ORIGINAL PAPER

Influence of fire on soil temperatures of pine forests of the middle taiga, Central Siberia, Russia

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Abstract Temperatures of sandy podzols of middle taiga pine forests with moss and lichen ground cover were analyzed which had been exposed to ground fires of low to medium intensity. In general, temperatures in lichen and moss plots of the pine forests under study, are close to each similar, but in the first year after a fire a noticeable contrast was observed. The reasons are an increase in the amplitude of daily temperatures on the soil surface and stronger heating of upper mineral layers. Temperatures in the mineral layer with depths up to 30 cm depend on the thickness of the forest floor. Analysis of the results show that the duration of post-fire effects in pine forests with sandy podzols is determined by a number of factors: the intensity of the fire, the degree of erosion of the ground cover and litter, and the recovery rate of these components.

Keywords Ground fire · Pine forests · Soil temperature

Introduction

The currently fixed steady surge in surface temperature is one of the leading factors determining not only the condition and productivity of forest ecosystems, but also the frequency and range of forest fires. In this regard, recently collected data confirm the trend of increasing number of fires and their frequency in mountainous forests in Central Siberia (Loupian et al. 2006; Ponomaryov and Kharuk 2016).

Fires are considered a powerful and influential environmental factor in soil formation as they have a complex and multifaceted impact on ecosystem processes such as erosion, subtraction (runoff) of organic matter and plant succession (Baldock and Smernik 2002; Certini 2005, 2014; Cerda and Doerr 2008; Guénon et al. 2013). Numerous studies of the influence of the pyrogenic factor on soil systems distinguish two types of this influence (Sharrow et al. 1977; Bezkorovaynaya et al. 2007; Tsibart and Gennadiev 2008; Krasnoschekov and Cherednikova 2012; Smits et al. 2016; Dymov et al. 2018; Deviatova et al. 2019): 1) pyrogenic transformation or the combustion by heat of soils as a result of direct pyrolysis, i.e., change of physical and chemical properties, strengthening of processes of mineralization of organic matter, increasing the amount of water-soluble compounds, decreasing acidity, decomposition of aluminosilicates, changes in granulometric composition, modified water and thermal modes; and, 2) pyrogenic transformation of soil formation

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factors, i.e., creation of a secondary post-fire relief resulting in the complexity and microcomplexity of soils, a lower level of perennial permafrost, swamping, natural draining of swamps, erosion, changes in the nature of the accumulative process, and the intensified processes of eluviation-illuviation.

After a fire, there is an increase in ash content (Pereira et al. 2014) and leaching of nutrients into deeper soil horizons (Bodi et al. 2014), compaction of the upper mineral layers and their structural transformation due to sintering or compaction of fine fractions into dense, stable aggregates (Ulery and Graham 1993; Ketterings et al. 2000; Mataix-Solera et al. 2011; Dymov et al. 2018). Such post-pyrogenic changes in soil structure also alter thermal properties (Certini 2005; Smits et al. 2016). In the first years following a fire, there are temperature increases, especially in the upper mineral layers (Vermeire et al. 2005; Bezkorovaynaya et al. 2007; Santana et al. 2010; Krasnoschekov and Cherednikova 2012). A rise in post-fire soil temperatures is a signal for biological processes to become activated (Bezkorovaynaya et al. 2005; Allison et al. 2010; Guénon et al. 2013) and can stimulate the vigorous growth of seedlings, playing a central role in the recovery of plant communities (Santana et al. 2010).

In spite of the aforesaid common features, the impact of fires on soil properties vary and may depend on physiographic conditions, forest and habitat types, initial soil properties, as well as fire type and its intensity (Conard and Ivanova 1997; Bezkorovaynaya et al. 2015; Dymov et al. 2018).

One of the limiting factors for the development and functioning of boreal forests is soil temperature. The temperature of the active soil layer is directly dependent on the degree of development of the thermo-insulating moss-lichen cover and the thickness of the forest floor (Prokushkin et al. 2002; Tarasov et al. 2011). Against the background of an increased frequency of forest fires and shortened intervals between fires in the territory of Siberia (Ponomaryov et al. 2019), there are a number of issues to consider concerning the emergence of the soil temperature regime in the post-fire period; precisely how much the heat supply of the active soil layer changes, how long the post-fire effects remain, and what they depend on.

The purpose of this study is to analyze and assess the dynamics of soil temperatures in post-fire pine forests growing on sandy podzols in the Central Siberian middle taiga.

Materials and methods

Study area

Research was carried out on the Ket-Sym lowlands on the left bank of the Yenisei River in the middle taiga pine forests on sandy podzols. The relief of the area is a chaotic alternation of flattened hills, walls, hillocks with short, shallow ravines, rill channels and shallow gullies. The climate is continental with temperatures reaching 90 ºC–95 ºC. However, this is a temperate cold humid area and the sum of temperatures above 10 °C is 800–1200 °C; Selyaninov's hydrothermal coefficient is 1.2–1.6 and characterizes the level of moisture and precipitation values in the territory, calculated as the ratio of the sum of precipitation (mm) for a period with average daily air temperatures above 10 °C to one tenth of the sum of temperatures for the same period. Depending on landscape features, the average annual temperatures vary from –5.4 to –3.1 °C, and annual rainfall from 400 to 600 mm. Average minimum and maximum air temperatures are – 48 ºC and +31 ºC, respectively. The area covered by forest is 84%, with a large area occupied by swamps (10.5%). Pine forests with moss and lichens account for 40% of the area. The frequency of fires in the forests under study is high, with a maximum number in June. In summer, this frequency is conditioned by long, dry periods during which forest areas are subject to extensive fires. Therefore, there are numerous, large fires at this time (Valendik 1995). For the landscapes of the West Siberian Plain near the Yenisei River, the average inter-fire period is 57 years, and for the Central Siberian middle taiga subzone, it varies from 25 to 40 years (Furyaev 1996).

Experimental sites are post-fire and close to other areas with lichen and moss pine forests *(Pinus sylvestris-Pleurozium+Cladonia* ssp.*)*: 1, 2, 4, and 5 years after the fire (60°38′N 89°41′E); 8 years after the fire (60°47′N, 89°21′E). All were ground fires of medium and low intensity. The control included pine forests which had not experienced fires (80-100 years). All areas are similar, average diameter and height of the stems were 25–30 cm and 17–20 m, respectively. Because of the thick bark at the base of the trunks, fire did not have an impact on tree canopies. The mapping of the canopies showed that the fires in this area were the same as the unburned control area and reached 8000 m^2 per 1 ha.

The surface of all sites is flat with a small number of rises 30–40 cm high and potholes of the same depth. Moss, *Pleurozium schreberi* (Brid.) Mitt. with lichens *Cladina rangiferina* (L.) Nyl. and *Cl. alpestris* (L.) Rabenh., dominate in the ground cover. The soil is homogeneous, represented by sandy podzols on alluvial fine non calcic sand. The profile of the podzols is differentiated into horizons: O–E–BF1–BF2–BF2–C (Bezkorovaynaya et al. 2005). The forest floor is heterogeneous due to its transformation of its constituent material and contains small coals. All mineral horizons consist of fine sand with the distribution of clay by profile, which is typical of podzols. The minimum clay content is in the podzol horizon E (4.3%), and the maximum in the upper part of the illuvial-iron podzol BF1 (8.4%). The soil has low humus content (up to 0.5 %) and accessible forms of nutrients (5–10 mg/kg), as well as unsaturated bases and high acidity (pH_{KC1} less than 4). These indicators decrease markedly down the profile. The extremely low content of finely dispersed fractions results in a low absorption capacity of the podzol (4–5 m mol/100 g) which contributes to the rapid downward movement of soil formation products.

Methods

At each experimental site, at randomly selected points in moss and lichen plots, forest floor thickness and stock were measured. Forest floor samples were taken from a 25 cm × 25 cm area with a metal frame (n =10) overlaid onto the forest floor and above-ground parts of plants were cut with scissors. The forest floor was then cut with a knife along the inner edge of the frame; the thickness of the forest floor was measured along each of the four sides and the sample packed into a cloth bag. In the laboratory, the samples were dried at 90–100 ºC and weighed. Density was calculated by dividing mass by volume, the derivative of the frame area multiplied by thickness of the forest floor. The results were processed by standard methods of mathematical statistics.

Using the values of thickness and density of the forest floor, the areal stock was calculated according to:

$$M = 10000\, dy\, h \qquad (1)$$

where M – forest floor stock, g/m^2; dy– density of forest floor, g/cm^3; h – thickness of forest floor, cm.

Ash content of forest floor was calculated according to formula 2:

$$A = 100 - OM, \qquad (2)$$

where A is the ash content, % of absolutely dry mass; OM – content of organic matter, % of absolutely dry mass

The organic matter content of the forest floor was determined using the calcination method. A porcelain crucible was filled with chopped forest floor material and weighed, and calcined (oxidized) in a muffle furnace at 800ºC for 1 hour. The crucible was cooled in a desiccator with calcium chloride and weighed again. The organic matter content was calculated using formula 3.

$$OM = \frac{(m_1 - m_2) \times 100 \times \mathrm{C_{H2O}}}{m_1 - m_0} \qquad (3)$$

where OM – the content of organic matter, % of mass of dry sample; m_0 – mass of an empty crucible, g; m_1 – mass of a crucible with air-dry mass, g; m_2 – mass of a crucible with calcined sample, g; C_{H2O} – coefficient of soil hygroscopy.

The hygroscopic factor was determined by the thermal balance method using a glass weighing bottle filled with a crushed sample of air-dry forest floor material and weighed. The bottle was dried to a constant weight at 105 ºC, cooled in a desiccator with calcium chloride and weighed again. The hygroscopic moisture content of the sample (formula 4) and the coefficient of the forest floor hygroscopy (formula 5) were then calculated:

$$W_H = \frac{(m_1 - m_2) \cdot 100}{m_2 - m_0} \qquad (5)$$

where W_h is the hygroscopic moisture content (weight), % of the dry sample mass; m_0 the mass of an empty weighing bottle, g, m_1 the mass of a bottle with an air-dry sample, g; and m_2 is the mass of a bottle with a dry sample, g.

$$\mathrm{C_{H20}} = \frac{100 + W_h}{100} \qquad (6)$$

where C_{H2O} – coefficient of hygroscopy; W_h – hygroscopic moisture content (weight), % of dry sample mass

An M-69 mobile albedometer was used to calculate the albedo in relation to the forest floor thickness on experimental sites.

The soil temperature was measured with a mobile soil thermometer in lichen and moss plots at noon on the surface of the forest floor, in the middle part of the litter and in the mineral layers at depths of 5, 10, 15, 20, and 30 cm. In total, 10 measurements were made in each plot. All measurements were made in the first half of August.

To measure the surface temperatures of the forest floor, maximum and minimum thermometers were used; they were and set at a distance of 5‒6 cm from each other from west to east. The minimum thermometers were placed horizontally on the surface, while the maximum thermometers were placed with a slight inclination.

For each variable, the average value ± SE was calculated. Comparison of the main forest floor characteristics and temperatures in moss and lichen plots in the control and post-fire areas was carried out using t-value Student test. The confidence probability was $P = 0.95$.

Results

In forest ecosystems, the temperature of the active soil layer is directly related to the extent of development of the thermo-insulating moss-lichen cover and the thickness of the forest floor (Sharrow and Wright 1977; Prokushkin et al. 2002; Ponomarev et al. 2019). The non-uniformity of the typical soil cover of the pine forests of this area (Kovaleva and Ivanova 2013) is responsible for the differences in the reserves and forest floor density of moss and lichen plots. In the control area, lichen plots have higher density (0.083 g m^{-3}), reserves (4150 g m^{-2}) and ash content (23.4%) (Table 1). However, the differences in these indicators with moss plots are not reliable (P = 0.6).

Table 1 Post-fire transformation of basic forest floor parameters with different plots in lichen –moss pine forests a year after the fire (mean±SE)

Years after the fire	Density, g/m^3	P	Areal stock, g/m^2	P	Ash content, %	P
Control group (pine forests with lichen and moss plots)						
Moss plot	0.072±0.010	0.59	3530±771	0.42	19.2±3.5	0.56
Lichen plot	0.083±0.009		4150±800		23.4±4.1	
One year after the fire						
Moss plot	0.082±0.007	0.95	2870±565	0.94	48.6±4.9	0.44
Lichen plot	0.101±0.007		3590±590		44.3±5.4	

The same holds true for most post-fire parameters of the forest floor one year after the fire. Thus, their analysis revealed a fall in stocks, as well as an upsurge in ash content and litter density in both plots (Table 1), yet reliable differences (P = 0.95) can be found only in litter density. This stems from the specificity of combustion in lichen plot, as a result of which the forest floor "contracts", which significantly increases its density (Table 1). In addition, compaction of the forest floor after running ground fires is caused by burning of the topmost and loosest layer, and also by essential increase in ash content.

The thickness of the forest floor and its density is of particular importance in the processes of heat exchange between the soil surface and mineral layers. In the control area, the average thickness is 3.9 cm for lichen and moss plots. Following combustion, part of the forest floor loses its thickness by more than a third in the first two years after the fire, but by eight years after, it approaches its original thickness (Fig. 1).

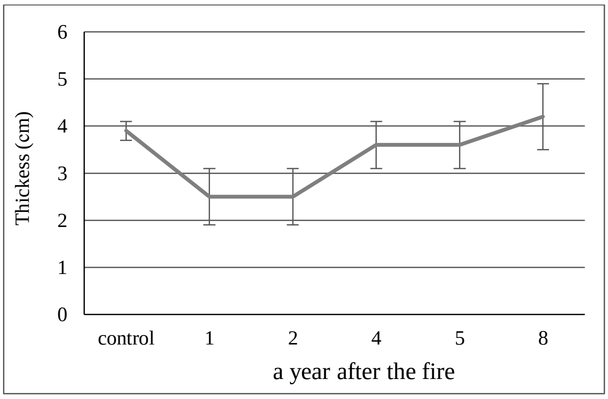

Fig. 1 Dynamics of forest floor thickess in lichen and moss pine forests in the post-fire period (average values of forest floor thickness are given due to the absence of reliable differences between the forest floor of moss and lichen plots).

Due to the pyrogenic transformation of the forest floor, which plays an important role in the heat exchange between the atmosphere and soil, the temperature conditions of the latter change noticeably.

It is first manifested in the contrast of the temperature range on the surface of the burned areas. On one hand, this derives from a significant reduction of albedo from 18%–20% to 10%–13%, and on the other, from more active heat radiation at night according to the Steffan-Boltzmann law. As a result, daily temperature fluctuations on the surface floor of the pine forests exposed to fires exceeded 40-50 ^{o}C on some days (with maximums of 44–55 ^{o}C, and minimums of 2.4–6.5 ^{o}C), while in the control area these indicators were 25–35 ^{o}C; 28–36 ^{o}C and 4.5–10 ^{o}C, respectively. Thus, surface temperatures of the burned areas show sharper contrast after the fire.

The analysis of post-fire temperature dynamics of the forest floor and upper mineral layer in the 5 cm layer measured in the first part of August showed that, within the first years after the ground fire, there was an average temperature increase by 1.5–2 ^{o}C (Fig. 2). A year after the fire, higher surface temperatures coupled with an increase in thermal conductivity of the forest floor add to greater heating of the mineral layer. As a result of these changes, one year after the fire, the average temperature difference of the upper 30-cm layer compared to the control does not exceed 2 ^{o}C. This difference gradually declines with depth (Fig. 3), and maybe explained by the influence of two factors: the first is an increase in albedo of the burned surface close to initial values caused by the restoration of the live ground cover and the abundant fall of post-fire needles; the second is an increase in the thickness of the forest floor which reduces of its thermal conductivity.

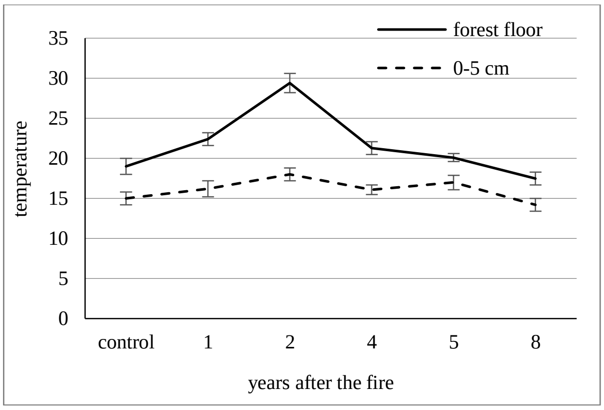

Fig. 2 Dynamics of soil temperature in the first years after the fire (measurements were made in the first part of August). Average temperatures for moss and lichen plots, n = 10

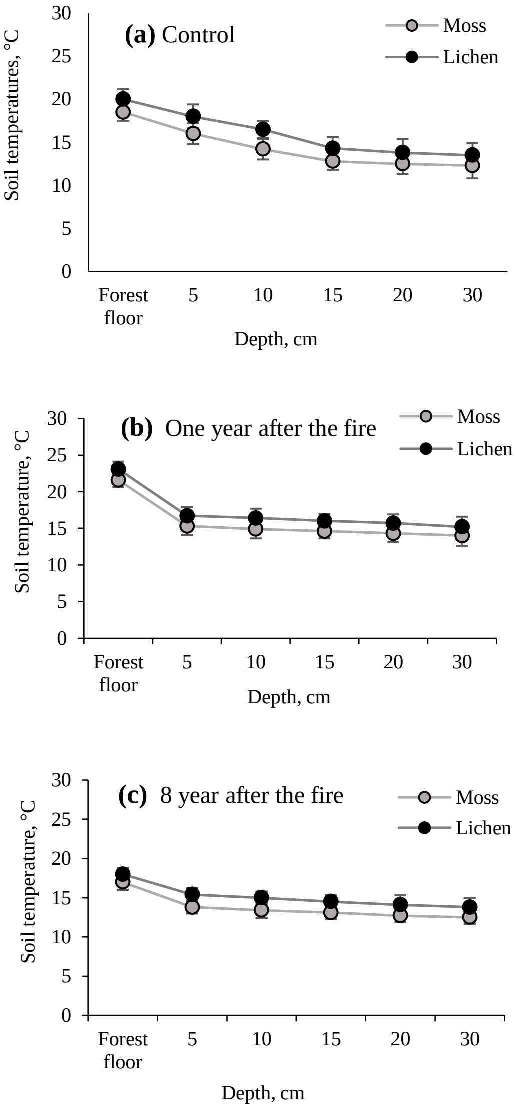

Fig. 3 Soil temperatures of various plots in the first decade of August, °C, n = 10

It can be assumed that, due to the high thermal conductivity of sand podzols (Gael and Smirnova 1999), their highest warming in a post-fire period can reach a depth of about 1-m. Such a depth was noticed in the research on increases in soil temperatures of burned areas in pine forests on sandy soils of the Transbaikalia and Altai regions (Evdokimenko 1979; Bekhovykh 2002).

Comparison of soil temperatures in moss and lichen plots has shown that lichens before and after the fire heat more, but the temperature differences between moss and lichen plots are not reliable ($P < 0.95$).

Eight years after the fire, due to the restoration of the live ground cover that shades the surface and to an increase in the forest floor thickness because of litter fall, temperature differences between the controls and burned areas have levelled out and account for tenths of a degree.

Other researchers have also pointed to a post-fire increase in soil temperatures (Sharrow and Wright 1977; Vermeire et al. 2005). The persistence of such a post-fire effect depends on the development and the speed of regeneration of vegetation cover and the forest floor and on the physical properties of soil. For example, in the first 12 years after a fire in the northern larch forests of Central Evenkia (Russia), temperatures in the forest floor and at a 10-cm depth of the mineral layer increased by 10–15 °C and only after 25 years did they correspond to pre-fire values (Prokushkin et al. 2002; Bezkorovaynaya et al. 2015).

Analysis of the data in this study revealed that forest floor temperatures are vaguely dependent on its thickness, while the influence of the thickness on temperatures of the mineral layers is more pronounced and increases with depth (Fig. 4).

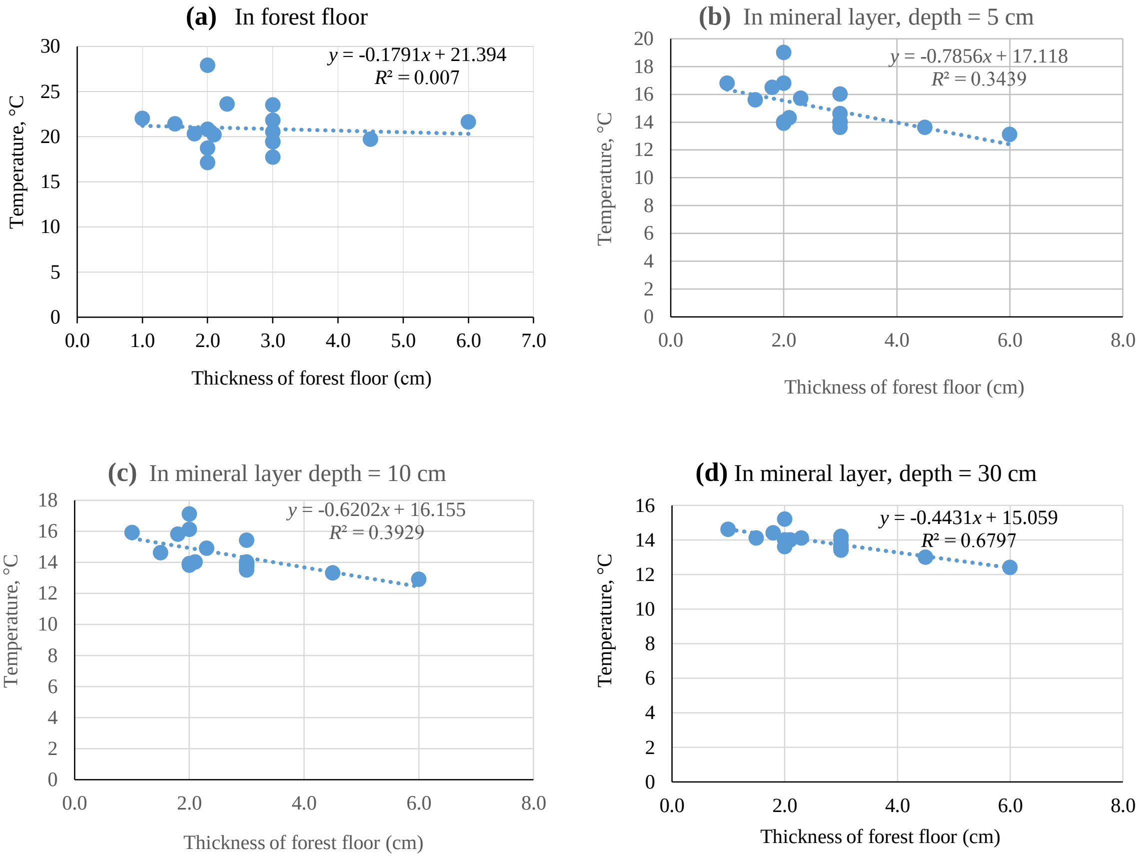

Fig. 4 Relationship of soil temperatures at different depths with forest floor thickness

Conclusion

Changes in the temperature regime of sandy podzols in pine forests exposed to ground fires are conditioned by pyrogenic transformation of the ground cover and forest floor, which exert a significant impact on the processes of heat exchange between the atmosphere and the mineral layers. These changes result in increased contrast of temperature conditions on the soil surface and greater heating of upper mineral layers.

This research has shown certain differences in soil temperature indicators for lichen and moss plots, which are different in their structure. To a considerable extent these differences are attributed to these biotopes determining the degree of pyrogenic impact on the forest floor, and on the living ground cover and their subsequent post-fire restoration.

Post-pyrogenic changes of temperature conditions in soils of lichen and moss pine forests cannot be estimated unequivocally. On the one hand, the sharpened contrast of temperature conditions of the surface of the burned areas makes their natural renewal more difficult, and on the other hand, better warming of the soil promotes the activation of many important physiological processes contributing to soil development.

The temperature regimes of sandy podzols in the middle pine forests change insignificantly after ground fires of low and medium intensity. Positive change in heat supply of the active soil layer is observed only within the first two years after the fire, and in eight years, it approaches its initial. Thus, the duration of post-fire influence on temperature conditions of sandy podzols under lichen and moss pine forests is regulated by the intensity of fire influence, which sets the extent of pyrogenic damage to the living ground cover and forest floor, and also determines the speed of restoration of these components.

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