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SOIL GENESIS AND GEOGRAPHY

Pyrogenic Transformation of Tundra Soils: Laboratory Simulation

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Abstract—Pyrogenic losses of carbon and nitrogen from the surface horizons of soils in shrub ecosystems of mountain tundra, which are the most affected by fires in natural environments, have been estimated in laboratory simulation tests. The specific features of pyrogenic transformation of the physical and chemical properties and microbiological processes after exposure to high temperatures simulating the effect of fires of different intensity have been identified. Pyrogenic nature of the impact depends not only on the intensity of a fire, but also on the soil type. Its impact on tundra soils leads only to short-term increases in CO_2 emissions due to the destruction of pyrogenic organic compounds. A high level of fire impact leads to a significant reduction in microbiological processes in soils and shows no trend toward recovery in the long term, even under optimal conditions.

Keywords: pyrogenesis, soil organic matter, carbon, nitrogen, microbiological processes, tundra, Khibiny

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INTRODUCTION

Fire as an environmental factor affecting all ecosystem subunits is relatively well studied for boreal forests. The increase in occurrence frequency [27] and large areas of fires [21] observed in the last decade in the tundra zone indicate that fire is becoming an important factor affecting these ecosystems. However, the consequences of tundra fires still remain unappreciated.

Due to low reserves of aboveground phytomass in tundra ecosystems, the main impact of a fire is on the litter and organogenic horizons of the soil, depositing carbon for a long time, which primarily affects the circulation of this element. Thus, $C-CO_2$ emission caused by one of fires in the Alaskan tundra was equivalent to the value of its annual discharge in Earth's entire tundra zone [23]. According to estimates [16], the 2007 fire that affected more than 1000 ha of Alaskan tundra cause emission of $C-CO_2$ equivalent to the amount of carbon accumulated in this territory in the last 50 years. A fire in the shrub ecosystem of the southern tundra near Vorkuta resulted in the loss of almost 30% of its carbon reserves [3]. In addition to destroying carbon reserves, a fire leads to a change in this element flux. Thus, in the tussock–cottongrass tundra of Alaska (Seward Peninsula), the emission of carbonaceous gases (especially CO_2) greatly increased immediately after the fire and decreased over time, and the ecosystem gradually transformed into carbon sink, compensating the losses [25]. The duration of recovery varies greatly, and the process can fluctuate around the equilibrium position of the carbon balance for a long time. The change in carbon fluxes under conditions of the southern tundra (Vorkuta) in the shrub ecosystem is different and depends on the season: in spring, undisturbed areas of tundra, as well as 8-year-old burned areas, function as a source of $C-CO_2$, and the 2-year-old, as a sink [3]. In summer, undisturbed areas of the tundra exhibit a multidirectional balance of $C-CO_2$ depending on the air and soil temperatures, and burned areas of different ages function as a $C-CO_2$ sink zone. In general, the carbon balance in a shrub ecosystem of postpyrogenic succession is unstable until the productivity of the sites reaches its maximum.

Disturbances of the carbon and nitrogen cycles from fire largely depend on the changes in the structure of soil microbial complexes. Most information on this issue relates to forest ecosystems, for which the negative effect of fire on soil microbiocenoses has been demonstrated (a decrease in the amount and biomass of microorganisms of the carbon–nitrogen cycle, in respiration rate, and in the composition of the microbiocenoses). There are also data on the transformation of the microbial complex of bog soils, which are the most functionally close to tundra soils [2, 15].

In particular, the regularities of burned areas being settled by new bacterial groups not typical of natural peat bogs have been revealed; this can cause disturbances in some ecosystem functions. The questions of microbial successions in burned areas in tundra and the degree of disturbance of their natural microbiological processes, as well as postfire adaptation processes, remain largely outside the attention of researchers.

The aim of this study is to evaluate under laboratory experiment conditions the influence of the pyrogenic factor of different intensities on the physical and chemical properties and the processes of the carbon and nitrogen cycles in the tundra soils of Khibiny, as well as to find the most informative indices for assessing the effect of fire on soils.

MATERIALS AND METHODS

The organogenic horizons (upper 5 cm) of tundra soils were sampled in two ecosystems: shrubby–lichen (SL) and bushy tundra (BT), located on the northwestern slope of Vudyavrchorr Mountain (Khibiny mountain massif) at 525 m above sea level. In the SL biogeocoenosis, dry-peat–podzolized brown illuvial–humus soil [4] (folic leptosol [20]) is formed; in BT, humus–coarse-humus leptosol (folic leptosol). Samples were collected in five replicates from plots with the area 25 × 25 cm, the plant remains that had not lost their anatomical integrity were removed, and then the soil samples were air-dried. The samples were sieved through a 2-mm sieve and divided into three parts. The first part was the control; the second part was heated in a muffle for 1 h at a temperature 200°C; the third part, for 1 h at 400°C, simulating the effect of a fire of varying intensity. Temperatures of 200 and 400°C were chosen as the extreme marks of the fire range observed on the soil surface during fires in forest ecosystems [24], as well as previously recorded during controlled burning of the Khibiny tundra in September 2016.

The weighed portions of the initial and heated soil were placed in plastic containers, moistened with distilled water to 60% field capacity, and were inoculated with fresh soil that had not been dried and heated by 1 g of inoculum per 50 g of soil. The incubation was carried out in a SANYO MIR-153 climate chamber in the dark for 60 days with a daily moisture control by the weight method.

Soil samples for analysis were taken immediately after wetting (0 days) as well as after inoculation with fresh soil on days 1, 3, 7, 15, 30, 45, and 60 of the experiment. The oxidation–reduction potential, pH, and specific electrical conductivity of the aqueous extract (soil : solution = 1 : 50) were determined.

The total content of carbon and nitrogen (C_{tot} and N_{tot}) was determined on an Elementar Vario EL III element analyzer. Labile compounds of the elements were extracted with 0.05 M K_2SO_4 [6]. Extractable organic carbon (C_{extr}) and total extractable nitrogen were determined on an automatic TOC-V_{CPN} (Shimadzu) analyzer; N-NH_4^+, by the indophenol method; N–NO_3^-, after reduction on a cadmium column to nitrite and production of a Griss-colored azo compound. Colorimetric determinations were performed on a GENESYS™ 10 UV spectrophotometer (United States). Nitrogen extractable organic compounds (N_{org}) were calculated from the difference between the extracted nitrogen and the sum of the inorganic compounds of the element. Carbon and nitrogen of the microbial biomass (C_{mic} and N_{mic}) were determined by the fumigation extraction technique [17, 31].

Basal soil respiration was determined after incubation of 0.5 g samples at a temperature of +22°C for 24 h on an Agilent 6890N chromatograph (Hewlett Packard, United States) equipped with a flame ionization detector and a methanator (Supelco 10182004 column with an internal diameter 3.175 mm and the length 1828.8 mm; the adsorbent is 80/100 Porapak Q; temperature of the column thermostat, 60°C; the carrier gas flow (helium), 20 mL/min; temperature of the detector, 300°C; temperature of the back port, 375°C; helium flow, 30 mL/min; air flow, 400 mL/min; the volume of the introduced gas sample, 1 mL).

Methanogenesis intensity was determined 7 days after incubation of 0.5 g samples at +28°C on a Crystal 5000 chromatograph with a flame ionization detector. Because of the low activity of methanogenesis, in addition to the actual one (without the addition of glucose), the potential (with the addition of 1% glucose solution) methane production rate was measured.

The actual nitrogen fixation rate was determined by the reduction of acetylene to ethylene after 0.5 g samples had incubated at +28°C for 7 days without the addition of glucose. The concentration of acetylene and ethylene was determined by gas chromatography technique a Crystal-2000 chromatograph (SKB Chromatek) with a flame ionization detector (column length 1 m, diameter 3 mm, filler Porapak N 80/100, column temperature 60°C, detector temperature 160°C, evaporator temperature 100°C, carrier gas flow (N_2) 50 mL/min, air flow 280 mL/min, hydrogen flow 28 mL/min). Nitrogen fixation activity was calculated with recalculation of the amount of formed ethylene to the amount of fixed nitrogen in a ratio of 1 : 3. Similarly, the potential nitrogen fixation rate was calculated by adding 1% glucose solution to the vials.

All of the soil biological activity parameters were determined in three to five analytical replications for each sampling period and each variant of the experiment.

Table 1. Main chemical parameters of the soil (Mean ± St. error).

Biogeocenosis, horizon	pH_{wat}	Eh, mV	Specific electrical conduction, μS cm^{-1}	C_{tot}, %	N_{tot}, %	C_{extr}, mg kg^{-1}	N_{org}, mg kg^{-1}	$N\text{-}NH_4^+$, mg kg^{-1}	C_{micr}, mg kg^{-1}	N_{micr}, mg kg^{-1}
SL, TJ	5.5 ± 0.3	508 ± 75	29 ± 5	29.4 ± 1.5	1.1 ± 0.2	1021 ± 110	41 ± 5	8.8 ± 0.7	1081 ± 121	70 ± 7
BT, AH	5.7 ± 0.2	646 ± 92	33 ± 5	25.4 ± 0.8	1.1 ± 0.3	866 ± 99	31 ± 4	6.4 ± 0.5	682 ± 91	63 ± 7

Table 2. Transformation rate of carbon and nitrogen compounds in the soil (mean ± SE)

Biogeocenosis, horizon	Basal respiration, mg $C\text{-}CO_2$ kg^{-1} day^{-1}	Methanogenesis, mg CH_4 kg^{-1} day^{-1}	Nitrogen fixation, mg N_2 kg^{-1} day^{-1}	Denitrification, mg N_2O kg^{-1} day^{-1}
SL, TJ	595.0 ± 38.9	4.7 ± 0.3	2.9 ± 0.6	0.3 ± 0.07
BT, AH	433.6 ± 27.1	2.6 ± 0.4	1.7 ± 0.5	0.2 ± 0.05

RESULTS AND DISSCUSSION

General Characteristics of the Studied Tundra Soils (Table 1)

Surface horizons have a slightly acidic reaction (pH 5.5–5.7), low salt content in aqueous extract, and high redox potential (ORP) typical of automorphic soils. Since only the upper 5 cm were sampled, including the lower subhorizons of the litter, the soils were characterized by a high carbon content (25–30%), but were relatively poor in nitrogen (1.1%, C/N = 23–27), which is due to conservation of weakly humified organic matter close in chemical composition to the mortmass of tundra plants in this layer [8, 9].

The most significant differences were typical of the labile and microbial components. However, the soil of the SL biogeocenosis contains significantly higher concentrations of labile (C_{extr}) and microbial (C_{mic}) carbon, as well as organic and ammonium nitrogen (Table 1). Nitrate nitrogen was found in trace amounts inherent to tundra soils [5, 18, 28]. In general, carbon and nitrogen concentrations of the labile and microbial components of the studied soils were close to the previously published values for tundra soils of Fennoscandia [7, 10].

Table 2 gives the potential transformation rate of carbon and nitrogen compounds in soils. The main process of carbon compound transformation is their aerobic oxidation with the formation of $C–CO_2$. Methane formation was hardly typical of the studied soils even in the optimal hydrothermal and anaerobic conditions of the laboratory experiment; this is due to the initial composition of the soil microorganism complex of the well-aerated upper horizons. The functioning of SL and BT ecosystems under conditions of periodic drying does not contribute either to methanogenesis.

Nitrogen fixation activity in tundra soils is rather weak. As a rule, nitrogen-fixing microorganisms in tundra and highlands are associated with mosses in wetland areas or with lichens in relatively dry habitats [29]; free-living nitrogen-fixing bacteria are not typical of cold climate ecosystems [26]. It should be noted that in the SL ecosystem, the soil nitrogen fixation process was twice as intense as in the soil of the BT biogeocoenosis. One reason for this is, in our opinion, the greater availability of C_{extr} for microorganisms, which contributes to the development and maintenance of the population of nitrogen fixers in the soil.

The denitrification process is not pronounced, which is obviously due to the low number of denitrifying microorganisms in the native soil due to the almost total absence of nitrates. In cold climate ecosystems, these processes occur only in water-saturated soils [29].

Pyrogenic Transformation of Soils

Losses during heating at different temperatures showed a significant difference in the behavior of organogenic soil horizons of the SL and BT ecosystems under pyrogenic impact. At 200°C, the soil of the SL ecosystem lost twice as much mass as the soil of the BT biogeocenosis. The difference in mass loss during heating of SL soil at 200 and 400°C was minimal and did not exceed 5%, which indicates the predominance of thermolabile compounds (e.g., cellulose and hemicellulose [11, 12]) in organic matter. This is consistent with the botanical composition of the community's mortmass, in which the dead parts of lichens and wasteland herbaceous plants predominate. Nondeciduous dwarf shrub debris is a minor fraction of the mortmass. Loss during BT soil heating at 200 and 400°C, on the contrary, increased twofold (from 20 to 39%), which indicates the predominance of heat-resistant compounds (e.g., lignin) in the soil organic matter content, formed due to the input of deciduous dwarf shrub leaf debris.

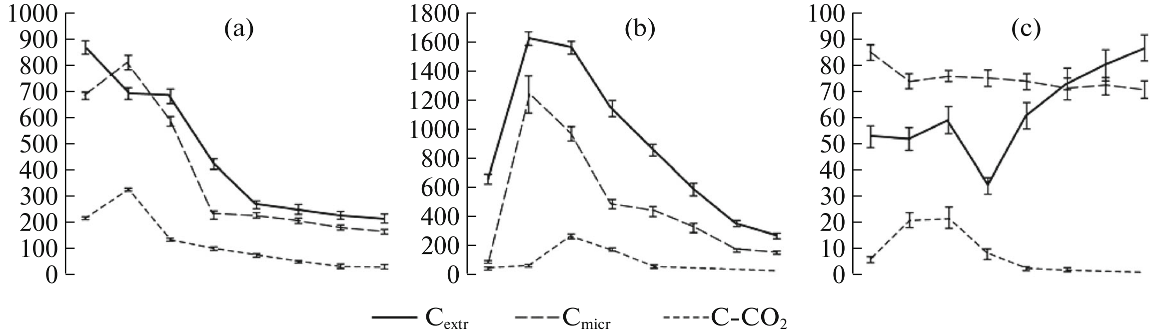

Fig. 1. Carbon dynamics (mg C kg^{-1}, mg $C\text{-}CO_2$ kg^{-1} day^{-1}) in soil of BT ecosystem: (a), control; (b), heating at 200°C; and (c), heating at 400°C.

The losses of soil mass as a result of heat exposure leads to an increase in the percentage of carbon and nitrogen, but also to a significant reduction (by 30–50%) of their reserves.

Pyrogenic impact leads to an increase in soil pH compared to the control. A significant increase in this indicator in the upper horizons after fires is related to the formation of potassium and calcium carbonates and (hydra)oxides during the pyrolysis of organic matter [30]. The possibility of pH increasing due to denaturation of organic acids during heating has been demonstrated for postpyrogenic forest soils in Siberia [1, 22]. In our experiment, this increase under pyrogenic impact is probably associated with the destruction of certain organic acids, since previously published data [13] indicate that the organogenic horizons of Vudyavrchorr tundra soils contain insignificant amounts of exchangeable calcium (3.9–12.1 mmol/100 g) and magnesium (6.6–9.3 mmol/100 g).

The thermal action significantly increases the concentration of mineral salts, which is expressed in 5–10 times increase of the specific electrical conductivity of water extract of SL ecosystem soil and 2–3 times increase for BT soils. The increase in specific electric conductivity is associated with the release of some of the mineral elements from the composition of the weakly humified organic matter of the soil during burning. Not less significant is the change of ORP: after burning, it decreases 2–4 times and approaches values corresponding to strongly reducing conditions, which is associated with an increase in the hydrophobicity of soil particles after the fire passage and the formation of an additional amount of anaerobic zones inside the soil.

The pyrogenic impact leads to a decrease in the C_{extr} and N_{org} concentrations in the surface horizons of tundra soils. It is proportional to the intensity of the thermal action, which is especially developed in soils of the BT ecosystem. The effect of fire on microbial biomass is almost the same: it leads to the death of microorganisms and soil loss of carbon and nitrogen compounds with gaseous combustion products. The death of microorganisms sharply reduces soil biological activity. This primarily affects their basal respiration: at 200°C it decreases 6–10 times and falls to zero at 400°C in comparison with intact samples. This is caused not only by the death of the microorganism population or just part of it, but also by a decrease in the availability of substrates.

Postpyrogenic Dynamics of Microbial Activity and Carbon and Nitrogen Fluxes in Soils

The pyrogenic effect alters the balance of labile carbon in soils. Not only the action, but also the intensity of the fire is very important. The Fig. 1 shows the dynamics of labile carbon, microbial biomass carbon, and $C–CO_2$ in the soil of the BT ecosystem.

In the control, during 60 days of incubation, a gradual decrease in the C_{extr} concentration occurred. The curve of the carbon microbial biomass dynamics has a classical form with a lag period of up to two days, a subsequent maximum, and a gradual decay. Such a C_{mic} dynamics is associated with the release of part of the microbial biomass carbon during soil drying, its transition to the labile pool, the subsequent use of the labile carbon pool by microorganisms as a source of nutrition, and its gradual depletion due to the respiration of microorganisms. The low-intensity pyrogenic effect (200°C),first leads to an increase in the labile carbon concentration in the soil, apparently due to depolymerization of its organic components with the formation of pyrogenic products ("black" carbon) [19], dehydration products of complex carbohydrates, and destruction of lignin [14]. Second, it leads to a significant increase in C_{mic} concentration and CO_2 emission. The increase in microbial biomass in the soil in this case is possible due to the combination of the following factors: an increase in the availability of carbon sources and energy due to the thermal destruction of biopolymers, an increase in mineral salt concentration, and the relatively weak impact of a short-term fire on the microbial pool. A more intense pyrogenic impact on the soil (400°C) leads to significant losses of labile carbon and almost complete death of microorganisms. The lack of available carbon, even against the background of a significant increase in the availability of mineral salts, does not promote the growth of microbial biomass in pyrogenic soil after inoculation.

The main trends in changes in the carbon pools of the soils under pyrogenic impact are also specific to the nitrogen pool. However, a significant increase in the concentration of mineral, especially ammonium, nitrogen with an increase in burning intensity should be noted. The increase in the net mineralization rate is related to the release of additional amounts of nitrogen from previously inaccessible forms and is due to a decrease in the net immobilization rate on the part microorganisms due to loss of available carbon in the soil. An increase in the nitrification rate is associated with both an increase in ammonium nitrogen concentration and a decrease in the nitrogen consumption by plants and microorganisms.

The studied soils showed an extremely low actual rate of methane production, nitrogen fixation, and denitrification, which, in our opinion, could be explained by the lack of available carbon for microbiota development and, obviously, by the low number of target groups of microorganisms.

Potential rates of methanogenesis, nitrogen fixation, and denitrification yield more evident indicators of changes in these processes under pyrogenic impact. So, additional introduction of glucose to the soil increases methane production, although it remains at a low level (within 3–8 ng CH4 g^{-1} day^{-1} for the control soils). The pyrogenic effect increases methane production by 1.5–2 times , which is associated with the formation of an additional amount of anaerobic zones and the creation of microaerophilic conditions in the soil.

The potential rate of nitrogen fixation in the control soils was 2.6–5.0 ng N_2 g^{-1} day^{-1}. In soils exposed to pyrogenic impact, the potential rate of molecular nitrogen fixation decreases two to four times, which is caused by the release of additional amounts of free, including mineral, nitrogen due to the thermal destruction of nitrogen-containing biopolymers. The relative increase in mineral nitrogen availability (in the absence of competition from plants) suppresses nitrogen fixation in tundra soils. With an increase in nitrogen availability, the potential denitrification rate also increases. In pyrogenic soils, nitrogen loss is five to six times higher than in the control soil. However, this is only true at the early stages of incubation; by approximately the middle of the incubation period, the denitrification rate in the control samples was almost equal to values typical of soils exposed to pyrogenic impact.

CONCLUSIONS

Fire significantly changes the physical and chemical parameters of tundra soils, as well the parameters of the carbon and nitrogen cycle. The result of pyrogenic impact depends both on the initial properties of the soil and the intensity of the fire. At a low burning rate, a positive response of microbial biomass growth (an increase in the carbon and nitrogen concentrations of the microbial biomass) and the release of additional amounts of labile carbon and organic and mineral forms of nitrogen were observed. A high-intensity fire results in almost complete loss of labile carbon by soil, which determines the low growth rate of its microbial biomass and the low biological activity of the soil. However, the concentration of mineral forms of nitrogen, primarily ammonium, substantially increases. The most sensitive parameter of the biological activity of tundra soils to pyrogenic impact is soil respiration. Methane production, molecular nitrogen fixation, and denitrification were poorly expressed due to the lack of available carbon. The potential rates of these processes were also small. An increase in methane production in pyrogenic soils due to the creation of microaerophilic conditions there was also noted. An increase in the availability of mineral nitrogen in tundra soils suppresses nitrogen fixation but stimulates denitrification.

It is obvious that pyrogenic impact on microorganisms is largely manifested not in direct thermal effects, but in changes in the availability and physical and chemical properties of the consumed substrates. This is the reason for the short-term stimulating effect of low-intensity thermal action (200°C) on the respiratory activity of the soil microbiocenosis.

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REFERENCES

1. Bogdanov, V.V., Prokushkin, A.S., and Prokushkin, S.G., Effect of creeping fire onto organic matter mobility in hemlock forests of middle Siberia cryolithozone, *Vestn. Krasnoyarsk. Gos. Agrarn. Univ.,* 2009, no. 2.
2. Zenova, G.M., Glushkova, N.A., Bannikov, M.V., et al., Actinomycetal complexes in drained peat soils of the taiga zone upon pyrogenic succession, *Eurasian Soil Sci.,* 2008, vol. 41, no. 4, p. 394.
3. Karelin, D.V. and Zamolodchikov, D.G., *Uglerodnyi obmen v kriogennykh ekosistemakh* (Carbon Exchange in Cryogenic Ecosystems), Moscow, 2008.
4. Shishov, L.L., Tonkonogov, V.D., Lebedev, I.I., and Gerasimova, M.I., *Klassifikatsiya i diagnostika pochv Rossii* (Classification and Diagnostics of Russian Soils), Smolensk: Oikumena, 2004.
5. Makarov, M.I., Leoshkina, N.A., Ermak, A.A., and Malysheva, T.I., Seasonal dynamics of the mineral

nitrogen forms in mountain-meadow alpine soils, *Eurasian Soil Sci.,* 2010, vol. 43, no. 8, p. 905.

6. Makarov, M.I., Shuleva, M.S., Malysheva, T.I., and Menyailo, O.V., Solubility of the labile forms of soil carbon and nitrogen in K_2SO_4 of different concentrations, *Eurasian Soil Sci.,* 2013, vol. 46, no. 4, p. 369.
7. Maslov, M.N., Carbon, nitrogen and phosphorus of microbial biomass in tundra soil of Northern Fennoscandia, *Vestn. Mosk. Gos. Obl. Univ., Ser. Estestv. Nauki,* 2014, no. 2.
8. Maslov, M.N., Kopeina, E.I., Zudkin, A.G., et al., Stocks of phytomass and organic carbon in tundra ecosystems of Northern Fennoscandia, *Moscow Univ. Soil Sci. Bull.,* 2016, vol. 71, no. 3, p. 113.
9. Maslov, M.N. and Makarov, M.I., Organic matter of the soil of the mountain tundra in North Fennoscandia, *Moscow Univ. Soil Sci. Bull.,* 2013, vol. 68, no. 3, p. 99.
10. Maslov, M.N. and Makarov, M.I., Transformation of nitrogen compounds in the tundra soils of Northern Fennoscandia, *Eurasian Soil Sci.,* 2016, vol. 49, no. 7, p. 757.
11. Masyagina, O.V., Tokareva, I.V., and Prokushkin, A.S., Modeling of the thermal influence of fires on the physicochemical properties and microbial activity of litter in cryogenic soils, *Eurasian Soil Sci.,* 2014, vol. 47, no. 8, p. 809.
12. Shapchenkova, O.A., Krasnoshchekov, Yu.N., and Loskutov, S.R., Application of the methods of thermal analysis for the assessment of organic matter in postpyrogenic soils, *Eurasian Soil Sci.,* 2011, vol. 44, no. 6, p. 677.
13. Shmakova, N.Yu., Ushakova, G.I., and Kostyuk, V.I., *Gorno-tundrovye soobshchestva Kol'skoi Subarktiki (ekologo-fiziologicheskii aspekt)* (Mountain-Tundra Communities of Cola Subarctic. Ecological-Physiological Aspect), Apatity, 2008.
14. Barcenas-Moreno, G. and Baath, E., Bacterial and fungal growth in soil heated at different temperatures to simulate a range of fire intensities, *Soil Biol. Biochem.,* 2009, vol. 41, no. 12, pp. 2517–2526.
15. Belova, S.E., Kulichevskaya, I.S., Akhmet'eva, N.P., and Dedysh, S.N., Shifts in a bacterial community composition of a mesotrophic peatland after wildfire, *Microbiology,* 2014, vol. 83, no. 6.
16. Bret-Harte, M.S., Mack, M.C., Shaver, G.R., et al., The response of arctic vegetation and soils following an unusually severe tundra fire, *Philos. Trans. R. Soc.,* 2013, vol. 368, no. 1624, p. 20120490.
17. Brookes, P.C., Landman, A., Pruden, G., and Jenkinson, D.S., Chloroform fumigation and the release of soil nitrogen: a rapid direct extraction method to measure microbial biomass nitrogen in soil, *Soil Biol. Biochem.,* 1985, vol. 17, no. 6, pp. 837–842.
18. Edwards, K.A., McCulloch, J., Kershaw, G.P., and Jefferies, R.L., Soil microbial and nutrient dynamics in a wet arctic sedge meadow in late winter and early spring, *Soil Biol. Biochem.,* 2006, vol. 38, no. 9, pp. 2843–2851.
19. Gleixner, G., Czimczik, C.J., Kramer, C., et al., Plant compounds and their turnover and stabilization as soil organic matter, in *Global Biogeochemical Cycles in the Climate System,* San Diego, 2001.
20. IUSS Working group WRB., World reference base for soil resources, *World Soil Resources Rep.,* Rome: FAO, 2006, no. 103.
21. Jones, B.M., Breen, A.L., Gaglioti, B.V., et al., Identification of unrecognized tundra fire events on the north slope of Alaska, *J. Geophys. Res.: Biogeosci.,* 2013, vol. 118, no. 3, pp. 1334–1344.
22. Kawahigashi, M., Prokushkin, A., and Sumida, H., Effect of fire on solute release from organic horizons under larch forest in central Siberian permafrost terrain, *Geoderma,* 2011, vol. 166, no. 1, pp. 171–180.
23. Mack, M.C., Bret-Harte, M.S., Hollingsworth, T.N., et al., Carbon loss from an unprecedented arctic tundra, *Nature,* 2011, vol. 475, pp. 489–492.
24. Neary, D.G., Klopatek, C.C., DeBano, L.F., and Efolliott, P.F., Fire effects on belowground sustainability: a review and synthesis, *For. Ecol. Manag.,* 1999, vol. 122, nos. 1–2, pp. 51–71.
25. Oechel, W.C., Net ecosystem carbon flux of age-specific subarctic tussock tundra stands following fire: implications for Alaska Interagency Fire Management, *Final Report to National Park Service,* Boise, ID, 1999.
26. Robinson, C.H. and Wookey, P.A., Microbial ecology, decomposition and nutrient cycling, in *Ecology of Arctic Environments*, Oxford: Blackwell, 1997.
27. Rocha, A.V., Loranty, M.M., Higuera, P.E., et al., The footprint of Alaskan tundra fires during the past half-century: implications for surface properties and radiative forcing, *Environ. Res. Lett.,* 2012, no. 7.
28. Schmidt, I.K., Jonasson, S., Shaver, G.R., et al., Mineralization and distribution of nutrients in plants and microbes in four arctic ecosystems: responses to warming, *Plant Soil,* 2002, vol. 242, no. 1, pp. 93–106.
29. Stark, S., Nutrient cycling in the tundra, Nutrient cycling in terrestrial ecosystems, in *Soil Biology,* Berlin, 2007, vol. 10.
30. Ulery, A.L., Graham, R.C., and Amrhein, C., Wood-ash composition and soil ph following intense burning, *Soil Sci.,* 1993, vol. 156, pp. 358–364.
31. Vance, E.D., Brookes, P.C., and Jenkinson, D.S., An extraction method for measuring soil microbial biomass C, *Soil Biol. Biochem.,* 1987, vol. 19, no. 6, pp. 703–707.

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