik (2003).

Black carbon and organic carbon in the organic layers

Stocks of black carbon in the organic layers accounted for $\leq 3.5\%$ of all organic carbon (Figure 2a). They were much smaller than estimates of 984–2074 kg charcoal ha^{-1} recorded

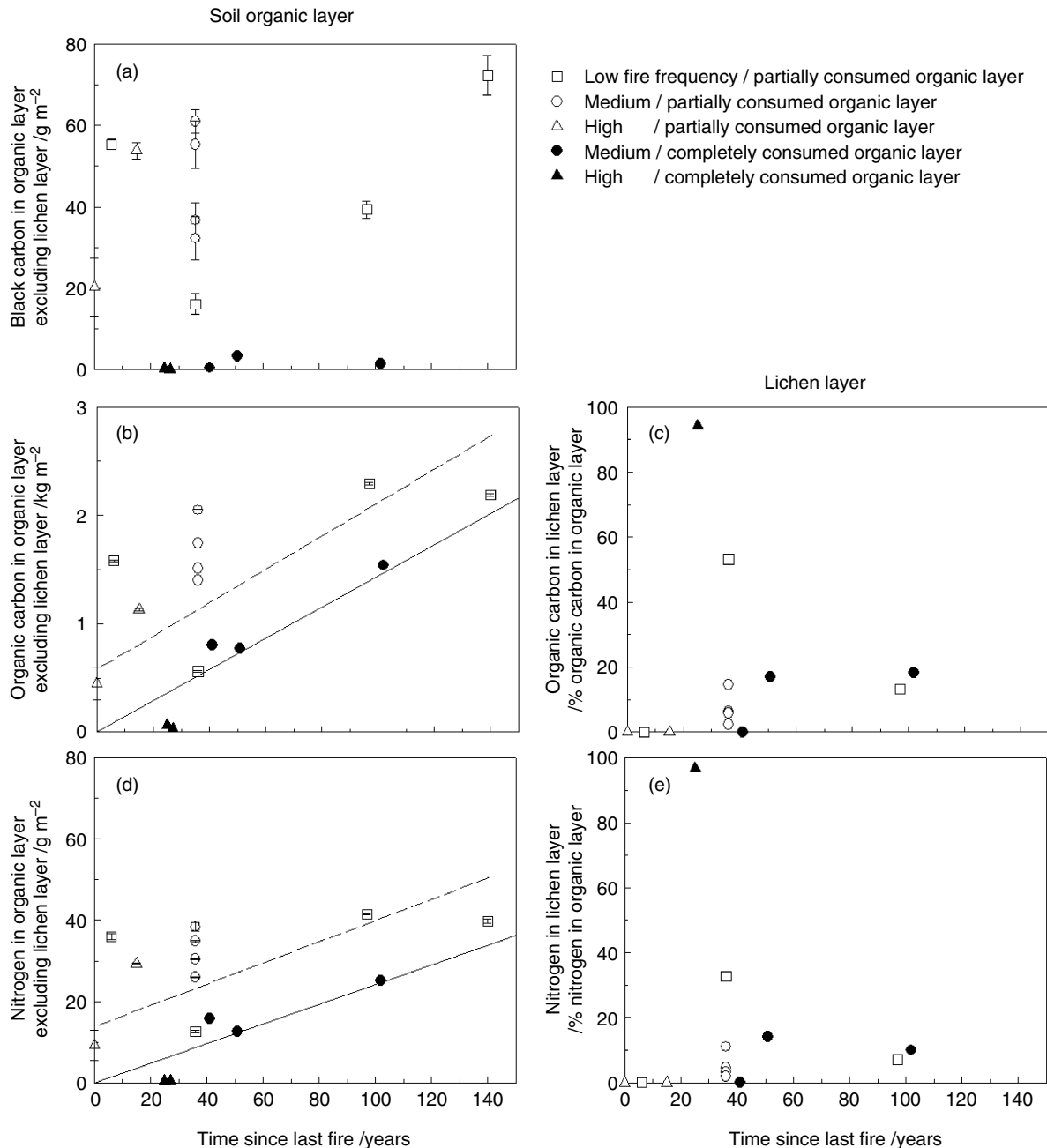


Figure 2 Stocks of (a) black carbon, (b) organic carbon, and (d) nitrogen in the organic layers, excluding living lichens, under three fire frequencies (note the different scales of the ordinates). Fraction of (c) organic carbon and (e) nitrogen in the lichen layer. Black carbon stocks $< 5 \text{ g m}^{-2}$ indicated a complete consumption of the organic layers (filled symbols), and stocks $> 5 \text{ g m}^{-2}$ a partial consumption (open symbols). The accumulation rate was $14.4 \text{ g m}^{-2} \text{ year}^{-1}$ for organic carbon ($R^2 = 0.89$) and $0.241 \text{ g m}^{-2} \text{ year}^{-1}$ for nitrogen ($R^2 = 0.82$). Accumulation rates were similar for completely consumed (solid line) and partially consumed organic layers (dashed line).

by Zackrisson *et al.* (1996) in more productive boreal forests of Scandinavia. However, direct comparisons are difficult, because amounts were determined with different analytical techniques and so captured different fractions of the black carbon (Schmidt *et al.*, 2001). There is currently no generally accepted consensus on how results obtained by different analytical techniques relate to each other. The technique we used here captures only more highly condensed structures. Thus we can expect the yields to be less than those found by Zackrisson *et al.* (1996) who manually selected pieces of charcoal.

Stocks of black carbon did not differ among regimes and did not follow any recognizable trend with time since the last fire both when expressed as stocks or when expressed as fractions of organic carbon. The stocks were similar regardless of whether the sites burned in crown fires (Figure 2a, open squares, and open triangles 27 years since fire and filled triangles 15 years since fire), or surface fires (Figure 2a, all other open and filled circles and triangles).

We could separate all organic layers into two subsets with 5 g black carbon m⁻² as a threshold value (Figure 2a). The amounts less than 5 g m⁻² seemed to be very small because each fire should produce some black carbon and the fires in our study region were much more frequent than in other forests (Conard & Ivanova, 1997). We know little about the amounts of organic matter converted to black carbon in fires of different intensities in boreal forests, though in Scots pine forests, conversion rates are most likely small because the organic layers are dominated by lichen biomass. The conversion rate for non-woody biomass is known to be small, e.g. 0.6–2.0% of pre-fire organic carbon content (Czimczik *et al.*, 2003). Small stocks of black carbon might also result from erosion, translocation into the mineral soil, decomposition, or oxidation during subsequent fires. Erosion is unlikely because the area is flat. Relocation into the mineral soil, e.g. due to infrequent uprooting of trees, seems possible but we did not observe it, and black carbon stocks in the mineral soil were much smaller than those in the organic layers. Not much is known about residence times of black carbon in soil, but they are probably in the order of decades to millennia depending on the environment. Thus, we think that the intensity of the last fire is the most important factor controlling stocks of black carbon in the organic layer. In forest stands where the last fire was very intense and consumed the entire organic layer, black carbon was oxidized to < 5 g m⁻² (Figure 2a, filled symbols). In contrast, where the last fires were of low intensity and burned only the upper part of the organic layer which had formed after the last fire, black carbon was produced in each fire and thus accumulated in the lower parts of the organic layer. Our hypothesis is supported by Ohlson & Tryterud (2000) who concluded that fire intensity might be the controlling factor for the accumulation of black carbon in Scandinavian Scots pine forests, overriding potential microbial decomposition or photochemical breakdown. We conclude that black carbon does not accumulate to a greater extent

over several forest generations in Siberian Scots pine forests, because it is consumed by intense fires.

Stocks of organic carbon (organic C) were similar among the three fire regimes. Maximum stocks within 140 years since the last fire were 2190 g organic C m⁻², similar to values for Canadian jack pine lichen forests recorded by Nalder & Wein (1999) (average 1200 ± 300 g m⁻²). When the lichen layer was included, the calculated stocks of organic carbon agreed well with earlier findings for the same region (FIRESCAN Science Team, 1996; Wirth *et al.*, 2002a,b). We found that stocks of organic carbon in the lichen layer became constant after about 40 years and represented about 20% of organic C in the organic layer (Figure 2c). This indicated that the lichen layer reached a steady state after reaching its maximum closure, i.e. the lichen layer continued to grow at its top and to decay at its bottom.

In contrast to the study by Nalder & Wein (1999) we found that in forests where the last fire was very intense, organic C accumulated in the organic layer with time since fire (Figure 2b, filled symbols). From this we derived a net accumulation rate of organic C of 14.4 g m⁻² year⁻¹. Litter trap data were available for the forest stand 102 years since fire of the medium fire frequency regime. Total litter fall was 103 g m⁻² year⁻¹ with an estimated organic C content of 48%. We calculated that the net accumulation rate of organic carbon corresponded to an accumulation of 29% of the organic C in the litter fall. This fraction was similar to that found for Canadian boreal forests, where 30% of the litter mass remained after 5 years (Prescott, 2002).

Litter accumulation rates were similar in all forest stands. Thus, we expected the stocks of organic carbon in forest stands where the last fires were less intense (Figure 1b, open symbols) to accumulate at a similar rate since fire as in stands where the last fire was very intense. By comparing the two cases, we calculated that 740 ± 320 kg organic C m⁻² remained in the organic layer after less intense fires. The efficiency of a fire occurring after 100 years would thus be 49%, on the assumption that 1440 g organic C m⁻² accumulated within 100 years.

The accumulation rate for nitrogen (N) with time since fire was 0.241 g m⁻² year⁻¹, with 17 ± 7 g N m⁻² remaining in the organic layers after less intense fires (Figure 2d,e). This accumulation of N with time could not be seen when the N in the organic layer was not corrected for the fraction stored in the lichen layer (Wirth *et al.*, 2002b).

As for black carbon, the intensity of the last fire and not frequency of fire seemed to control organic matter accumulation in the organic layer. Although the forest is fairly homogeneous, our data suggest that the intensity of the last fire was very variable.

Black carbon and organic matter in the mineral soil

Stocks of black carbon in the mineral soils of the infrequent fire regime showed no trend with time since fire (Figure 3a). The stocks accounted for 0.02% of organic C within the top

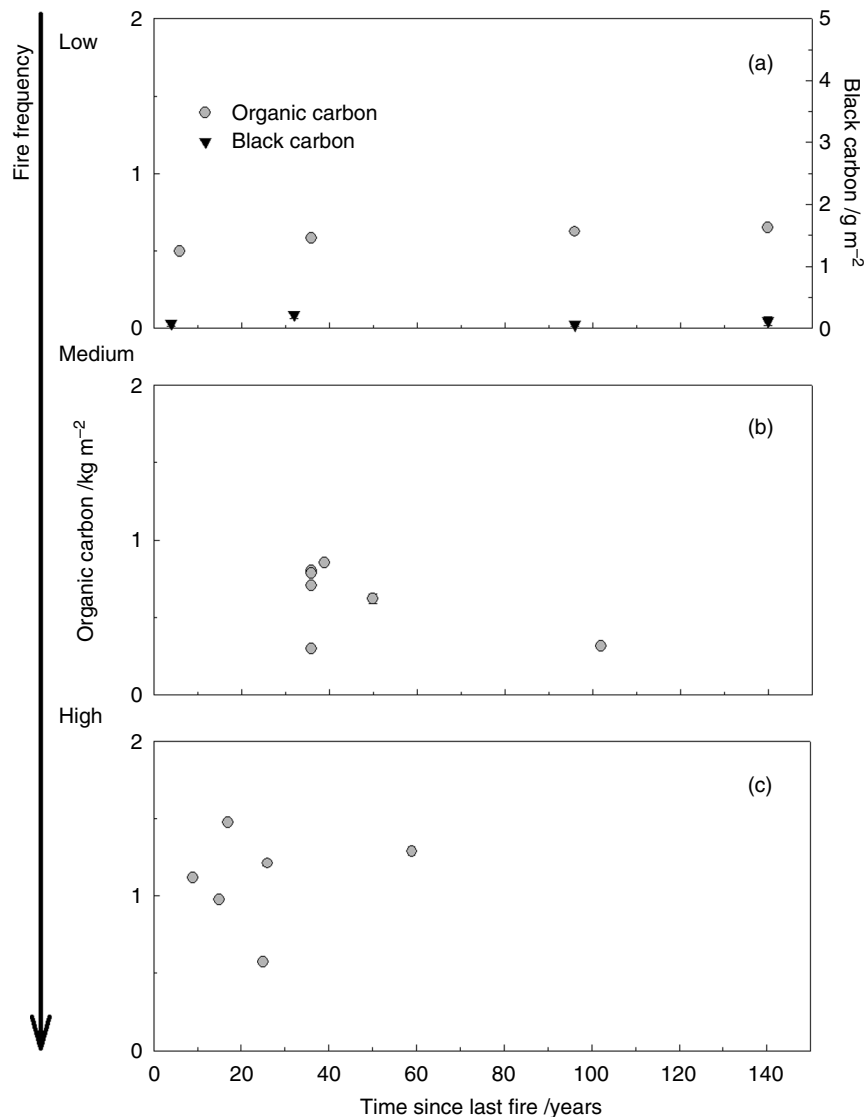


Figure 3 Stock above and below ground. (a) Black carbon stocks in the mineral soil (0–0.25 m) with infrequent fires. (a–c) Organic carbon stocks in the mineral soil (0–0.25 m) with time since fire under three fire frequencies. Note the different scale on the ordinate for black carbon.

0.25 m of the mineral soil. This was in sharp contrast to earlier measurements for the same region by Schulze *et al.* (1999) who estimated that 20% of the organic C was black carbon. The thermal oxidation technique they used to quantify black carbon (Kuhlbusch, 1995) yielded larger estimates than our approach (Schmidt *et al.*, 2001). Also, Schulze *et al.* (1999) sampled fewer sites and the larger proportions of black carbon proportions they found might not be representative for the whole region.

Within the upper 0.25 m of the mineral soil, stocks of organic carbon increased somewhat with increasing fire frequency (low and medium fire frequency: $600 \pm 15 \text{ g m}^{-2}$; high: $1100 \pm 340 \text{ g m}^{-2}$) (Figure 3, Table 2). Also, the fraction of all organic C stored within the top 0.25 m increased with increasing fire frequency (low fire frequency 39%, medium 43%, high 56%) (Table 2). Stocks of organic C were in the range for boreal forest soils, where typically about 50%

(0–1 m) are found within the uppermost 0.2 m (Jobbagy & Jackson, 2000).

Stocks of organic C and N did not follow any recognizable trend with time since fire within each regime (Figure 3a–c). This accords with findings by Slaughter *et al.* (1998) for southern boreal forests of fir, oak, and pine. Stocks were within the range of earlier findings by Wirth *et al.* (2002b) for the same region, although there was a consistent offset between both studies caused by slightly different sampling approaches.

The distribution of organic C within the soil profiles was typical for Podzols. Modern ¹⁴C (bomb-¹⁴C produced during nuclear weapon tests from 1954 to 1962) in the E horizon and upper spodic B horizon suggested that carbon was transported from the organic layers into the mineral soil (Figure 4) (Trumbore & Harden, 1997). The age of charcoal pieces in the lower organic layer and the E horizon

Table 2 Mineral soil stocks of organic carbon, black carbon, and nitrogen in Siberian Scots pine forests (standard errors in parentheses)

Fire frequency	Organic carbon /g m ⁻²	Black carbon		Nitrogen /g m ⁻²
		/g m ⁻²	/% organic carbon	
0–0.2 m depth				
Low	454 (43)	0.1 (0.04)	0.02	32.6 (9.8)
Medium	551 (74)	ND	ND	21.5 (2.9)
High	987 (109)	0.18 (0.09)	0.02	40.8 (5.8)
0–1 m depth				
Low	1325 (117)	0.16 (0.03)	0.01	97.2 (38.7)
Medium	1352 (193)	ND	ND	65.9 (11.9)
High	1789 (316)	0.25 ^a	0.02 ^a	85.2 (11.3)

^aTotal soil profile depth 0.8 m.

ND, not determined.

did not differ from mean age of organic matter at similar sampling depths (Figure 4).

The concentrations of organic carbon within the E horizons increased significantly with increasing fire frequency (Table 3). We think these did not result from a greater production below ground. Wirth *et al.* (2002b) showed that surface fires induced a short-term decline in production above ground, and differences in the age of the forest stands explained the variation of it, whereas the earlier history of the fire regime had less influence. Animals and trees (through windthrow) rarely mixed organic carbon into the E horizon, as we observed in the field. Trees brought down by fire or animals following a fire broke at or near their bases, leaving the roots embedded in the soil.

Distribution of organic matter between the organic layer and the mineral soil

When we calculated the distribution of black carbon between the organic layer and the first metre of the mineral soil for the soils of the infrequent fire regime we found that less than 1% of black carbon was in the mineral soil (Figure 5). We also calculated the distribution of organic C for all soils with a depth of ≥ 1 m (Figure 5). In the regimes with low and medium fire frequency, the stocks were 3000 g m⁻² or 249 mol m⁻². This was half of those in the more productive Scots pine forests of Finland (*Vaccinium* type 6000 \pm 900 g m⁻²) (Liski & Westman, 1995), but similar to those in Canadian jack pine forests (1500–3000 g m⁻², organic layer plus 0.7 m mineral soil) (Trumbore

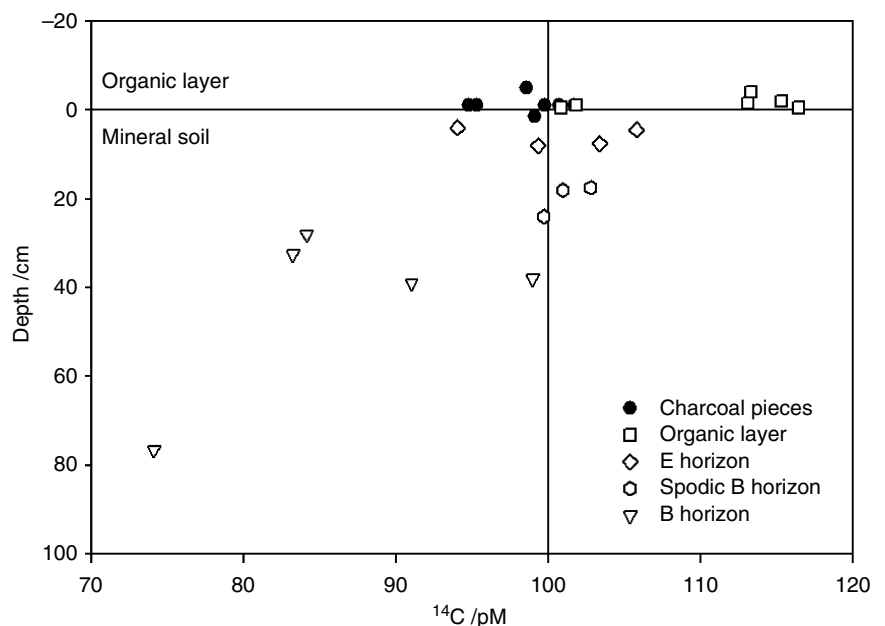


Figure 4 ¹⁴C concentrations of organic layers and mineral soil horizons, and of individual charcoal pieces found in organic layers or mineral soils within the study region at different depth. ¹⁴C values > 100 pM indicate bomb-¹⁴C or modern organic carbon (post-1950). The precision of the measurements was < 0.4 pM.

Table 3 Results of non-parametric rank correlation analyses ($n = 18$)

E horizon		Spearman's ρ	P
Concentration of organic carbon	Time since last fire	-0.081	0.748
	Time since last crown fire (= stand age)	-0.091	0.720
	Fire frequency	0.528	0.024
	Bulk density of E horizon	-0.597	0.009
	E-horizon thickness	-0.834	< 0.001
Thickness	Time since last fire	-0.026	0.918
	Time since last crown fire	0.283	0.255
	Fire frequency	-0.438	0.069
	Bulk density of E horizon	0.536	0.022
Bulk density	Fire frequency	-0.247	0.323

& Harden, 1997). Almost 50% of organic C was stored in the mineral soil (Figure 5), and the fraction stored in the organic layer decreased with increasing fire frequency.

Conclusions

Increasing frequency of fire changes the amount, composition, and distribution of black carbon and organic matter within soils of Siberian Scots pine forests. The longer is the time since the last fire the more organic matter there is in the organic layer. Frequent fires seemed to accelerate the transfer of

organic matter from the organic layer into the mineral soil. The intensity of the last fire (rather than fire frequency) seemed to control the fate of black carbon which did not accumulate over several forest generations, probably because it was oxidized during subsequent fires. The largest proportions of black carbon were in the organic layers (99% of stocks in the organic layer plus 1 m of mineral soil). Thus, black carbon did not contribute to any large extent to the storage of organic matter in these soils. Greater intensities and frequencies of fires could reduce the amounts of organic matter in the organic layers of the soil and increase amounts in the mineral soil.

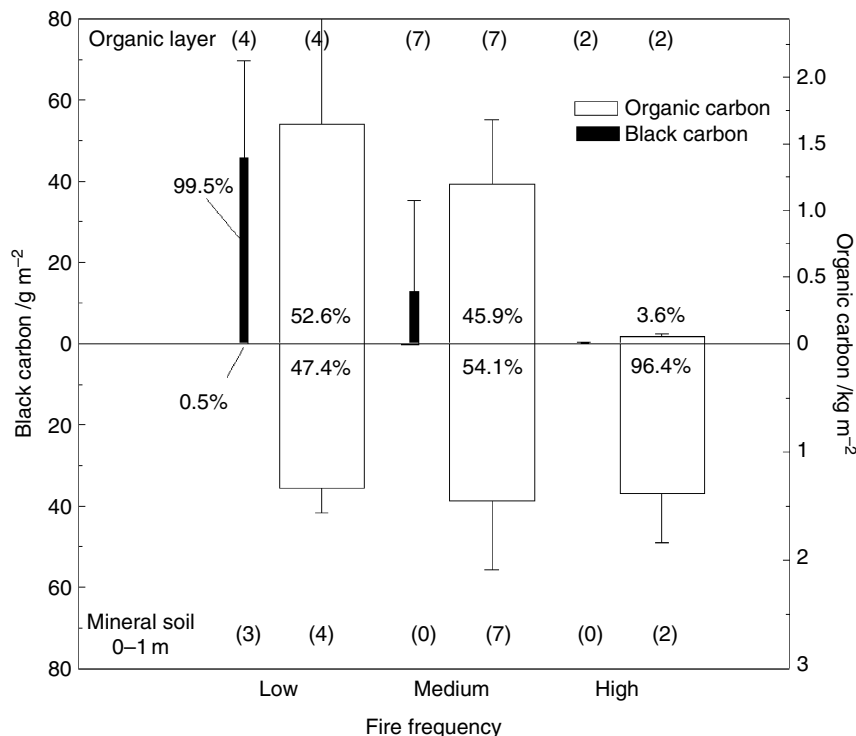


Figure 5 Distribution of black carbon between the organic layer and the mineral soil for the chronosequence with low fire frequency, and distribution of organic carbon stocks between the organic layers and the mineral soil under three fire frequencies for mineral soil profiles with a depth > 1 m. Note the different scale on the ordinate for black carbon. Bars indicate standard deviation.

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