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The Impact of Catastrophic Forest Fires of 2021 on the Light Soils in Central Yakutia

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Abstract: This paper presents the results of studying changes in the main parameters and properties of soils in larch and pine forests growing on sandy soils of the Lena-Vilyui interfluve of Central Yakutia, where catastrophic forest fires occurred in 2021. According to the remote monitoring information system of Rosleskhoz, in 2021, almost 8.5 million hectares of forests burned in Yakutia, which is considered as one of the largest forest fires in Russia and in the world in that year. After the fire passes through the forest floor, the content of organic matter decreases as a result of combustion processes. The acidity of the soil changes towards its alkalization due to the entry of combustion products. Changes in soil profiles occur; turbation processes begin more intensively, which in turn change the natural distribution of soil indicator values such as the organic carbon content, the pH, and the number of exchangeable bases. Due to the sharp increase in heat supply after a fire, the depth of seasonal thawing in the soils of burnt larch forests increases by a quarter and by twofold in pine forests. With the beginning of the thawing of the seasonally frozen layer, all the soils experience waterlogging, and ground water occurs above the permafrost.

Keywords: Central Yakutia; forest fire; permafrost; sandy soils

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1. Introduction

Climate change has become increasingly pronounced in recent decades. The average trend of the temperature increase for the territory of Russia during 1976–2020 has amounted to 0.51 °C for a decade (10 years), which is almost two times higher than the global average increase [1]. Climate warming and low precipitation, especially in the boreal forest zone, lead to unfavorable conditions for the growth and development of this biocenosis. The greatest vulnerability of Russian forestry is associated with forest fires. Despite the high interannual variability of fire impacts, one can note a tendency towards an increase in the number and area of forest fires in Russia [2,3]. Boreal forests are extremely vulnerable to forest fires due to the predominance of coniferous species. According to the remote monitoring information system of the Russian Federal Forest management Agency (Rosleskhoz), the area of forest fires in 2021 was the largest since the beginning of the 21st century and reached 18.2 million hectares [4,5]. Thus, since the beginning of the 21st century, based on satellite data, 2021 has become the most catastrophic year for Russian forests in terms of the area covered by fire over the entire observation period [5,6]. Almost 8.5 million hectares of forests burned on the territory of Yakutia in 2021 (Figure 1), which is considered to be one of the largest forest fires in the world in that year [5,6]. Such fires occur on the territory of Yakutia approximately once every 40 years [7–14]. On the territory of Central Yakutia, larch forests absolutely dominate (88%) in the composition of lands covered with forest vegetation, while pine forests which grow on the light soils occupy 3.5% of the area [13]. These dominating light coniferous forests in Yakutia are considered

one of the most fire-prone biomes in Northern Eurasia [7,13,15–18]. Due to the very slow decomposition of organic material in coniferous forests of the permafrost region, as a rule, a large amount of litter accumulates on the soil surface, representing a reserve of flammable matter [5].

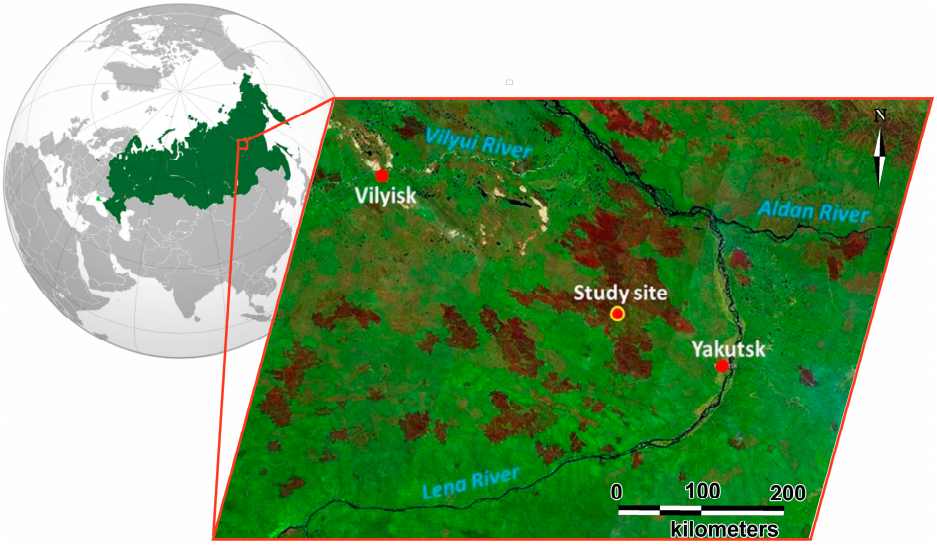


Figure 1. Forest fires on the territory of the Lena-Vilyui interfluve.

After fires, the partial or complete destruction of woody vegetation, grass cover, and forest litter occurs, which leads to a change in a number of physical conditions: organic carbon (C), insolation, and the associated heating and cooling of soils, which leads to sharp dynamics in moisture and temperature regimes [6,19–28]. In the permafrost area, the main result of post-fire changes is the increase in the active layer depth (ALD) due to an albedo decrease and an increase in soil thermal conductivity [26,27]. Also, there are significant changes after a fire in compaction, increased processes of organic matter mineralization, an increase in the amount of water-soluble compounds, a decrease in acidity, the decomposition of aluminosilicates, changes in the particle size distribution, an increase in eluviation-illuviation processes, and the formation of new forms of microrelief [28–34].

Poor knowledge of pyrogenic succession in permafrost zone forests is primarily due to poor transport accessibility, large distances, and the complexity and diversity of the landscape of burnt areas. This becomes the main reason for the beginning of systematic studies of post-fire succession. Sandy soils of Central Yakutia are characterized by a low thickness of the mineral-humus horizon; therefore, fires should have a significant and deeper impact on the mineral part of the soil profile. This paper presents the results of changes in the basic physical and chemical properties and hydrothermal regime of soils in larch and pine forests growing on the sandy soil forming sediments in the Lena-Vilyui interfluve, where catastrophic forest fires occurred in 2021 (Figure 1).

As a result of this study, it was established that post-pyrogenic changes in the individual components of burned ecosystems are multifactorial and depend on environmental components. The study of the processes of the post-fire restoration of forests in the center of the continental permafrost region has great theoretical importance as the basis for the development of forestry in conditions of the zone of continuous permafrost.

2. Materials and Methods

The study area is located in the central part of the Lena-Vilyui interfluve, 200 km west of Yakutsk city, on the Central Yakutian Plain and has an altitude of 300–400 m a.s.l. (Figure 1). The formation of relief is greatly influenced by the presence of continuous permafrost, where the depth of permafrost reaches 400–700 m [35]. The relief is rolling plain with shallow valley landscapes and alas depressions (thermokarst). The inter-alas

areas are uneven and composed of depressions and elevations, where light-coniferous taiga with *Larix cajanderi* and *Pinus sylvestris* predominates.

To study the impact of 2021 catastrophic fires on the soils, the control plots with two sites were established in the summer of 2022 within a 10 × 10 km square near the Asyma village, on the areas of pine and larch forests most affected by fire (Figure 2). At each forest, the monitoring sites were located on similar landscapes according to the following scheme: 1. **larch.cont**—in a larch forest untouched by fire, 2. **larch.pyr**—burnt area affected by a ground fire in the larch taiga, 3. **pine.cont**—unburnt control site in a pine forest with signs of old weak ground fire and 4. **pine.pyr**—pine forest burned out after a strong ground fire.

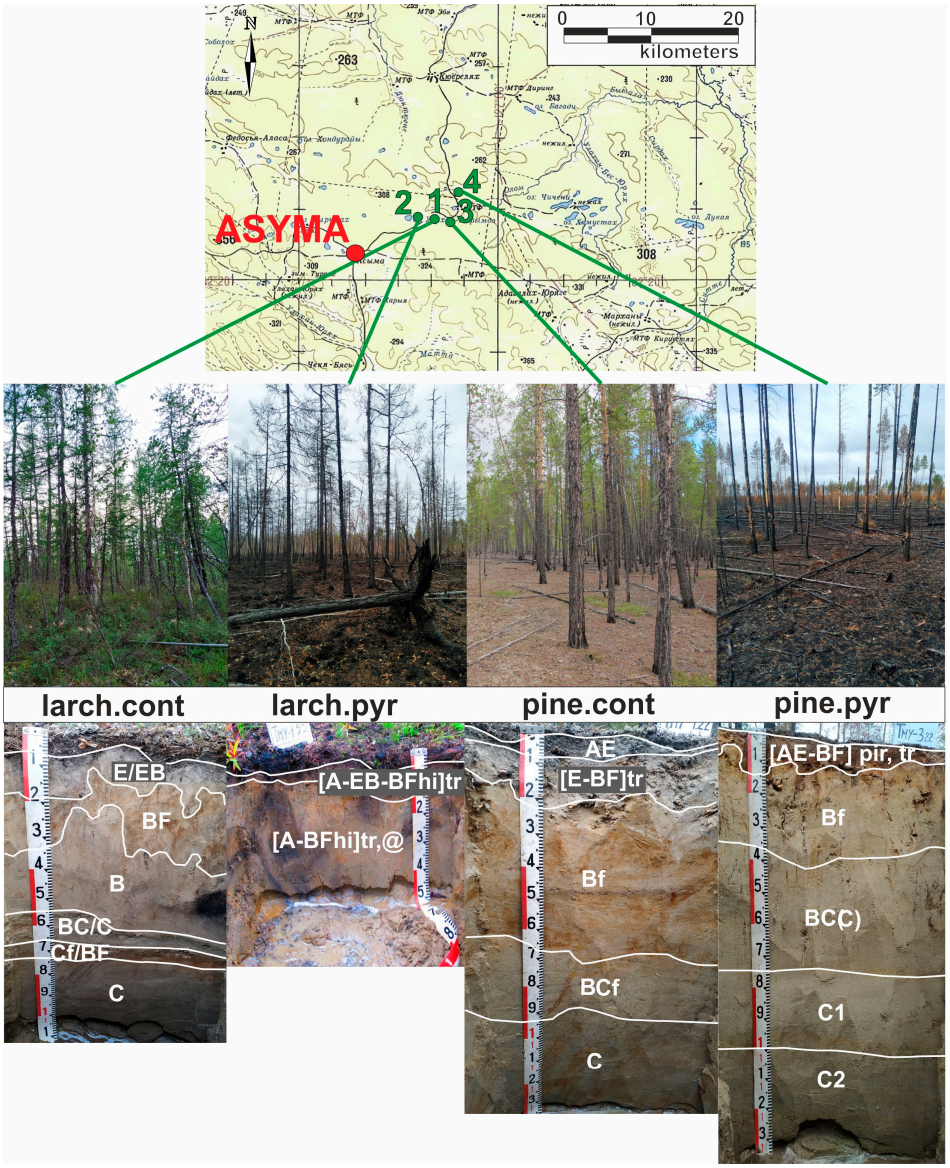


Figure 2. Location and general view of monitoring sites and soil horizons.

The soils of the studied area are formed on aeolian-alluvial sands. In natural conditions, the larch forest soil has a well-defined organic horizon with a small thickness. In the pine forest, the soil is characterized by the presence of a very thin organic horizon on the surface, consisting of litter and plant remains with a low degree of decomposition.

The main feature of the Lena-Vilyui interfluve central part climate is a sharp continentality, manifested in large annual temperature fluctuations and low precipitation. The mean annual air temperature for the period of instrumental observations at the Berdigestyakh

weather station (1944–2023) is −10.0 °C. The average monthly temperature in January is −38.8 °C, and that in July is +17.0 °C [36].

According to long-term data, the absolute minimum air temperature reached −64 °C, and the absolute maximum was +35 °C. The transition to positive daily temperatures occurs on 1–5 May, and the transition to negative temperatures occurs on 1–5 October. The duration of the period with air temperatures above +5 °C is 105–116 days, and the period with temperatures above +10 °C is 75–81 days (June–August). The average annual precipitation is 298 mm [36]. Stable snow cover forms at the end of September to the first half of October and finally disappears at the end of April to the beginning of May. The average snow depth in winter is 27 cm, and the number of days with snow cover is more than 200.

Since the late 1980s, there has been a positive deviation of the mean annual air temperature (MAAT) from the long-term average (Figure 3). The difference averages 1.2 °C over the past 30 years. The warmest years have been observed since 2017, reaching a maximum in 2020 (difference of 3.6 °C). During this period, the amount of annual precipitation was below the long-term average for four years (from 2017 to 2021), which led to the great drying and the fire risk of forests of the studied area (Figure 4). In the fire year of 2021, the temperature of the summer months was abnormally high (June–August) and was higher than the long-term average for 3.6, 2.3, and 3.2 °C, respectively.

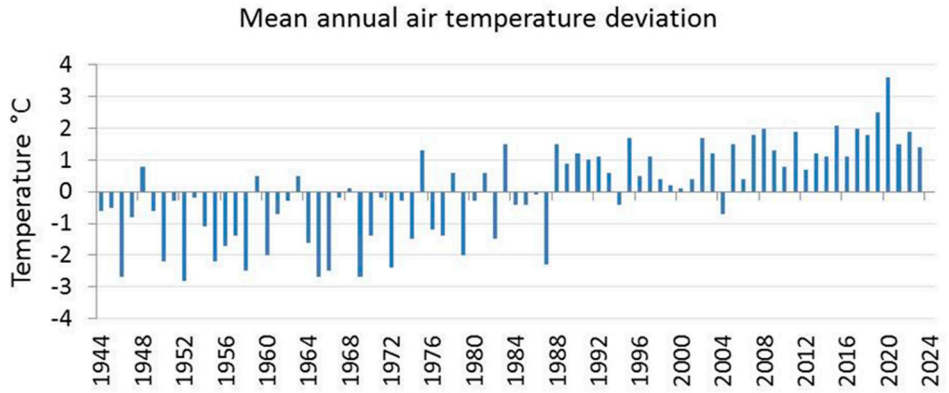


Figure 3. Deviation of the MAAT from the long-term average for the measurement period (1944–2023), Berdigestyakh weather station.

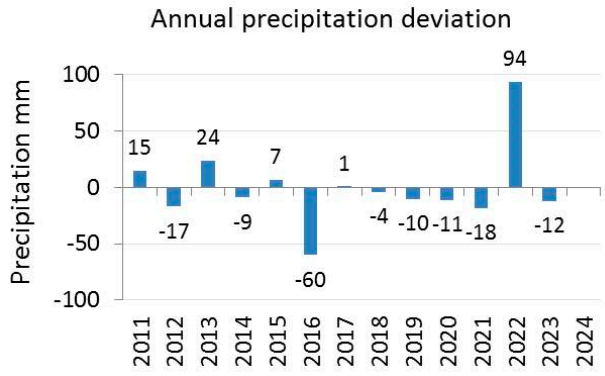


Figure 4. Difference in annual precipitation from the long-term average for the measurement period (2011–2023), Berdigestyakh weather station.

To study the soils hydrothermal regime, the temperature loggers were installed at each site, and field soil moisture was measured to the entire depth of the active layer at different terms. The soil temperature was measured using certified four-channel temperature loggers HOBO U12-008 (Onset Computer Corporation, Bourne, MA, USA), with the measurement interval being 3 h. In control and burnt larch forests, the temperature due to the shallow

thawing depth was measured at the depths of 20, 40, 60, and 100 cm. In the pine forest sites at the depths of 20, 40, 60, and 160 cm, soil moisture was measured three times during the warm period from the surface at a depth of 5 cm and then every 10 cm until the bottom of the active layer was reached using the gravimetric method.

The study of the physical and chemical properties of soils included the determination of the following: the pH, particle size distribution [37], organic carbon (Ignition method, %), exchangeable cations Ca^{2+} and Mg^{2+}, and hydrolytic acidity using the Kappen method [38]. Two forms of iron were determined in soils: amorphous, by the Tamm method, and non-silicate, by the Mehra-Jackson method [39].

To visualize and identify the degree of fire influence on the upper organic and lower mineral horizons of larch and pine forests soils, the main physicochemical indicators of the soil were statistically processed using correspondence analysis (CA) in the PAST 4.0 program [40,41].

Thus, the study of the soil parameters dynamics after the large forest fires were carried out on the dominant biocenoses of the region that were subject to catastrophic fires.

3. Results

In the first years after a fire that destroyed forest vegetation, there were visible morphological changes in permafrost soils, which are associated with the formation of a pyrogenic layer, which is noticeably different from analogous horizons in control sites, indicated by a decrease in the morphological manifestation of the albic layer and enhanced cryoturbation processes [42–44].

On the control site of the larch forests (**larch.cont**), the soil is represented by permafrost illuvial-ferruginous podzol (Albic Podzol (Arenic, Gelic)) and has the following profile structure: O (0–4 cm)–AO (4–5/10 cm)–E/EB (5/10–10/24 cm)–BF (10/24–24/36 cm)–B (24/36–42 cm)–BC/C (42–52/65 cm)–C/AE′ (52/65–67 cm)–Cf/BF′ (67–69/74 cm)–C (69/74–98 cm)–ground water. The soil profile contains buried soil of the same type. The microrelief is uneven and weakly polygonal-fissured. The thickness of the forest litter is small, rarely exceeding 2 cm. The degree of decomposition is very low; in the lower part under moss cover, it turns into a thin coarse humus or humus horizon. The transition boundary is sometimes quite difficult to discern due to the thinness of the organic layers (total thickness litter-humus horizon taking into account litter of 4 cm) (Figure 2).

The burnt area of 2021 (**larch.pyr**) in the wild rosemary-lingonberry larch forest was chosen as a site disturbed by fires. The litter burned out to its full thickness, affecting the upper part of the coarse humus horizon, and some charred fragments of plants retained their structure. The soil profile structure has a different horizon: Opir (0–1 cm)–AOpir (1–2/10 cm)–[A-EB-BFhi]tr (2/10–3/15 cm)–[A-BFhi] tr,@ (3/15–50 cm), and the underlying active layer is saturated with water. The soil type changes to illuvial-ferruginous post-pyrogenic cryoturbated podzol (pyrogenic Albic Podzol (Arenic, Gelic, Turbic)). As can be seen, the characteristic surface horizons of typical forest soils disappeared after the fire, and the pyrogenic layer mixed with the ash, under which lie cryoturbated, highly disturbed fragments of the mineral layers. The appearance of signs of post-fire cryoturbation in the upper part of the profile is enhanced in cryogenic and high-moisture conditions (Figure 2).

On the control site of pine forests (**pine.cont**), the soil is permafrost sandy slightly podzolized surface-turbated soil (Albic Arenosol (Gelic, Protospodic, Turbic)), which has the following morphological structure: O (0–1 cm)–AO (AOpir) (1–2/3 cm)–AEphragm (2/3–4/8 cm)–[E-BF]tr (4/8–15/24 cm)–Bf (15/24–62/68 cm)–BCf (62/68–95 cm)–C (95–135 cm). The litter and organic horizon contain pyrogenic remnants (3–4 year-old fire that did not destroy the forest) in the form of charcoal inclusions and horizon thickness thinning after the fire. The lightened horizon with albic material is fragmentary and slightly mixed with the spodic horizon due to the past fires. The soil-forming material is represented by light beige aeolian-alluvial-layered sandy deposits (Figure 2).

Burnt pine forests soil (**pine.pyr**) has the following structure: Opir (0–1 cm)–AOpir (1–2 cm)–[AE-BF]pir,tr (2–9/14 cm)–Bf (9/14–34/42 cm)–BC(C) (34/42–75 cm)–C1

(75–100 cm)–C2 (100–130 cm). After the fire, the upper organic horizon was severely damaged. Due to its initial thinness, it is now fragmentary and intermittent. There have also been noticeable transformations in the soil surface mineral layer, apparently due to the oxidation and crystallization of iron due to high temperatures; albic material is practically not visible—the upper 9–14 cm of the soil has a light brick color. The soil can be classified as slightly podzolized post-pyrogenic permafrost sandy soil (pyrogenic Arenosol (Gelic, Protospodic, Turbic)) (Figure 2).

Soil pH. In the upper horizons of post-fire soils, an increase in pH is observed. The pH in the pyrogenic layer of **larch.pyr** is 5.84 (slightly acidic), which is higher than in the organic horizon of **larch.cont**—4.64 (medium acidic) (Table 1). The same trend is not observed in mineral horizons. In the **pine.pyr**, the pH of the pyrogenic layer reaches 6.06 (slightly acidic); below, in the ferruginous layer, it is moderately acidic (4.88); and lower, in the mineral part, there is a gradual increase in acidity (from 4.63 to 5.34). Here, as well as in larch forests, in the upper fire-affected horizon, a process of acidity reduction is observed due to the alkalization of the organic material with combustion residues.

Table 1. Physical and chemical properties of soils.

Horizon	Depth, cm	pH	$C_{org.}$ %	Cations mmol/100 g		Hydrolythic Acidity, mmol/100 g	CEC, %	Sum of Salts, %
				Ca^{2+}	Mg^{2+}			
larch.cont—Albic Podzol (Arenic. Gelic)								
O	0–4		87.10					
AO	4–5	4.64	29.21 *	-	-	20.00	-	0.267
E/EB	5 (10)–10 (24)	4.68	0.30	1.10	0.50	1.37	53.87	0.025
BF	10 (24)–24 (36)	5.09	0.15	1.20	0.60	1.18	60.40	0.015
B	24 (36)–42	5.17	0.10	0.95	0.45	0.80	63.64	0.015
BC/C	42–52 (65)	5.32	0.08	0.70	0.40	0.66	62.50	-
	org. interlayer.	5.22	2.35	6.65	2.15	4.71	65.14	-
C/AE′	52 (65)–67	5.45	0.29	3.80	1.85	1.53	78.69	-
Cf/BF	67–69 (74)	5.65	0.10	1.50	0.70	0.80	73.33	-
C	69 (74)–98	5.96	0.07	1.25	0.55	0.61	74.69	-
larch.pyr—pyrogenic Albic Podzol (Arenic. Gelic. Turbic)								
Opir	0–1pir		67.10 *					
AOpir	1–2 (10) pir	5.84	33.52 *	-	-	45.90	-	0.156
[A-EB-BFhi]tr	2 (10)–3 (15) dark spots	4.29	2.51	1.80	0.85	3.69	41.80	0.069
	2 (10)–3 (15) light spots	4.25	1.25	2.20	0.95	5.73	35.47	0.032
[A-BFhi]tr.@	3 (15)–50 dark spots	4.98	3.36	4.00	1.95	10.30	36.62	0.034
	3 (15)–50 light spots	4.19	0.08	0.85	0.40	0.83	60.10	0.015
pine.cont—Albic Arenosol (Gelic. Protospodic. Turbic)								
O	0–1		91.70 *					
AO (AOpir)	1–2 (3)	4.53	17.56 *	2.70	0.65	7.11	32.03	0.022
AE	2 (3)–4 (8)	4.94	1.71	2.15	0.35	3.63	40.78	0.017
[E-BF]tr	4 (8)–15 (24)	4.70	0.45	0.65	0.30	2.16	30.55	0.013
Bf	15 (24)–62 (68)	5.04	0.08	0.73	0.47	1.01	54.30	0.008
BCf	62 (68)–95	5.44	0.06	1.05	0.45	0.61	71.09	-
C	95–135	5.62	0.06	1.50	0.55	0.70	74.55	-
pine.pyr—pyrogenic Arenosol (Gelic. Protospodic. Turbic)								
Opir	0–1pir		81.65 *					
AOpir	1–2pir	6.06	53.14 *	-	-	-	-	0.209
[AE-BF] pir.tr	2–9 (14)	4.88	1.01	1.00	0.45	2.07	41.19	0.022
Bf	9 (14)–34 (42)	4.63	0.11	0.35	0.18	0.85	38.41	0.013
BC (C)	34 (42)–75	4.80	0.06	0.93	0.27	0.75	61.54	0.008
C1	75–100	5.26	0.03	0.60	0.25	0.44	65.89	-
C2	100–130	5.34	0.03	0.58	0.27	0.43	66.41	-

* Ignition loss.

Soil organic carbon. In both the pine and larch forests, the C content in the litter horizons (O) decreases after fire from 87.10% to 67.10% and from 91.70% to 81.65%, respectively. In coarse humus horizons, located in a thin layer under the litter, the content of organic matter varies greatly due to the thinness and the degrees of mixing with mineral particles (Table 1).

The mineral horizons of the **larch.pyr** soil profile are characterized by an uneven distribution of organic C along the profile due to turbation processes (Figure 2). Thus, in the [A-EB-BFhi]tr horizon, the C ranges from 1.25 to 2.51% in different-colored spots. In the lower horizon, the range of the organic C content is wider: from 0.08% (in light) to 3.36% (in dark). At a depth of approximately 50 cm, the C contents in both **larch.cont** and **larch.pyr** become the same. The organic C content in the mineral horizons of the whole soil profile of **larch.cont** is characterized by a low content (<0.30%), which is typical for similar soils in the region in their natural state.

On the pine forests, the C content in the mineral horizons of the **pine.cont** exceeds in the **pine.pyr**. The maximum values in the profiles are small: 1.71% in the **pine.cont** upper mineral horizon (AE) and 1.01% in the upper horizon ([AE-BF] pir, tr) of **pine.pyr**.

Cations exchange capacity. The values of exchangeable cations in the upper horizons in the larch forest increased after the fire. The number of calcium and magnesium cations slightly increased in the upper 50 cm. In the pine forests, on the contrary, the values of the cations generally decrease after a fire (Table 1).

Soil granulometric composition. After the fire, the granulometric composition undergoes changes; in particular, there is an increase in the number of the largest fractions (1–0.25 mm). This trend is clearly visible in the upper mineral horizons, which are most susceptible to the temperature effects of fires. Thus, in the **larch.cont** mineral horizons E/EB (5–10 cm) and BF (10–24 cm), the amount of this fraction is 52.5% and 59.3%, respectively. After the fire, at the same depth, the percentage of particles in the [A-EB-BFhi]tr horizon (2 (10)–3 (15) cm) increased to 61.38% (dark spots) and 60.3% (light spots). In the **pine.cont** AE (2–4 cm) and [E-BF]tr (4–15 cm) horizons, the amount of the same fractions is 56.9% and 69.%. In the **pine.pyr**, the proportion of 1–0.25 mm fractions in the [AE-BF] pir,tr horizon (2–9 cm) is increased to 74.8%, and in horizon Bf (9–34 cm), it is increased to 72.9% (Table 2).

Table 2. Granulometric composition of soils.

Horizon	Depth, cm	Moisture, %	Bulk Density, g/cm^3	Particle Size (%) mm						Sum of Particles <0.01, mm
				1–0.25	0.25–0.05	0.05–0.01	0.01–0.005	0.005–0.001	<0.001	
larch.cont—Albic Podzol (Arenic. Gelic)										
E/EB	5–10	0.27	1.77	52.5	39.1	3.3	0.8	0.4	3.9	5.1
BF	10–24	0.20	1.75	59.3	32.1	3.9	0.6	1.2	2.9	4.7
B	24–42	0.07	2.34	55.8	35.2	1.9	1.0	3.0	3.1	7.1
BC/C	42–52	0.13	1.79	55.7	39.6	0.8	0.2	0.4	3.3	3.9
C/AE′	52–67	0.73	2.32	30.7	57.7	1.5	2.2	1.8	6.1	10.1
Cf/BF	67–69	0.32	2.18	58.1	34.9	1.0	1.2	4.5	0.3	6.0
C	69–98	0.21	2.33	64.3	31.6	0.2	1.5	0.4	2.0	3.9
	org. interlayer	0.22	-	41.5	45.6	2.5	1.0	3.0	6.4	10.4
larch.pyr—pyrogenic Albic Podzol (Arenic. Gelic. Turbic)										
[A-EB-BFhi]tr	2 (10)–3 (15) dark spots	1.10	2.65	61.8	31.5	0.2	1.0	0.8	4.7	6.5
	2 (10)–3 (15) light spots	0.13	1.86	60.3	35.0	0.2	0.8	0.4	3.3	4.5
[A-BFhi]tr.@	3 (15)–50 dark spots	1.25	2.04	54.2	33.0	0.8	2.1	1.8	8.1	12.0
	3 (15)–50 light spots	0.42	1.80	69.0	27.2	0.7	0.4	0.2	2.5	3.1
pine.cont—Albic Arenosol (Gelic. Protospodic. Turbic)										
AE	2–4	0.30	1.98	56.9	35.6	1.6	0.4	2.0	3.5	5.9
[E-BF]tr	4–15	0.20	1.71	69.0	23.7	1.4	0.6	1.8	3.5	5.9
Bf	15–62	0.20	1.91	64.8	29.7	1.2	0.6	0.4	3.3	4.3
BCf	62–95	0.20	1.85	64.7	30.9	0.6	1.5	1.4	0.9	3.8
C	95–135	0.20	2.50	61.0	32.3	2.4	0.6	0.6	3.1	4.3
pine.pyr—pyrogenic Arenosol (Gelic. Protospodic. Turbic)										
[AE-BF] pir.tr	2–9	0.28	1.79	74.8	19.5	1.6	0.4	0.4	3.3	4.1
Bf	9–34	0.14	1.80	72.9	19.1	1.0	3.6	1.1	2.3	7.0
BC (C)	34–75	0.20	1.70	65.5	29.2	0.4	0.4	0.8	3.7	4.9
C1	75–100	0.20	1.85	71.2	19.8	1.5	3.6	0.6	3.3	7.5
C2	100–130	0.07	2.46	67.9	22.7	1.9	3.2	1.4	2.9	7.5

Soil temperature. Forest fires on the light soils have a long-term impact on the hydrothermal regime of the active layer and upper permafrost. In the first year after the fire, the temperature of the burned sites at both forests changed significantly. At the end of January on the 20 cm depth of **larch.cont** soil, the minimum temperature was −4.43 °C, and on the **larch.pyr**, it was colder, at −6.02 °C (Figure 5). At the same date, the lowest temperature at the 40 cm depth was observed on the **larch.pyr** (−5.14 °C). In the **larch.cont**, there was a significant delay, and the minimum temperature was reached only on February 12 (−3.66 °C). At the depths of 60 cm and 100 cm, the soil temperature reached its minimum simultaneously at both monitoring sites in mid-February: in the **larch.cont** at the depth of 60 cm, on February 13 (−2.92 °C), and at 100 cm, on February 14 (−1.61 °C). On the **larch.pyr** in the 60 cm layer, it was reached on February 12 (−4.14 °C), and in the 100 cm layer, it was reached on February 13 (−2.61 °C) (Figure 5). The difference in minimum soil temperatures between burnt and control larch forests decreased from 1.59 °C (20 cm) to 1 °C (100 cm), which indicates that the influence of fires gradually weakens with the soil depth (Figure 6).

The temperature at the depths of 20 and 40 cm in **larch.cont** and **larch.pyr** reached its maximum on July 2 and 3, respectively. In the **larch.cont**, the temperature at the depth of 20 cm is 10.05 °C, and at 40 cm, it is 7.34 °C. In the **larch.pyr**, it is 14.20 °C at a 20 cm depth and 11.22 °C at a 40 cm depth. As the depth increases, the date of soil warming to the maximum differs greatly. At the 60 cm depth of the **larch.cont**, it reached 5.44 °C (3–4 July), and at the 100 cm depth, it reached 2.49 °C (27 July). In **larch.pyr**, soil warming was higher and reached a maximum of 9.12 °C (26 July) and 7.19 °C (22 August) at 60 cm and 100 cm depths, respectively (Figure 5). The difference in the maximum soil temperatures between the burnt and control larch showed a gradual decrease in the impact of fire with increasing depth, being 4.15, 3.88, and 3.68 °C for 20, 40, and 60 cm, respectively. But at a depth of 100 cm, the difference between the **larch.pyr** and **larch.cont** was 4.70 °C (Figure 6).

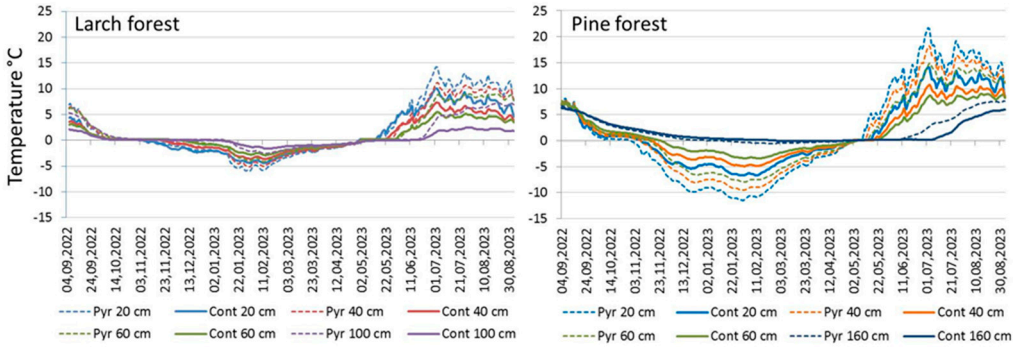


Figure 5. Soil temperature in the studied forest soils (dotted lines—burnt sites, solid lines—control sites).

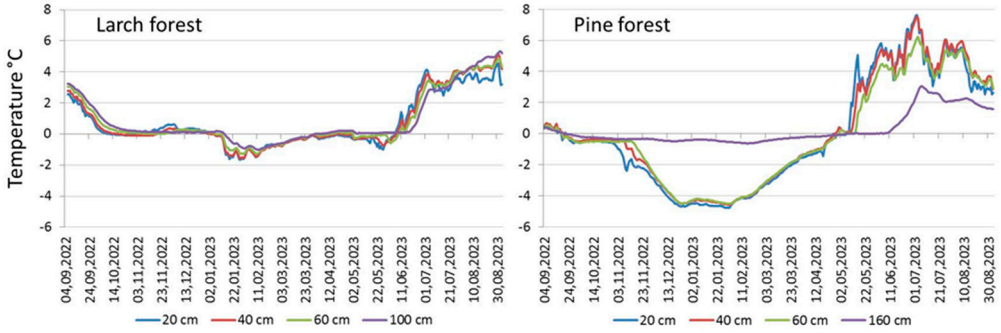


Figure 6. Temperature difference in soils of burnt and control forests.

In the **pine.cont** and **pine.pyr** the temperature amplitude is higher than in larch sites (Figure 5). At a depth of 20, 40, and 60 cm, the soil temperature in the **pine.pyr** reached its minimum almost on the same day (January 31–February 1): −11.51 °C,

−9.54 °C, and −7.93 °C, respectively. At 160 cm, the lowest temperatures were recorded on February 21–24 and were equal to only −0.54 °C. In the **pine.cont**, the minimum temperatures at a depth of 20 and 40 cm, as in the burnt forest, were recorded on January 31 (−6.72 °C) and February 1 (−4.96 °C). Deeper, at 60 cm, the minimum temperature of −3.45 °C was reached much later (February 13). At a depth of 160 cm, the minimum was on March 28. The difference between the minimum temperatures in the burnt and control pine forest was 4.79, 4.58, 4.48, and 0.44 °C for 20, 40, 60, and 160 cm, respectively (Figure 6).

The maximum positive soil temperatures in the **pine.pyr** were recorded almost a month earlier than in the **pine.cont**. So, on the **pine.pyr**, on July 2, it was 21.69 °C (20 cm), on July 3, it was 18.27 °C (40 cm), on July 4, it was 14.91 °C (60 cm), and on August 3, it was 7.6 °C (160 cm). In the **pine.cont**, the temperatures were relatively lower and reached the annual maximum later—from August 5 to August 24 (Figure 5). The difference between the maximum temperatures in both sites decreased with depth from 7.09 °C to 1.11 °C (Figure 6).

Soil moisture. In the first year after the fires (2022), significant increases in the soil moisture and active layer depth (ALD) were observed in both forests. The maximum thawing depth of **larch.cont** was 183 cm, but in the **larch.pyr**, the thawing depth reached 225 cm (Figure 7). At the same time, the lower horizons were completely saturated with water, forming groundwater, which in wintertime may not freeze at depths of 190–210 cm and remain in a thawed state until the next year. In Figure 7, the soil moisture down to the groundwater table is shown. The moisture in the **larch.cont** in the spring reached up to 40%, while in the **larch.pyr**, it was only 15–25% in the upper 20 cm of the soil. In August, the moisture of **larch.pyr** increased significantly (20–30%) compared to 5–10% in the **larch.cont**. In autumn, before freezing, the moisture of the **larch.pyr** also remained high and increased by 30% at both sites in the lower part of the profile. In the first year after the fire, there was a significant difference in soil moisture between the burned and control sites.

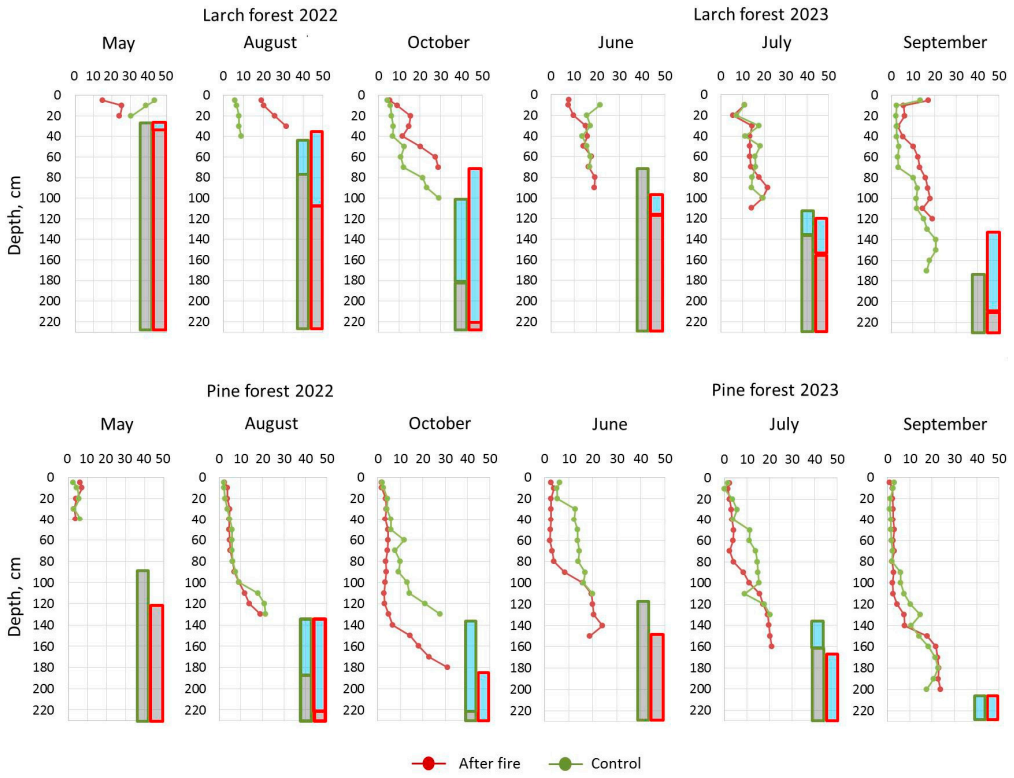


Figure 7. Soil moisture (in %) after the fire in larch and pine forests in 2022–2023. The columns show the depth of soil thawing and the groundwater level: gray column—permafrost, blue column—groundwater. The colors of the columns' perimeters indicate control (green) and burnt (red) sites.

In the second post-fire year, in the **larch.cont**, there was a decrease in ALD soil thawing to 170 cm. In June, the soil moisture in the upper part of the **larch.cont** profile reached up to 20%, while in the **larch.pyr**, it was lower (7–10%) due to evaporation. Below 30 cm, the moisture of both sites was comparable and amounted to about 14–20%. In July, the moisture of all soil profiles dried out equally. In September, due to precipitation, there was a synchronous increase in the moisture of the upper 10 cm horizon up to 12–18%. Below, in the mineral part, the moisture of the **larch.pyr** was higher than that of the **larch.cont** for 5–10% (Figure 7).

In pine forests, the soil moisture was generally lower than in larch forests. In the first year after the fire on both **pine.pyr** and **pine.cont**, almost the same level of moisture (3–7%) was observed in the upper part of the profile. In August, a similar pattern was observed, but in the **pine.cont**, below 1 m, the moisture increased to 20%. Before freezing in October, due to the low water holding capacity of sand, the upper 140 cm part of the **pine.pyr** was practically dried out (2–6%). On the **pine.cont**, 50 cm deep, drying was also observed, but in the deeper layer, the moisture slightly increased (8–10%); above the groundwater level, the moisture reached 28–32%. In the second post-fire year, the **pine.cont** had noticeably high soil moisture; in June from 30 cm and in August from 50 cm, the moisture increased up to 15–20%. At the same time, in the upper 70–80 cm horizon of **pine.pyr**, the soil moisture was only 1–3%. Above the permafrost and groundwater, the moisture increased up to 20%. In autumn, in the upper part of the profile (up to 100 cm), the soil moisture decreased to the minimum, remaining high only in the lower part (18–23%) (Figure 7).

Active layer depth and groundwater level. The thawing depth of the light soils is especially susceptible to the effects of fires. After a forest fire, due to the destruction of the vegetation and organic layer, albedo decreases and there is an increase in the insolation and thermal conductivity of soils [26,45]. The melting of the upper permafrost layers leads to an increase of supra-permafrost waters in soils and changes the water regime of post-fire and adjacent areas.

The ALD of **pine.cont** was 220 cm by the autumn of 2022 and deepened to 300 cm in the second post-fire year (2023). In burnt areas, the ALD probably reached more than 350–400 cm in the autumn. In Figure 7, the columns show the thawing depth and groundwater levels. In pine forests, the groundwater level is lower than in larch forests. In 2022 mid-summer, the **pine.cont** and **pine.pyr** groundwater levels were the same, despite the difference in ALD. But in autumn, due to an increase in the thawing depth and insufficient initial soil moisture, the groundwater level in the **pine.pyr** decreased significantly. In autumn 2023, in the **pine.pyr**, an increase in ALD is observed, which entails a decrease in the groundwater level below the level of 2022 (Figure 7). Thus, if the soil has thawed up to 400–500 cm, then all the moisture, due to the low holding capacity of the sandy soil, moves down to the surface of permafrost.

In 2022, the maximum ALD in **larch.cont** reached 180 cm, while the **larch.pyr** increased up to 230 cm. In 2023, there was a slight decrease in ALD up to 170 and 210 cm in both **larch.cont** and **larch.pyr**, respectively. It can be seen that in **larch.pyr**, there was an increased level of groundwater due to the thawing of moisture preserved in the permafrost. At the beginning of soil thawing in May 2022–June 2023, waterlogging was not observed in the soils of the **larch.cont**. In the first year after the fire (2022), the groundwater in **larch.pyr** was higher than in 2023. In the **larch.cont**, the supra-permafrost groundwater disappeared in September 2023, while in the **larch.pyr**, water was present from the depth of 130 cm, reaching 210 cm.

4. Discussion

In the studied types of forests, an increase in the pH after the fire in the organic horizon occurs (Table 1), which is noted in the works of many researchers [5,32,46]. The main reason for the acidity decrease in the upper part of post-fire soils is the formation of ash, which neutralizes organic acids. Similar data were obtained in the territory of the Amur region

in brown taiga podzols under larch forests, in the Nadym region of the Yamal-Nenets Autonomous Okrug in sandy podzols, in the soils of the Primorsky Range, etc. [47–53].

After a fire on the forest floor, regardless of its type, the content of organic matter decreases as a result of combustion processes [52–55]. Ignition loss in **larch.pyr** soil decreased by 22%, and in the **pine.pyr**, it decreased by 11%. The effect of fire on the organic C content in the underlying mineral horizons, due to the short fire affect time, is practically absent. Relatively high values of organic C in post-fire larch are associated with cryoturbation processes. As a result, organic C penetrates from the overlying organic horizon [56]. As for the post-fire pine forest, the relatively lower values of organic C content in the mineral horizons are associated with the initial weak development of the soils of this forest.

In both studied forests, after the fire, an increase in the proportion of large particles (1–0.25 mm) is observed, which, according to some researchers, is due to the processes of the cementation and adhesion of aggregates after the exposure to fire, but this does not exclude the initial heterogeneity of the granulometric composition at the monitoring sites under consideration [57–59]. The absence of significant changes in other indicators is due to the short period of soil functioning in post-fire conditions (the first year after a large forest fire).

To compare the main physicochemical properties and analyze the similarity of the studied soils, a Scatter plot of correspondence analysis was performed (Figure 8).

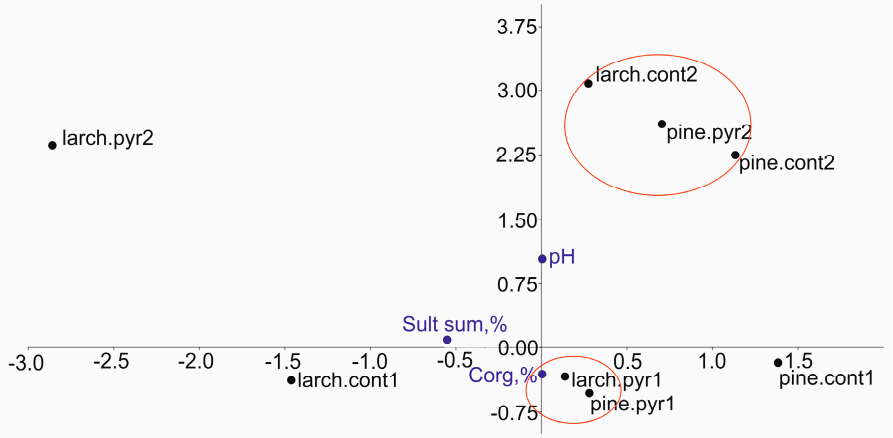


Figure 8. Scatter plot of correspondence analysis of soil properties. Indicators: pH—acidity; Salt sum—sum of salts, %; Corg—organic carbon, %. Sample groups: **larch.cont**—soil under an untouched larch forest; **larch.pyr**—soil under burnt larch forest; **pine.cont**—soil under untouched pine forest; **pine.pyr**—soil under pine burnt forest. The numbers next to the sample groups indicate the location of the sample in the profile: 1—organic horizon, 2—upper part of the mineral layer.

In Figure 8, two slightly separated but quite distinct groups can be distinguished. The first group is the upper pyrogenic layers, similar in pH and C content, the second group is the mineral layers in the **larch.cont**, **pine.cont**, and **pine.pyr**, the similarity of which indicates a weak transformation of the determined properties of the mineral part of soil in the first year after the fire in pine forests. The difference in the properties of the upper part of the **larch.pyr** mineral layers is associated with the movement of combustion products fragments and organic matter into the underlying layers due to cryoturbation and cryogenic processes that intensified after the fire under conditions of high humidity [56]. That is, in larch forests, the influence of fire on the mineral layer is greater than in pine forests.

Thus, the sandy soils of Central Yakutia are characterized by the absence of a mineral humus horizon; the organic horizon is represented by litter, with an underlying coarse humus layer with a total thickness of up to 5 cm. As a result of a fire, such thin litter and soil humus burn out completely or partially. So, there occurs the death of the soil biota of the upper horizons and of the specific pyrogenic layer, the shielding properties of which are much lower. The acidity of the soil changes towards its alkalization due to the entry

of combustion products such as ash. In the soil profile under burnt larch, the turbation processes begin to manifest themselves more intensely, which in turn change the natural distribution of soil indicator values along the profile (organic carbon content, pH, sum of exchangeable bases).

The soil temperature in continental climate differs sharply from the temperatures of other climatic zones. In more temperate latitudes, the prevailing view is that in winter, the destruction of the forest canopy after a fire leads to a decrease in snow interception, and more snow is accumulated on the ground surface, increasing the isolating effect, which leads to more heat being kept in the soil [45,60]. On the contrary, in a continental climate with low winter precipitation, a strong cooling of the soil occurs. So, the soils of the pine forest are cooled more than the soils of larch forests, with a difference of up to 5 °C. According to Andréassian [61], Chang [62], and Szczypta [63], unburned areas have more interception of snow by branches and tree crowns, reducing the isolation effect on the surface, thereby cooling the active layer and permafrost. But this statement, in our case, is not so relevant, since soil cooling in winter largely depends on the type of forest and surface vegetation. This is clearly visible in Figures 6 and 7, which show the range of temperatures and thawing depths. Also, low air exchange in unburnt forests plays a certain role in preventing heat loss from the soil [45,64].

Thawing depth and soil temperature are directly related to the thickness of the organic layer [65]. This is due to the fact that organic litter has a low bulk density and lower thermal conductivity and effectively isolates the mineral part of the soil.

After a year, the effect of fire on the ALD increases [45]. In our sites, in the same way, there is a significant increase in ALD and a rise in the groundwater level in comparison with control soils. The difference in ALD between burnt and control areas amounts up to 40–70 cm. According to literature data, in more favorable climate conditions of western Siberia, the average temperature difference of the upper 30 cm layer of the burnt area compared to the control site does not exceed 2 °C, while in the conditions of Central Yakutia, the difference reaches more than 4 °C [34]. Also, generally in post-pyrogenic forests, the amplitude of daily soil temperature fluctuations is higher than under an undisturbed tree stand [66]. During the second post-fire year, a lot of litter from dead trees is accumulated on the soil surface. This must lead to an increase in the albedo of the burned surface close to the initial values; at the same time, there is an increase in the litter thickness, which reduces its thermal conductivity [34]. Due to the high thermal conductivity of sandy podzols, it was measured that the penetration of temperature changes in the post-fire period can reach a depth of about 1 m. Such depth was noticed when studying the increase in the temperature of burnt soils in pine forests on sandy soils of Transbaikalia and Altai [19,34,67–69]. In our pine sites, the penetration of post-fire temperature changes reaches up to 160 cm.

In general, in western Siberia, an increase in the heat supply of the active layer is observed only during the first two years after the fire, and after eight years, it approaches its original state [34]. Thus, the duration of the post-fire impact on the temperature regime of sandy podzols under lichen-moss pine forests is regulated by the intensity of the fire impact, which determines the degree of pyrogenic damage to living ground cover and forest litter [34]. Immediately after a fire, the darker soil surface of pine forests not only heats up more strongly during the day, but also radiates heat more actively at night [70]. This effect is enhanced by the lower thickness of the heat-insulating layer of the litter and the death of the tree stand, the crowns of which previously weakened the radiation of the soil [71]. This trend can be traced in many works from Mongolia, Altai, and the forests of the Stanovoy Range [19,71,72]. Thus, our work should be continued for at least 8–10 years to trace the changes in and restoration of post-fire forests.

Due to the destruction of the vegetation cover, forest litter, and organic horizon by fire, the depth of positive temperatures penetration increases significantly and, in the first post-fire year, leads to the waterlogging of soils due to the release of moisture preserved in permafrost. In the second year, there is a slow restoration of the soil moisture balance. In control larch forests, groundwater disappears; in pine forests, the groundwater level

decreases. The ALD in burnt areas remains high, and severe drying of the upper part of the soil profile occurs. In non-permafrost areas, natural soil moisture remains only deeper than 1 m, but in permafrost areas, it is deeper than 1 m, and severe soil waterlogging occurs [69]. The main role in recovery after a fire is played by living vegetation and litter, which significantly reduce the physical evaporation of soil moisture from the surface [73].

Thus, forest fires not only change the physical properties of permafrost soils, but large changes also occur in the hydrothermal balance of the soil active layer and permafrost [26,44,73–75].

5. Conclusions

Large forest fires that took place in Central Yakutia in 2021 had a significant impact on the soils. The destruction of forests significantly affects the temperature and water regime of light soils—the soil warms up to great depths and permafrost melts, releasing significant volumes of moisture and causing the waterlogging of the profile. The impact on the morphological structure of the soil is reflected in the burning of the litter and organic part of the soil, the formation of a thin pyrogenic layer with a high coal content, the deepening of the active layer depth, and the intensification of cryoturbation processes. In this regard, the physicochemical properties of soils also change: the upper layers become alkalized, organic carbon reserves decrease, and the distribution of values along the profile of some indicators becomes uneven.

Since the studied territory is composed of alluvial light sediments and large areas are occupied by blown sands (tukulan), the emergence of vast new burnt territories with increased wind conditions can cause a significant expansion of desert-like tukulan areas.

Soils formed on sandy sediments may have a different response to an intense fire, depending on the type of vegetation and the level of the protective function of vegetation and litter. Thus, pine forests soils are more resistant to the consequences of fires, since they are initially characterized by good soil heating due to sparse vegetation and thin litter.

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