



## Consequences of the catastrophic wildfire in 2020 for the soil cover of the Utrish State Nature Reserve

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### ABSTRACT

Present work aimed to assess the impact of pyrogenic effect on the flora, and quality and health of soils of the Utrish Reserve. Studies performed on the territory of reserve within a month after the fire revealed that the areas showed varying degrees of damaged characteristics due to catastrophic fire. The entire damage was recorded in a 40-hectare region, while the vegetation on another 26 hectares of the reserve was damaged to a lesser extent. In total, 4,800 trees were eliminated, 73% of them belonged to rare and endangered species, such as Junipers (*Juniperus* spp.), Mt. Atlas mastic trees (*Pistacia mutica*), and Pitsunda pines (*Pinus brutia* var. *pityusa*). In the areas of severe disturbance, the soil surface was covered with a constant layer of ash two weeks after the fire. As a result, there was an increase in the pH values, and the chemical composition of brown soil (Cambisol) was determined after the fire. There was also an increase in the organic carbon content and peroxidase activity. Catalase activity, which is sensitive to pyrogenic effects, decreased in all soil samples obtained at post-pyrogenic areas. The effect of fire on the biological state of soils may diminish over time, however, the restoration of the damaged ecosystems may take hundreds of years. The results of this study can be used in assessing the damage to ecosystems after the wildfires, as well as in developing methods to accelerate the restoration of soils after a fire impact.

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## 1. INTRODUCTION

Fires are one of the most important catastrophic events that disrupt ecosystems worldwide. A recently disastrous event called 'Black Summer' burnt more than 8 million hectares of Australian vegetation, which may have left impacts on ecosystems such as failure of regeneration, a decline in landscape scale, and loss of endangered species (Godfree et al., 2021). Forest fires are fairly common in the southern part of Russia, including that in the protected areas. Fires are a common global phenomenon as well, however, to protect biodiversity, it is necessary to incorporate management practices and evaluate the loss caused by fires, especially in the protected areas (Pereira et al., 2012). Thus, the pyrogenic changes of biota and biological activity of soils have significant importance and have occasionally and fragmentarily been studied (Gongalsky, 2011; Kazeev et al.,

2020; Kazeev et al., 2019; Korobushkin et al., 2017; Odabashyan et al., 2019). The fires have a range of adverse consequences including air pollution, water contamination as well as soil cover, and biota (Martin et al., 2016).

In August 2020, a fire affected the area of the Utrish State Nature Reserve, located in Krasnodar Krai, Russia, and covered almost 10 thousand hectares. As a result of the fire, more than 125 hectares of relict forest have burned down. The dry Eastern Mediterranean subtropics are a unique ecosystem of the Abrau Peninsula, the only well-preserved area in the reserve. For this reason, the soils of the Utrish State Nature Reserve are an object of protection, being of great interest for the biological monitoring of the Eastern Mediterranean landscapes. The original Mediterranean flora is a dominant part of the reserve; it is represented by such

endemics as Greek juniper (*Juniperus excelsa*), Foetid juniper (*Juniperus foetidissima*), Mt. Atlas mastic trees (*Pistacia mutica*), Pitsunda pines (*Pinus brutia* var. *pityusa*), and European smoke tree (*Cotinus coggygria*).

The consequences of fires can combine effects that both increase and decrease ecosystem biodiversity. After fires, a mosaic and mixed-age vegetation structure are formed and, at the same time, there is a decrease in vegetation biodiversity. Forest fires have a significant impact on the balance of carbon in the atmosphere. The impact of fires on the carbon balance is determined by two processes, physicochemical, consisting of the rapid release of carbon dioxide during combustion of combustible forest materials (fire emission) and a fairly long release of CO<sub>2</sub> as a result of biological degradation of plant residues (post-fire emission). Post-fire emissions can last for many decades. Net carbon emissions from wildfires are equivalent to 41% of global fossil fuel consumption in 1997-1998 (Landry & Matthews, 2016). In turn, carbon and greenhouse gas emissions from wildfires lead to global climate change: higher summer temperatures, longer periods of drought, and redistribution of precipitation. Climate change then leads to changes in fire regimes. Therefore, the influence of fires on many ecosystem components, including soils, is currently an urgent research area for scientists all around the world. In ecosystems, soils occupy an important position and are responsible for the formation of vegetation cover and the sustainability of ecosystems, as well as being a habitat for many organisms. As part of an ecosystem, soils are also affected by fires in many ways. Soil cover and soil properties are disturbed as a result of fire. Disturbances can be directly from the fire itself, as well as from recovery successions after fires. The pyrogenic factor not only disrupts soil chemistry, impairs water permeability, and affects environmental response, but also destroys some microorganisms for long periods of time (Köster et al., 2021). However, immediately following a fire, there is also often a significant increase in soil fertility due to available organic matter from the burned plant material and ash residues. Thus, all soil properties are affected by fire in a complex way. Some changes, such as decreased microbial abundance, increased pH, and changes in soil temperature, are only temporary (Ngole-Jeme, 2019), while other soil properties may undergo irreversible changes (Certini et al., 2011). For example, the top organic layer significantly loses organic matter due to combustion, and full recovery of this layer can take many years if there is no erosion.

The determination of the activity of soil enzymes and the assessment of organic carbon content are widely used methods for biological diagnostics of soil parameters for assessing the quality and health of soils (Bünemann et al., 2018; Burns et al., 2013; Kolesnikov et al., 2021; Thiele-Bruhn et al., 2020). The activity of enzymes from the class of oxidoreductases is significantly decreased when exposed to fire, high temperatures, and smoke (Kazeev et al., 2020). The effect of fire on the enzyme activity of soils in the Western Caucasus persists for at least 10 years (Kazeev et al., 2019). The study aims to assess the immediate consequences of high-intensity fire in 2020 on the vegetation cover and soils of the Utrish State Nature Reserve.

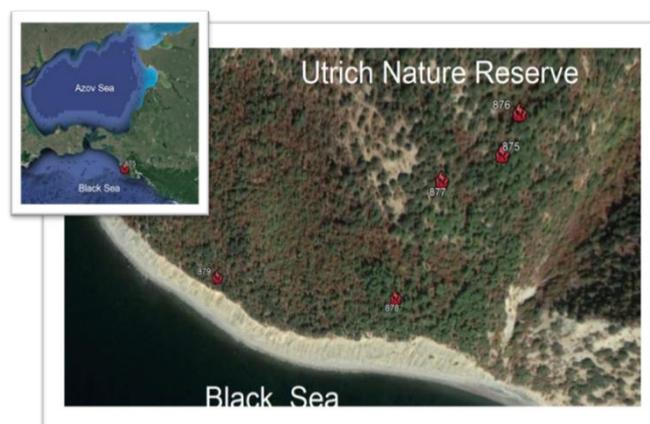
**Table 1.** Location of some survey areas

No	Degree of burn	Geographical coordinates	Height above sea level (m)
877	Control forest	44.73012 N, 037.43170 E	70
876	Hard	44.73029 N, 037.43235 E	77
878	Medium	44.72909 N, 037.43119 E	34
879	Low	44.72924 N, 037.42844 E	14

## 2. MATERIAL AND METHODS

### 2.1. The study area and soil sampling

Field studies were carried out in September-October 2021. The Juniper woodland was studied in the coastal part of the reserve in the areas affected differently by the fire (Table 1). The study included brown soils (Cambisol), which are rare for Russia, and widespread on most of the Abrau Peninsula, including the Utrish State Nature Reserve. The peculiarity of the soils is preconditioned by the low mountain dissected ridged relief of this territory. In the Utrish State Nature Reserve, brown soil and rendzic prevailed (Kazeev et al., 2015; Kazeev, Kolesnikov, et al., 2016). Their taxonomic diversity is quite great due to differences in relief conditions, rockiness, parent rocks, vegetation, and the degree of manifestation of erosion processes. In the Utrish State Nature Reserve, most of the soils are classified as incompletely developed genera of brown soils, due to their formation on dense rocks of different compositions (Fig. 1). The control plot is a juniper sparse forest area typical for the reserve with a grassy layer and forest litter on the soil surface. In all the studied areas affected by the wildfire, the presence of ash and unburned residues of plant material on the soil surface was noted. The maximum coverage of cinders and ashes with a layer of 0.5-2.0 cm was noted in the area with a severe degree of burns (№ 876). There is no forest litter and grassy vegetation in this area, the trees burned down and are completely charred. The moderately damaged area (№ 878) has entire trees with damage to only the lower parts of the trunks. While on the site with slight damage (№ 879), herbaceous vegetation is still preserved in some places but damaged after the impact of the fire.



**Figure 1.** Location of the study sites

The degree of damage to the soil and vegetation cover was assessed in accordance with the standard methods (Parson et al., 2010). Geographical coordinates were obtained using the GPS Garmin navigator. Soil samples were taken from the most biologically active surface layer of the soil from a depth of 0–3 cm. Plant residues and ash were not included in the sample. Soil samples were dried, the plant residues and ash were removed, and the soil was sieved through a sieve with a pore diameter of 1 mm. Analytical studies were performed at the Department of Ecology and Environmental Management of the Southern Federal University (Rostov-on-Don, Russia) using methods accepted in ecology, biology, and soil sciences (Kazeev, Chernikova, et al., 2016).

## 2.2. Statistical analysis

Statistical data processing was performed using correlation and variance analyses using STATISTICA. When discussing the results, statistically significant differences with a significance level of 5% ( $p < 0.05$ ) were taken into account ( $p < 0.05$ ).

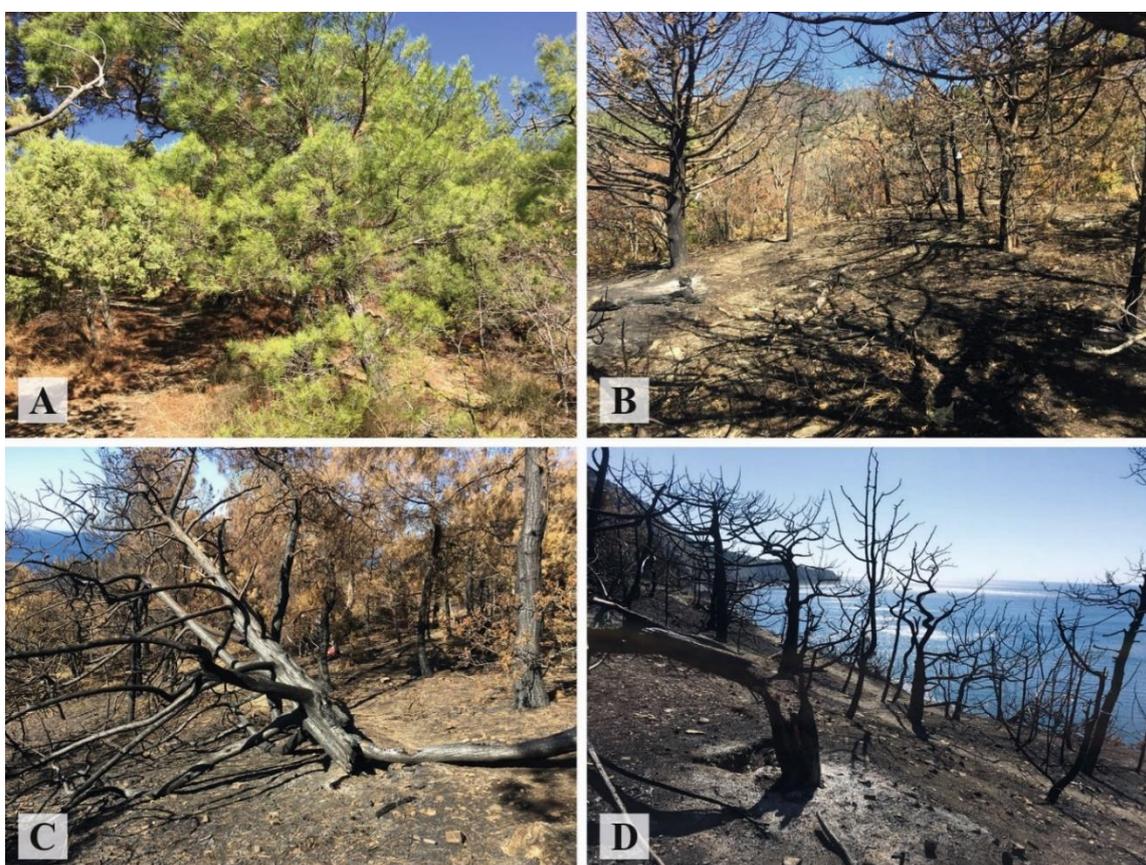
## 2.3. Determination of soil properties

The determination of the gross chemical composition in soil samples was carried out by the X-ray fluorescence method on the Spectroscan MAKSGV instrument. The content of such compounds as SiO, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, CaO, MgO, K<sub>2</sub>O, Na<sub>2</sub>O TiO<sub>2</sub>, R<sub>2</sub>O<sub>5</sub> was determined. The soil pH values were determined by the potentiometric method using soil suspension in the ratio of 1:2.5 for soil: water. The content of organic carbon in the humus was determined using the method of oxidation with a chromic mixture on a

spectrophotometer UNICO 1201 (United Products & Instruments, Inc., USA). The enzyme soil activity was estimated on the basis of the activity of oxidoreductases enzyme: (catalase, peroxidase). Determination of the enzymatic soil activity was based on the amount of the substrate processed during the reaction or the formation of the reaction product under optimal conditions of temperature, pH of the medium, the concentration of the substrate, and soil hinge. Catalase activity (H<sub>2</sub>O<sub>2</sub>: H<sub>2</sub>O<sub>2</sub>-oxidoreductase, EC 1.11.1.6.) was determined by using the volumetric method according to the volume of decomposed hydrogen peroxide per minute (Kazeev, Kolesnikov, et al., 2016). Peroxidase activity (donor: H<sub>2</sub>O<sub>2</sub>-oxidoreductase, EC 1.11.1.7.) was determined using hydroquinone which got reduced to 1,4-p-benzoquinone.

## 3. RESULTS

A ground fire which got transformed to the crown fire on August 24–26, 2020, covered 66.53 hectares of xerophytic sub-Mediterranean formations of the altitudinal vegetation zone of the Utrish State Nature Reserve. Here, the vegetation of the coastal area had suffered a significant loss, where about 89% of the area was affected; in particular, these were Pistachio-juniper, juniper forests and woodlands, and communities of *Pitsunda pine* (Fig. 2). However, communities of the primary Shiblyak dominated by downy oak *Quercus pubescens*, Downy oak-hornbeam forests, and woodlands, fragments of juniper communities with inclusions of xerophytic shrubs were affected to a lesser extent (about 11% of the area).



**Figure 2.** Effects of catastrophic fire on the Utrish State Nature Reserve vegetation; a) control, b) low, c) medium and d) hard

**Table 2.** The content of the main elements (%) and pH in the burn soils

No	Degree of burn	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	K <sub>2</sub> O	Na <sub>2</sub> O	TiO <sub>2</sub>	P <sub>2</sub> O <sub>5</sub>	pH
877	control forest	52.6	6.9	3.5	3.5	1.0	1.7	0.9	0.4	0.23	7.3
879	low	59.5	7.9	3.7	4.9	1.2	1.9	0.7	0.4	0.30	7.5
878	medium	54.3	6.3	3.2	6.4	0.9	1.6	0.6	0.4	0.42	7.6
876	hard	63.8	8.2	3.5	4.2	1.1	1.9	0.5	0.4	0.28	7.7

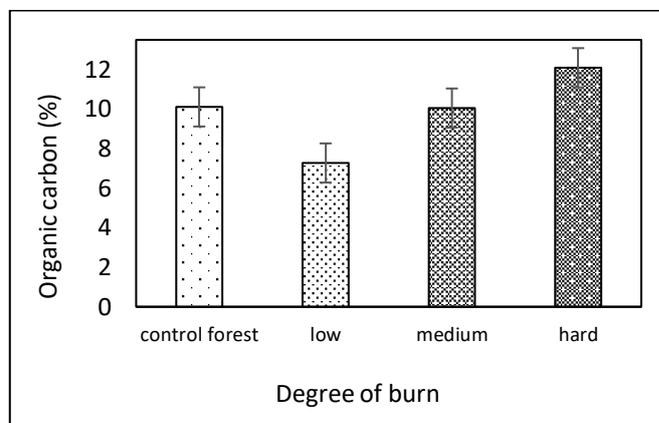
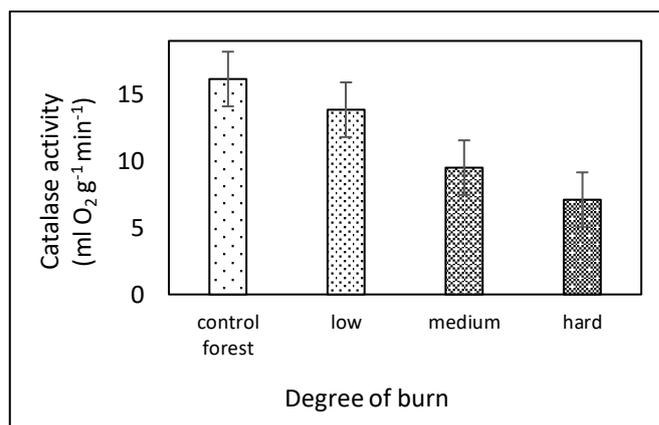
In October 2020, the affected site was surveyed, where the areas with disturbed stability (26.1 hectares, or 39%) and with lost stability (40.4 hectares, or 61%) were identified taking into account the impact of both ground and crown fire. A total timber stock was 3,860 m<sup>3</sup> and the loss of wood during a fire was 1,093 m<sup>3</sup> (748,650 kg, or 28%).

The loss of wood in a fire event was the sum of the volume of trees damaged with no growth cessation (329 m<sup>3</sup>) and the volume of trees destroyed down to total growth cessation (764 m<sup>3</sup>). In total, the fire destroyed 4,800 trees of different species, ages, and diameters to total growth cessation. The share of rare and endangered species such as Greek juniper (*Juniperus excelsa*), prickly juniper (*Juniperus deltoids*) R.P. Adams (*J. oxycedrus auct.*), Mt. Atlas mastic tree (*Pistacia mutica*), Pitsunda pine (*Pinus brutia* var. *pityusa*) was 73% while sessile oak (*Quercus petraea*), oriental hornbeam (*Carpinus orientalis*), European ash (*Fraxinus excelsior*) accounted for about 27%; coniferous trees which were mostly affected by the fire were about 67%.

Two weeks after the fire, field studies were carried out in several areas of the reserve in the coastal belt of pistachio-juniper, juniper forests and woodlands, and in the communities of Pitsunda pine. The first site strongly affected by the fire was located in the vicinity of Bazovaya Shchel valley (No. 876). The vegetation was represented by Pitsunda pine and junipers, under the canopy, by the thickets of butcher's-broom *Ruscus aculeatus*. The ash layer was 3-4 mm on the soil surface. The second site was located in the mouth part of the starboard side of the Bazovaya Shchel valley which was also badly damaged by ground fire ((Number) No 878). The vegetation here was represented by Pitsunda pine, burned-out butcher's-broom, and juniper undergrowth. The third damaged site was the seaside terrace (No 879), represented by juniper woodland. The pristine (control) area was the background forest not affected by the fire (No 877), where the vegetation was represented by Pitsunda pine, less often by juniper, and undergrowth of butcher's-broom.

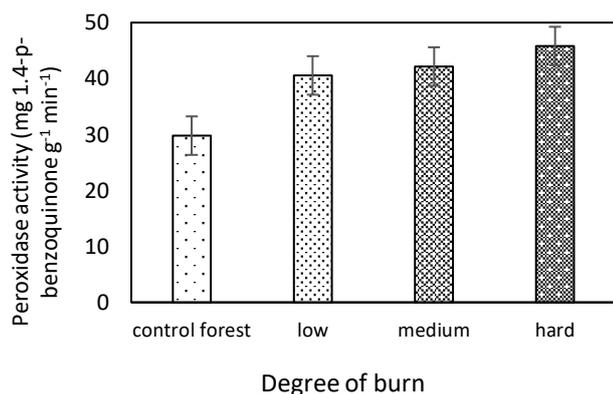
Gross chemical analysis data showed increased contents of calcium and phosphorus in soils in all three studied areas compared to control values, which is explained by the formation of ash and coal (Table 2).

The high content of organic carbon was noted in the samples of post-pyrogenic soils of the Utrish State Nature Reserve. In the surface layer (0-3 cm) of the first site (No 876) designated as hard based on burn degree, the organic carbon content was 20% ( $p < 0.05$ ) higher compared to the control samples. Whereas, at the second (No 878) sites designated as medium (burn degree) the carbon content practically does not differ relative to the pristine soils. At the third site (No 879) designated as low (burn degree), the carbon content decreased by 28% ( $p < 0.05$ ) (Fig. 3).

**Figure 3.** The content of organic carbon in brown soils after the fire**Figure 4.** The catalase activity of brown soils after the fire

The activity of oxidoreductases in the damaged soils differed from that observed in the control samples. At all three sites, the fire event inhibited the catalase activity. Catalase activity in post-pyrogenic soils was reduced relative to the pristine soils (Fig. 4). The maximum inhibition of enzyme activity was noted for the site with a severe degree of damage by 56% ( $p < 0.05$ ). While in the area with an average degree of damage, the decrease in the enzyme is 41% ( $p < 0.05$ ), and for weak damage by 14% ( $p < 0.05$ ). Thus, the more damaged the area is from the impact of fire, the lower the activity of the enzyme in the soil.

The peroxidase activity at all three sites affected by the fire was higher than that in the pristine area (Fig. 5). Stimulation of peroxidase activity in burned soil increases with the degree of fire exposure. At the same time, the increase in enzyme activity for the area with weak damage is 36% ( $p < 0.05$ ), and for the area with strong damage, it is 54% ( $p < 0.05$ ). For the site with an average degree of damage, the activity of the enzyme was 41% higher ( $p < 0.05$ ) compared to the control soil.



**Figure 5.** The peroxidase activity of brown soils after the fire event

**Table 3.** Correlation coefficient of different soil samples of biological variables and pH from the study data

	pH	Organic carbon	Catalase activity	Peroxidase activity
pH				
Organic carbon	0.14			
Catalase activity	-0.33	-0.49		
Peroxidase activity	0.45	-0.15	-0.06	

Correlation analysis was carried out to determine the dependence of enzyme activity and pH values on the content of organic carbon. Table 3 shows that enzyme activity is weakly correlated with the content of organic carbon ( $r = -0.49 - -0.15$ ). There is also no correlation between enzyme activities with each other ( $r = -0.06$ ).

#### 4. DISCUSSION

The soil cover of the Reserve is represented by varieties of brown soils. Most often, leached varieties of brown soils are found on the territory of the reserve, the soil profile of which is completely free of calcium carbonates. In the southern part of the reserve, brown soils are located at altitudes below 100 meters (Kazeev et al., 2015). The main features of brown soils included the brown color of the soil profile; intense textural lining of the middle part of the soil profile; eluvial-illuvial type of decarbonization closed to the neutral reaction of the environment; soil richness with elements of mineral nutrition. The studied soils in the Utrish State Nature Reserve have higher stoniness and rubble, no carbonate growths, fragmentation of the forest floor due to the low-mountain dissected relief of the territory. At the same time, most soils are classified as underdeveloped genera of brown soils due to their formation on dense rocks of different compositions. In this regard, brown soils contained a significant number of fragments of dense rocks in their profile (Opanasenko & Evtushenko, 2019).

Long-term studies of soils in the territory of the Utrish Reserve have shown the main patterns of their biological

activity (Kazeev, Chernikova, et al., 2016; Kazeev et al., 2015; Kazeev et al., 2019). As a result of many years of research, the dependence of the number of microorganisms and the enzymatic activity of brown soils on soil-forming rocks, relief, exposure and steepness of the slope, degree of stoniness and type of vegetation was revealed. Down the soil profile, biological activity decreases due to a decrease in the content of organic matter, the abundance of plant roots, and the number of microorganisms. The control plot in this study corresponds to the main background territory of the reserve in terms of the nature of the relief, vegetation, composition and properties of soils. The fire destroyed forest vegetation and litter on the soil surface.

After the fire, an increase in pH values up to 7.7 units was noted, which was 5% higher than the values of the control area. To a greater extent, the increase in pH values occurred for the site with a strong degree of damage. Combustion of organic matter and ash production which releases large quantities of base forming ions calcium (Ca), magnesium (Mg) and potassium (K) during burning is the main explanation used to justify the increase in pH values observed with an increase in fire intensity and duration (Ngole-Jeme, 2019).

An increase in carbon content was associated with the ingress of pyrogenic carbon into the soil in the form of coal particles (Liu et al., 2014). The research also reported an increase in the organic carbon content in the upper layers of soil (Gabbasova et al., 2019; Gyninova et al., 2019). There was a high probability of a decrease in organic carbon content in near future due to erosion in the areas devoid of vegetation, especially on the steep slopes of the coastal parts of the reserve. Morphological changes in post-pyrogenic soils are due to burnout of the upper organogenic layers and the preservation of pyrogenic traits in soils for more than 100 years after a fire event (Startsev et al., 2017). Some researchers have noted an improvement in soil properties after ground fires (Gabbasova et al., 2019; Kumar et al., 2013).

The top layer of soil down to a depth of 3-5 cm was more exposed to high temperatures during the fire. As a result, the biological activity of the soil of this layer degrades to the greatest extent. Therefore, inversions of biological activity were noted in the soil profile below the penetration depth of the pyrogenic impact. The enzyme activity of burned soil in the lower horizons practically does not differ from the control values.

After fires, it takes a long time to restore the structure of the bacterial community (Pérez-Valera et al., 2019). Soil organisms are able to survive at temperatures significantly higher than the accepted threshold of 60°C for a one-minute duration evidenced. Soil fungi and bacteria mortality thresholds were reported for temperatures from 60°C to 400°C and 80°C to 400°C for 2–30 min durations (Pingree & Kobziar, 2019). A decrease in enzyme activity was directly related to the pyrogenic effect: as the soil temperature increased, the protein structure of enzymes was destroyed. In addition, the biological activity of soils was also influenced by the indirect consequences of fire, such as combustion of litter and humus, a decrease in water seepage accompanied by an increase in soil hydrophobicity, increased temperature on a bare surface, a change in vegetation cover, and others. The

high sensitivity of catalase to pyrogenic effects was also reported earlier (Kazeev et al., 2020; Kazeev et al., 2019). The increase in the calcium content in soils after the fire noted in Table 2 could affect the activity of catalase. A significant relationship between the biological activity and the content of calcium carbonates in soils and parent rocks was previously noted for the mountainous soils of the Caucasus.

An increase in the peroxidase activity was due to the presence of ash as an additional source of carbon in the coal samples. Over time, this pyrogenic effect on the enzymatic activity and organic carbon content is expected to decrease (Kazeev et al., 2019; Köster et al., 2016). There is not a great amount of published literature on the effects of burning on peroxidase activity. Further experimentation is necessary to provide more conclusive evidence on how peroxidase activity is affected by the fire.

Some extracellular, intracellular, and "soil" enzymes have thermal stability. In most cases, the optimum activity of enzymes is below 50°C, and at high temperatures, denaturation of enzyme protein molecules occurs (Dadwal et al., 2021). The enzymes of thermophilic microorganisms and, first of all, hyperthermophilic archaea, which live in environmental conditions above 100–106°C, have higher thermal stability. The optimal environmental temperatures of the common ancestors of Bacteria and Archaea are ~80–93°C and ~81–97°C, respectively (Akanuma et al., 2013). An increase in the thermal stability of enzymes is enhanced in the zonal series of soils from north to south. Immobilized enzymes have increased thermal stability. Immobilization limits the movement of enzymes at higher temperatures, which leads to an increase in their stability (Dadwal et al., 2021). Enzymes adsorbed on the solid surface of soil colloids are less prone to denaturation. Pure free enzymes are partially inactivated at a temperature of about 60°C, intracellular enzymes are completely inactivated already at 60–80°C, and the activity of soil enzymes decreases gradually and partially remains even after heating to 140–180°C. Thermal denaturation is time dependent, and for an enzyme the term "optimum temperature" has little real meaning unless the duration of exposure to that temperature is recorded (Robinson, 2015).

Our results demonstrate that fire regime attributes (fire severity) affect soil biochemical properties. Previous works have shown that soil biochemical properties are highly sensitive to environmental disturbances as wildfires (Kazeev et al., 2020; Odabashyan et al., 2019). Even 10 years after the fire in the forests of the Utrish Reserve, differences were noted in the biological activity of post-pyrogenic and background forest soils (Kazeev et al., 2019; Vilkova et al., 2021). Based on previous studies of the pyrogenic impact, we assume that the full restoration of ecosystems after a strong fire in 2020 will take many years and even decades to restore soils and ecosystems.

## 5. CONCLUSION

In the Utrish State Nature Reserve, 40 hectares of xerophytic forest were destroyed by the fire, and another 26 hectares of forest were severely affected. The fire destroyed several thousand coniferous trees of rare species. The

pyrogenic effect was significant to the ecological and biological properties of the soils of the Utrish State Nature Reserve. After the fire, there was an increase in pH values, as well as the accumulation of phosphorus and calcium. The content of organic carbon was higher in the soils affected by the fire than in the pristine soils. The activity of the studied soil enzymes differed in particular areas. The fire event inhibited the catalase activity but promoted the peroxidase activity. The consequences of the fire will affect the soil and vegetation cover for many years. It is particularly disturbing that the possible development of erosion processes may destroy the soil cover quickly at the steep slopes and during intense rainfall.

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## Declaration of Competing Interest

The authors declare no competing financial or personal interests that may appear and influence the work reported in this paper.

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