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Changes in the Pools of Total and Labile Soil Organic Carbon during Post-Fire Succession in the Khibiny Mountain Tundra Ecosystems

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Abstract—The changes in the total soil carbon pool and the pools of labile and potentially mineralizable organic matter in Entic Folic Podzols of the Khibiny Mountains (Murmansk region, NW Russia) caused by wildfires of high and moderate intensity and during the post-fire succession are discussed. Although a moderate-intensity wildfire has no statistically significant impact on the total soil carbon pool, it triggers the active erosion processes leading to the carbon losses comparable to the direct pyrogenic carbon losses in a high-intensity fire. In the post-fire soil restoration, the type of organic carbon accumulation changes: the surface carbon accumulation in the form of peat is characteristic of the control site, while up to half of soil carbon is accumulated in the mineral horizons at late stages of the postpyrogenic succession. A high-intensity fire leads to almost complete destruction of labile, microbial, and potentially mineralizable carbon pools in both the organic (pyrogenic) and mineral horizons. A moderate-intensity fire does not cause any statistically significant changes in these pools as compared to the control. The restoration dynamics of the labile and potentially mineralizable pools of organic matter in the pyrogenic horizons of soil differ: the trend of a steady increase in the pools of labile and microbial carbon is observed for three years after the fire and later, while the pool of potentially mineralizable carbon reaches its maximum three years after the fire and then becomes stabilized at this level.

Keywords: carbon stocks, labile organic matter, microbial biomass, potentially mineralizable organic matter, Entic Folic Podzols

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INTRODUCTION

In terrestrial ecosystems, soils are the major reservoir for a long-term storage of the carbon sequestered from the atmosphere. Wildfires directly influence the soil organic matter (**SOM**) and vegetation cover, thereby assisting the loss of the carbon accumulated by ecosystems in the form of gaseous combustion products, as well as the loss of dissolved carbon during both the wildfire and the postpyrogenic restoration of ecosystems. Assessment of the effect of wildfires on SOM is a relevant issue and a rapidly developing area in modern soil science, because changes in the SOM content and quality caused by wildfires directly and indirectly influence not only the carbon turnover but also many soil properties [4, 19, 23, 25, 28]. Traditionally, most data have been obtained for the soils of forest ecosystems [4, 5, 17]. The forest litter and upper humus horizon are maximally affected by fire, which results in the loss of SOM and the formation of the so-called pyrogenic humus, which is stable to biodestruction and oxidation [28, 35]. The study of the SOM behavior after a pyrogenic impact and assessment of the time required for restoration of the initial parameters is of considerable interest. However, there is still no universal opinion on the processes taking place in SOM under the impact by wildfires. Correspondingly, accumulation and interpretation of the data on post-fire changes in the SOM affected for different time intervals by different types of fires are among the important tasks of ecology and soil science.

Wildfires in tundra ecosystems have been for a long time rather rare and poorly studied events. However, an increase in their frequency [34] and unusually large areas [31, 33] of the wildfires recently observed in the Arctic tundra suggest that these events have become an ever more important factor controlling the carbon cycle in these ecosystems. According to the existing predictions, the frequency of tundra wildfires will constantly increase in the 21st century [29]. The tundra wildfires mainly affect the litter and organogenic soil horizons, because the aboveground phytomass in tundra ecosystems is rather small. Note that most tundra wildfires are of moderate intensity and affect the aboveground phytomass, litter layer, and a part of soil

Table 1. Characterization of ecosystems of post-fire chronosequence

Ecosystem	Date of wildfire (years after fire)	Wildfire intensity	Phytocenosis
0+ (HI)	2018 (0)	High	Absent
0+ (MI)	2017 (0)	"	"
1+	2017 (1)	"	"
2+	2014 (2)	"	*Arctoo–Empetretum hermaphroditi*, *Polytrichum juniperinum* phase
3+	2013 (3)	Moderate	*Arctoo-Empetretum hermaphroditi*, *Vaccinium myrtillus* phase
12+	2004 (12)	"	*Arctoo–Empetretum hermaphroditi*, *Vaccinium uliginosum* phase
60+	1954 (60)	"	*Arctoo-Empetretum hermaphroditi*, *Vaccinium vitis-idaea* phase
ShE	Not recorded	–	*Arctoo–Empetretum hermaphroditi*

HI, high-intensity fire; MI, moderate-intensity fire; and ShE, shrub ecosystem.

organogenic horizon. High-intensity wildfires, which almost completely destroy the soil organogenic horizon, are rather rare in the tundra zone.

The goal of our study was to estimate the effect of high- and moderate-intensity wildfires on the pools of total and labile carbon and to clarify the main patterns of the changes in these parameters during the soil restoration after moderate-intensity wildfires.

OBJECTS AND METHODS

Soils of mountainous tundra ecosystems of a post-fire chronosequence in the Khibiny Mountains (Murmansk region, NW Russia) were sampled on the slopes of Mts. Vud'yavrchorr, Aikuaivenchorr, Kukisvumchorr, and Yuksporr. The mountainous tundra zone in the Khibiny Mountains is characterized by a short growing season (90–110 days) with the sum of effective daily air temperatures of 500–700°C [20]. The plots of mountainous tundra directly after moderate- or high-intensity wildfires and after certain periods (1, 2, 3, 12, and 60 years) of self-restoration of the phytocenoses were studied (Table 1). The selected plots were exposed to the north or northeast and located at the heights of 600–650 m a.s.l. Wildfires were dated using the records of the Polar Alpine Botanical Garden-Institute and personal observations. Dwarf shrub ecosystems were used as a control. Such ecosystems are most frequently affected by wildfires, because they are allocated to dry areas on the ridges with a slow mineralization of the organic matter in combination with the abundance of shrubs and lichens (see [8] for a comprehensive description of post-fire ecosystems).

The post-fire plant communities inherit the floristic composition of the previous phytocenoses and belong to the association *Arctoo–Empetretum hermaphroditi,* successively passing the phases from prevalence of mosses to the restoration of dwarf shrub dominance. The vegetation cover is restored at the expense of both the colonization by adventitious species and restoration of the survived belowground shoots of shrubs. The post-fire phytocenoses significantly differ in the total aboveground plant biomass and its structure (Fig. 1). During the first years after a wildfire, the aboveground biomass restores rather intensively owing to the survived belowground shoots of shrubs and colonization of burned sites by mosses and grasses. Later (with an increase in shrub prevalence), the restoration rate of the total aboveground biomass decreases, so that the burned sites of 3 and 12 years in age do not differ in this characteristic. The aboveground biomass restores to the level that does not statistically significantly differ from the control plot only on the plots burned 60 years ago. Although a considerable part of the aboveground dead organic matter burns out, its total amount at burned sites 1+ does not differ from that of the control communities, which is explained by a significant dying-off of the plants damaged by fire. A considerable decrease in the dead organic matter is observed in the further succession, which is determined by the soil erosion and by a small amount of annual plant litter. The amount of aboveground dead organic matter is very slowly restored remaining smaller than that at the intact sites even 60 years after the fire.

The soil of the control plot is a Folic Entic Podzol [30] with a typical profile TJ–BH–C [7]. Note that the post-fire soils poorly match the existing soil classifications. When selecting the burned plots, several soil sections to a depth of at least 40 cm were made in the surrounding unburned sites to confirm that the soil actually belonged to the type of Folic Entic Podzol. At all stages of postpyrogenic succession, the surface organic horizons of soils contained the features attesting to the pyrogenic impact. The presence of charcoal particles is visually evident at the boundary of organic and illuvial horizons even 60 years after the fire. The

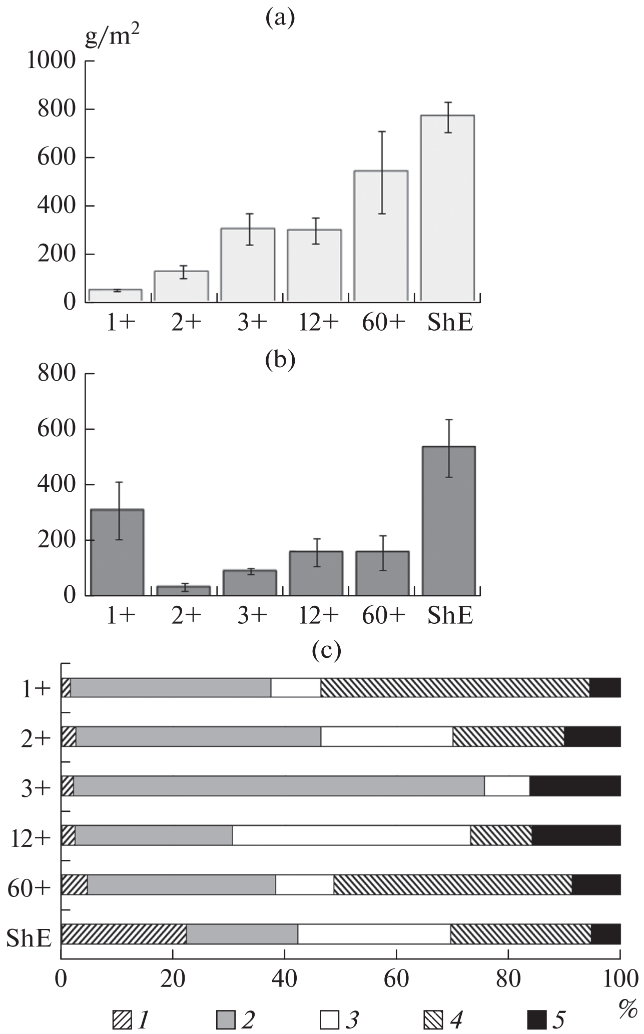

Fig. 1. Pools of (a) aboveground biomass and (b) dead organic matter and (c) the structure of aboveground plant biomass in the mountainous tundra ecosystems during post-fire succession: 1+, 2+, 3+, 12+, and 60+ are biogeocenoses 1, 2, 3, 12, and 60 years after a moderate-intensity wildfire; ShE, dwarf shrub ecosystem (control); *1*, lichens; *2,* mosses; *3*, evergreen dwarf shrubs; *4*, deciduous dwarf shrubs; and *5*, herbs.

lower part of the profile has the morphology typical of Entic Podzols. Soil samples were taken from the organic or pyrogenic and from the underlying illuvial horizons taking into account their bulk density. The latter was assessed by weighing a known volume of a sample with an undisturbed structure.

The total carbon and nitrogen contents (C_{tot} and N_{tot}) in soil were determined on an Elementar Vario EL III elemental analyzer. The total carbon storage was computed taking into account soil bulk density. The labile SOM was extracted from fresh soil samples with deionized water and 0.1 M NaOH solution at the soil-to-solution ratio of 1 : 50 for mineral horizons and 1 : 100 for organic (pyrogenic) horizons. The solutions were filtered through 0.45-μm membrane filters before determining the concentration of water-soluble SOM. The carbon and nitrogen contents of microbial biomass (C_{micr} and N_{micr}) were determined by fumigation–extraction method [24, 37] as the difference between the extracted carbon and nitrogen in the fumigated and nonfumigated samples. The C_{micr} and N_{micr} concentrations were measured in fresh soil no later than two days after sampling (as recommended in [9]). The extractable organic carbon and total extractable nitrogen contents were assayed in a liquiTOC Elementar automated analyzer.

The potentially mineralizable SOM pool was assessed by biokinetic fractionation. The theoretical grounds for this method were described earlier [14, 16] and its essence is in taking into account the C–CO_2 production by soils during a long-term (140–150 days) incubation of soil samples at a temperature of 22°C. The cumulative C–CO_2 production (mg C/100 g) was determined by adding the amount of produced carbon at each time point to the sum over the previous intervals. To calculate the content of potentially mineralizable SOM pool and determine the constant of its mineralization, the curve of C–CO_2 accumulation dynamics was approximated by the following single-component exponential regression equation:

$$C_t = C_0\left(1 - \exp^{-kt}\right),$$

where C_t is the C–CO_2 cumulative amount (mg C/100 g) over time *t* (days); C_0 is the content of potentially mineralizable carbon in SOM (mg C/100 g); and *k* is the constant of SOM mineralization rate (day^{-1}). SOM mineralization activity (mg C/(100 g day)) was estimated according to the index obtained by multiplying C_0 by mineralization constant *k*.

All experiments were performed in three–five replicates. Tables and diagrams show the mean values ± the error of the mean; calculations were made for absolutely dry soil (105°C, 12 h). The data were statistically processed using Statistica 10.0 software package. The significance of differences between samples was assessed with *t*-test; and correlation between the particular characteristics, with Spearman's test. The effect of duration of post-fire restoration on the total amount and content of fractions was estimated by one-way ANOVA. The level of $p < 0.05$ was regarded as significant for all types of statistical analysis.

RESULTS AND DISCUSSION

The Effect of Wildfire and Postpyrogenic Restoration on the Total Carbon Pool in Soils

First and foremost, the wildfire influences the carbon pool in the surface organic (pyrogenic) horizons. The direct carbon losses in a high-intensity wildfire reach up to 75% of its initial content (Δ = –3.5 kg C/m^2; Fig. 2a). A moderate-intensity wildfire does not cause a statistically significant decrease in the carbon pool of pyrogenic horizon as compared with the control ($p > 0.05$). During the next two years of post-fire soil development in the sites affected by a moderate-intensity wildfire, the total carbon content in pyrogenic horizon decreases mainly because of developing erosion processes. The erosion ceases with the restoration of vegetation cover, in particular, herbs and dwarf shrubs, and the soil carbon content in surface pyrogenic horizons commence to restore; however, this is a slow process and only a 60-year-old burned site does not differ in a statistically significant manner ($p < 0.05$) from the control plots. An increase in the share of herbs and mosses in the vegetation cover enhances an active carbon accumulation in the soil.

The wildfire independently of its intensity insignificantly influences the content of organic carbon in the illuvial horizon (Fig. 2b). A statistically significant decrease in C_{tot} in the 20-cm mineral horizon is recorded only during the second year after a moderate-intensity wildfire, while the trend of an increase in C_{tot} in the illuvial horizon is observable at later stages of post-fire restoration. A considerable increase in the carbon pool as compared with the control plot ($\Delta = +2.1$ kg C/m^2) is recorded at later stages of the postpyrogenic restoration. The increase of organic carbon pool in mineral horizons is associated with two factors: (1) the migration of water-soluble SOM and fine combustion products along the soil profile and (2) an increase in the amount of roots in illuvial horizons with the development of herbs owing to their intravital excreta and annual root dying-off. Thus, the type of organic carbon accumulation changes during the post-fire soil restoration: at the control plot, the organic carbon accumulates on the surface as peat or raw humus, whereas at the late stages of postpyrogenic development up to 50% of carbon accumulates in the mineral horizon. The enrichment of mineral horizons with carbon in post-fire soils was earlier observed in forest soils [6, 12, 18]. However, the absence of this effect and the predominant carbon accumulation in pyrogenic horizons have been also described [19].

The total organic carbon content in the upper 20-cm layer (which corresponds to the minimal soil layer directly after a high-intensity wildfire) was calculated in order to more accurately compare the soils of postpyrogenic succession that considerably differed in their thickness (Fig. 2c). The direct pyrogenic carbon losses in a high-intensity wildfire amount to 2.5 kg C/m^2. Although the direct pyrogenic losses of SOM in a moderate-intensity wildfire are rather small, the decrease in the total carbon storage in the soil by the second year after the fire ($\Delta = -2.4$ kg C/m^2) is comparable to the direct carbon losses in a high-intensity wildfire. The total soil carbon pool starts to restore with the restoration of the vegetation cover, in particular, the development of herbs and dwarf shrubs; in twelve years after the fire, its difference from the level

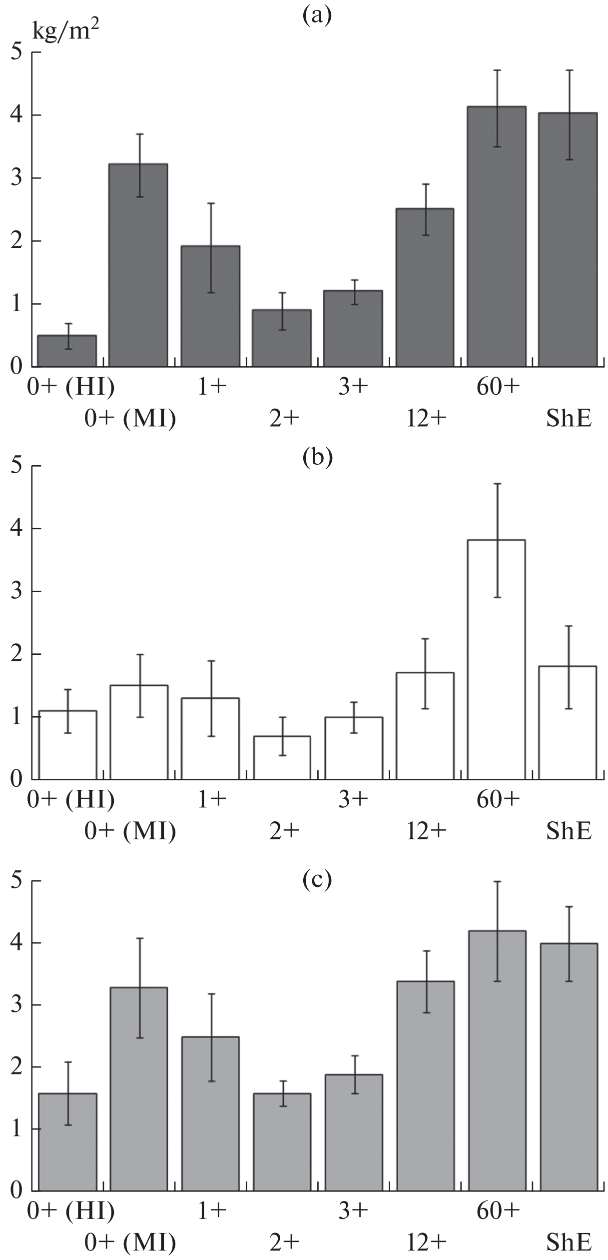

Fig. 2. Dynamics of the organic carbon pool in (a) organic (pyrogenic) horizon, (b) mineral humus-illuvial horizon with a thickness of 20 cm, and (c) upper 20-cm layer of soil profile: 0+ (HI) is the soil after a high-intensity wildfire, and 0+ (MI) is the soil after a moderate-intensity wildfire.

characteristic of the control plot becomes statistically insignificant.

The Effect of Moderate and High-Intensity Wildfires on the Pools of Labile Organic Matter and Microbial Biomass Carbon

A high-intensity wildfire leads to an almost complete destruction of the water-soluble carbon pool in the surface horizon and a statistically significant

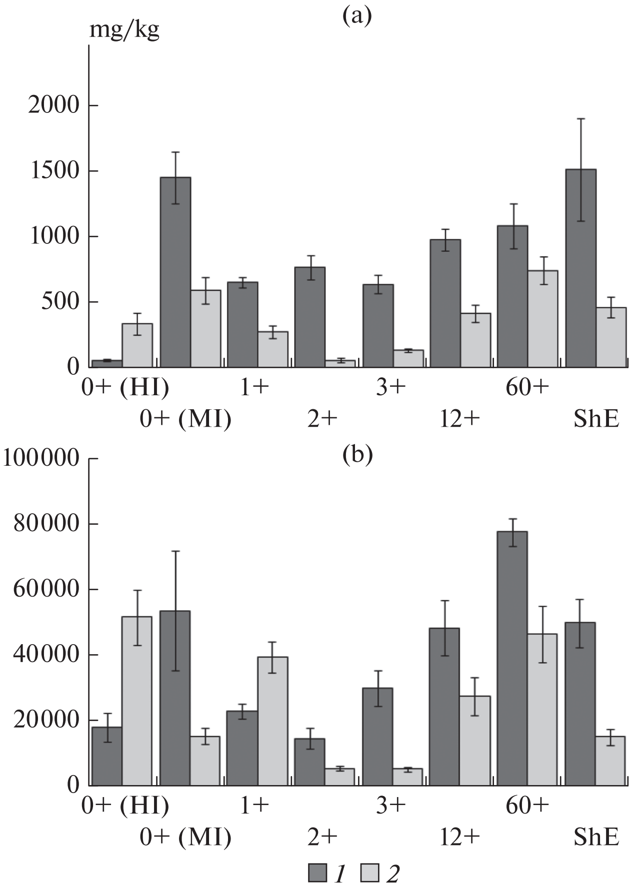

Fig. 3. Dynamics of the carbon content of (a) water-soluble and (b) alkali-soluble fractions of SOM during postfire soil restoration: *1*, organic (pyrogenic) horizon and *2*, mineral horizon.

($p < 0.05$) decrease in the concentration of the carbon extractable with 0.1 M NaOH (Fig. 3). A moderate-intensity wildfire does not lead to a statistically significant decrease in the labile carbon pool in the soil as compared to the control. A direct pyrogenic impact on the contents of water- and alkali-soluble organic carbon in soil mineral horizons has not been observed.

Table 2. Effect of different intensity wildfires on the carbon and nitrogen pools in microbial biomass (above the line, organic (pyrogenic) horizon; below the line, mineral horizon)

Ecosystem	C_{micr}, mg/kg	N_{micr}, mg/kg	C : N
0+ (HI)	31 ± 4 / 45 ± 7	5 ± 1 / 7 ± 1	6.9 ± 0.4 / 6.5 ± 0.9
0+ (MI)	1333 ± 165 / 143 ± 10	148 ± 20 / 16 ± 2	9.0 ± 0.7 / 8.7 ± 0.9
ShE	1453 ± 230 / 160 ± 15	151 ± 7 / 21 ± 4	9.6 ± 0.5 / 7.6 ± 0.3

HI, high-intensity fire; MI, moderate-intensity fire; and ShE, shrub ecosystem.

A significant decrease in the concentration of carbon in water-soluble compounds after the heating to 300–400°C was demonstrated in a laboratory experiment with the larch litter from Siberia [11]. Note that the heating to 200°C, simulating a moderate-intensity wildfire, did not change the concentration of water-soluble organic matter only in one series of experiments with the litter from the slope of northern aspect. slope. As for the larch litter from the south-exposed slope, its heating to 200°C led to an increase in the content of labile carbon, which is explained by the formation of water-soluble products of lignin degradation, dehydration of carbohydrates [11], and partial lysis of microbial cells [26]. An increase in the content of water-soluble carbon in the litters after heating at 200°C has been shown [13, 21]. On the other hand, a twofold decrease in the concentration of water-soluble carbon after a moderate-intensity wildfire has been observed under natural conditions in the litter of Siberian larch stand [1]. A laboratory simulation of the wildfire thermal impact on the soil organic horizons of two Khibiny Mountain tundra ecosystems also demonstrates a decrease in the labile carbon pool in a moderate-intensity fire and almost complete carbon incineration in a high-intensity fire [10].

A high-intensity wildfire almost completely kills the microorganisms in the soil surface horizon and considerably decreases the C_{micr} and N_{micr} pools in the mineral horizon (Table 2). The decrease in C_{micr} by 50–85% after a wildfire was observed in the litter of larch stands [2] and by 50–70% in the litter of pine stands in the Angara region [3]. As for the mineral horizons of the same plots, a 1.5–3-fold decrease in the abundance of all ecological and trophic groups of microorganisms was recorded. Note that the soil fungi is the group most affected by a wildfire [22, 27, 36]. A moderate-intensity wildfire statistically insignificantly decreases the carbon and nitrogen pools of the microbial biomass in the soil organic (pyrogenic) and mineral horizons. We have earlier described the laboratory experiment demonstrating a short-term effect of an increase in C_{micr} pool and basal respiration after the heating of dry-peat soil horizon samples to 200°C, which simulates the thermal impact of a moderate-intensity wildfire [10]. An increase in the microbial biomass in the soil after a fire was provided by the combination of the following factors: (1) an increase in the availability of carbon and energy sources owing to thermal destruction of biopolymers; (2) an increase in the concentration of mineral salts; and (3) a relatively weak impact of a short-term fire on the microbial pool. The further long-term dynamics of the carbon and nitrogen of microbial biomass in the soil surface horizons during the postpyrogenic succession under natural conditions was considered earlier [8]. The data published earlier must be supplemented by that the decrease in C_{micr} and N_{micr} at the early restoration stages is associated with the postfire erosion and

Table 3. Pool of potentially mineralizable SOM (above the line, organic (pyrogenic) horizon and below, mineral horizon)

Ecosystem	Potentially mineralizable SOM (C_0)		Mineralization rate constant k, day^{-1}	Activity of SOM mineralization, mg C/(100 g day)
	mg C/100 g	% of C_{tot}		
0+ (HI)	18 ± 2 / 52 ± 2	0.2 / 0.4	0.153 ± 0.019 / 0.025 ± 0.002	2.8 ± 0.3 / 1.3 ± 0.1
0+ (MI)	3895 ± 1036 / 811 ± 25	11.0 / 5.2	0.012 ± 0.001 / 0.016 ± 0.001	46.7 ± 1.5 / 13.0 ± 0.9
1+	2548 ± 167 / 371 ± 20	10.0 / 3.3	0.014 ± 0.001 / 0.020 ± 0.002	35.7 ± 2.2 / 7.4 ± 0.8
2+	1564 ± 97 / 95 ± 3	16.9 / 2.7	0.010 ± 0.001 / 0.026 ± 0.002	15.6 ± 1.0 / 2.5 ± 0.2
3+	7946 ± 561 / 300 ± 10	65.2 / 18.0	0.003 ± 0.001 / 0.035 ± 0.002	23.8 ± 1.6 / 10.5 ± 0.8
12+	4766 ± 397 / 174 ± 6	19.4 / 1.3	0.006 ± 0.001 / 0.034 ± 0.003	28.6 ± 1.4 / 5.9 ± 0.3
60+	4950 ± 136 / 480 ± 21	13.5 / 2.2	0.011 ± 0.001 / 0.039 ± 0.003	54.4 ± 2.1 / 18.7 ± 1.1
ShE	5139 ± 76 / 200 ± 9	16.1 / 1.1	0.012 ± 0.001 / 0.021 ± 0.002	61.7 ± 2.5 / 4.2 ± 0.8

HI, high-intensity fire; MI, moderate-intensity fire; and ShE, shrub ecosystem.

total loss of SOM rather than with a direct pyrogenic effect. Unlike C_{micr}, the content of which does not differ in a statistically significant manner from the control as early as in three-year-old burns, the N_{micr} pool restores considerably slower: its lower content is characteristic of the plots of 2, 3, and 12 years of post-fire development [8].

Characteristic of the SOM in the organogenic horizon of Entic Folic Podzols in a dwarf shrub ecosystem is the maximum content of potentially mineralizable carbon compounds (C_0 = 5139 ± 76 mg C/100 g) with the mineralization rate constant $k = 0.012 \pm 0.001$ day^{-1} (Table 3). A moderate-intensity wildfire reduces the pool of potentially mineralizable carbon in the surface pyrogenic horizon (3895 ± 1036 mg C/100 g) but does not change its mineralization rate constant. A high-intensity wildfire leads to an almost complete destruction of the pool of potentially mineralizable SOM in pyrogenic horizon (18 ± 2 mg C/100 g). Although the mineralization rate constant in this horizon is high, it nonetheless displays the minimum SOM mineralization activity. The pool of potentially mineralizable SOM comprises the totality of compounds available for microbial consumption independently of their structure, composition, and properties [15]. The quantity and quality of the incoming organic matter, microbial activity, and the degree of protection of the organic matter are the major factors that influence the C_0 pool size; correspondingly, a high C_0 content in the dry-peat horizon, mainly represented by poorly degraded plant remains, is quite natural [14]. A pyrogenic impact causes charring of a part of SOM with the formation of carbonaceous particles, rather resistant to the microbial attack. In the case of a high-intensity wildfire, a large part of the organic horizon is completely incinerated, and the remaining part is represented by carbonaceous material. A drastic reduction in the pool of potentially mineralizable SOM after a high-intensity wildfire is also associated with the death of microorganisms.

The impact of a wildfire on the potentially mineralizable SOM pool in the humus-illuvial horizon is not that unambiguous as in the case of pyrogenic horizon. After a moderate-intensity wildfire, the potentially mineralizable SOM pool increases fourfold as compared with the control. This is associated with the fact that the dying-off plant roots and lysed microbial cells are included into the SOM, as well as with partial illuviation of the products of decomposition of the litter and dry-peat horizon. In the case of a high-intensity wildfire, the amount of potentially mineralizable SOM in the mineral horizon decreases fourfold as compared with the control.

Dynamics of the Labile and Potentially Mineralizable Pools of Organic Matter during Postpyrogenic Soil Restoration

A long-term restoration of the labile SOM pool after a moderate-intensity wildfire generally follows the pattern typical of the total SOM pool, displaying a decrease in the first years after the impact (because of erosion and the absence of stable vegetation cover) and an increase in the subsequent years with the restoration of vegetation. The pool of water-soluble SOM in the studied soils of the Kola Peninsula restores more rapidly as compared with the postpyrogenic forest ecosystems of Siberia [1] and the north of European Russia [6]. However, note that we consider the first stages of soil restoration after a wildfire in more detail. The water-soluble and labile carbon pools in the soils of post-fire succession poorly correlate with one another ($r = 0.45$, $p < 0.05$) but are tightly associated with the total soil carbon content. In the pyrogenic horizons, the total carbon and the carbon of alkali-soluble fraction display the tightest correlation ($r = 0.75$, $p < 0.05$); in the mineral horizon, the tightest correlation ($r = 0.92$, $p < 0.05$) is observed between the total and water-soluble carbon pools.

The potentially mineralizable SOM pool and its mineralization rate constant change during the postfire succession. During the first two years after a wildfire, the content of potentially mineralizable SOM decreases in pyrogenic horizons, which is mainly associated with soil erosion. Later, this pool drastically increases in the pyrogenic horizon of the three-year-old burned site (to 7946 ± 561 mg C/100 g) and then decreases to the level characteristic of the control soil. Any differences in the potentially mineralizable SOM pool in a 12-year-old burned plot and the control are undetectable; however, the mineralization rate constant in the former is almost twofold lower as compared with the control. The organic horizon in the 60-year-old burned plot differs from the control in neither the content nor mineralization rate constant of the potentially mineralizable SOM. Thus, the postfire dynamics of the labile and potentially mineralizable SOM pools in the organic (pyrogenic) horizon are different: a stable increase in the content of water- and alkali-soluble carbon pool starts during the third year after a wildfire versus the potentially mineralizable pool, which reaches its peak in a 3+ burned plot and then remains stable. This pattern is associated with the change in the structure of plant biomass, because herbs, first and foremost, *Festuca ovina* and *Chamaenerion angustifolium,* actively colonize a three-year-old burned site. The activity of SOM mineralization in the first years of post-fire succession gradually decreases; however, this value starts to increase after the third year. On the other hand, the SOM mineralization activity in the organic horizon even of a 60-year-old burned site is still lower than in the control, suggesting a decrease in the carbon losses associated with the soil microbial respiration during the post-fire succession.

The dynamics of the potentially mineralizable SOM pool in the mineral horizon in general coincide with the above-described changes in the content of the labile pool. Note that the potentially mineralizable SOM pool and its mineralization rate constant in the mineral horizon of a 60-year-old burned plot are twofold higher as compared with the control soil. These characteristics increase against the background increase in the labile SOM pool in the humus-illuvial horizon. The activity of SOM mineralization in the humus-illuvial horizon of pyrogenic soil at the late stage of restoration (60 years after a wildfire) is fourfold higher as compared with the control. On the other hand, the respiration activity of microorganisms in the mineral horizons of mountainous tundra soils under natural conditions is rather low because of the low temperature and high humidity. Thus, part of the SOM in the mineral horizon is conserved during a post-fire succession.

Despite the differences in the postfire dynamic patterns, the pool of potentially mineralizable SOM correlates well with the content of water-soluble carbon ($r = 0.70$, $p < 0.05$). A statistically significant correlation between the alkali-soluble and potentially mineralizable SOM pools is undetectable. The absence of correlation between these characteristics suggests that not all SOM extractable with 0.1 M NaOH is biologically active, since certain amount of conserved SOM can be also extracted in addition to the labile SOM. However, the potentially mineralizable and water-soluble SOM pools are not completely analogous despite the observed correlation, because only some part of the organic matter is in the dissolved state accessible for microbial consumption. The water-soluble SOM pool is heterogeneous in its composition and bioavailability [32] and includes poorly degradable compounds of an aromatic nature. Thus, the chemical and biokinetic fractionation methods make it possible to assess different parameters of the SOM quality and state.

CONCLUSIONS

The effect of fire on the total pool of soil carbon is ambiguous and depends on the wildfire intensity. Although a moderate-intensity wildfire does not influence the total carbon pool in soil in a statistically significant manner, it nonetheless triggers active erosion processes, so that the eventual carbon losses by soil are comparable with the direct pyrogenic losses in a high-intensity wildfire. The restoration of vegetation, first and foremost, herbs, contributes to stabilization of the soil carbon pool. The postpyrogenic effect of excessive carbon accumulation in the soil appears at late stages of the post-fire self-restoration.

A high-intensity wildfire almost completely destroys the water-soluble and potentially mineralizable SOM pools and significantly decreases the microbial biomass carbon pool. A moderate-intensity wildfire decreases only potentially mineralizable SOM pool, which is explained by the formation of carbonaceous particles relatively tolerant towards the microbial attack.

During the postpyrogenic soil self-restoration, the labile pool of soil carbon (water- and alkali-soluble) in general follows the pattern of the total carbon pool decreasing in the first two–three years and then increasing up to the level characteristic of the control intact plot. The potentially mineralizable SOM pool in pyrogenic horizons follows another pattern with the maximum in the soil of the three-year-old burned site, which is associated with its colonization by herbs. As for the soils of post-fire chronosequence in a long-term prospect, a decrease in the SOM mineralization activity in the organic (pyrogenic) horizons and its increase in the mineral horizon are observed. On the other hand, a low microbial activity in the mineral horizons of mountainous tundra soil under wildlife conditions suggests that part of the SOM in the mineral horizon is conserved during the post-fire succession.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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