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Impact of forest fire on soil properties (review)

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We examined changes in the morphological, physicochemical properties and features of the organic matter of forest soils impacted by wildfires on the territory of Russia. Morphological signs of pyrogenesis (pyrogenic horizon formation, partial charring of litter and illuviation of organic compounds) are most evident detected in the first decade after a fire. Ground fires in lichen pine forests, formed on Albic Podzols lead to complete burning of litter. Low intensity ground fires in sphagnum pine forests, developing on Histic Podzols, contribute to partial burning of litter (charring). Fires change the hydrothermal regime of soils, which is most clearly demonstrated for soils formed on permafrost soils / cryosols. Fires lead to hydrophobization of the upper mineral horizons, estimated from the contact angle of wetting. Resistant products of pyrogenesis (charcoals, soot) are retained in soils for several centuries. The most common changes in the physical and chemical properties of soils after fires are a decrease in acidity by 1–2 units of pH, an increase of saturation with base saturation. Fires increase aromaticity of soil organic matter. After fires, the content of polyaromatic hydrocarbons in soils increases, and the concentrations of water-soluble organic compounds decrease. Restoration of soil properties to the prefire state takes a decade to several centuries. The introduction of a universal subtype “pyrogenic” is proposed in describing the morphological characteristics of forest soils.

Keywords: fires, forest soils, soil organic matter, secondary successions, black carbon.

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Влияние лесных пожаров на свойства почв (обзор литературы)

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Морфологические признаки влияния пирогенеза (формирование пирогенного горизонта, частичное обугливание подстилок и иллюирование органических соединений) наиболее чётко проявляются в первое десятилетие после пожара. Устойчивые к разложению продукты пирогенеза (угли, сажа) сохраняются в почвах до нескольких столетий. Наиболее общими изменениями физико-химических свойств почв после пожаров являются снижение кислотности на 1–2 ед. pH, возрастание степени насыщенности основаниями, увеличение гидрофобности поверхности минеральных горизонтов почв. Пожары приводят к увеличению ароматических структур в составе почвенного органического вещества. После пожаров увеличивается содержание полиароматических углеводородов в почвах, уменьшаются концентрации водорастворимых органических соединений. Для восстановления близких к исходным свойствам почв после пожара необходимо от десятилетия до нескольких столетий.

Ключевые слова: пожары, лесные почвы, почвенное органическое вещество, вторичные сукцессии, чёрный углерод.

Forest fires are a natural factor of the ecosystem development [1]. Russia as well as the USA, Canada, Portugal, Spain and Australia, are among the countries, which forests are regularly exposed to fires [2, 3]. Forest fires affect ecosystems in a holistic manner. They can have both positive (on individual tree species) and negative effects (e. g., contribute to significant ecosystem degradation) [4]. Warm season climate conditions are the major factors in the frequency and an area of forest fires (Fig. 1). The pyrogenic factor and the climate control the age and mosaic structure of the plant cover, its development, flows of matter and energy [5–7]. The fires frequency in boreal forests of the European Russia varies from 1–2 per century to 1–2 per Millennium [8], and the average interval between fires in Siberia forests is estimated at 50 years [9]. Forest fires dominate in the middle and southern taiga, forest-steppe, but in some hot years the areas of fires can spread to the North – to the northern taiga, forest-tundra and tundra. The accumulation of significant reserves of combustible materials on the soil surface in such ecosystems (including those formed on permafrost) causes a high natural fire hazard of these territories [10, 11].

There has been an increase in various anthropogenic pressures on forest ecosystems in previous decades, as well as an increase in the frequency and area of fire-affected forests. The fires'number increases due to climate changes – "heat waves", which leads to droughts. In addition, fires of anthropogenic nature were an integral part of slash farming and affected large areas of the taiga [12, 13]. As a result, the vast majority of modern forest landscapes of Russia represent different stages of post-fire successions.

Recently, fires have been attributed to one of the leading soil-forming factors [14]. Despite the wide spread of pyrogenesis, in most cases pyrogenic effects are recorded by researchers in the burnt soils and burnt tree stands only within the first post-fire years and are not taken into account in the analysis of the further functioning and development of forests. In this regard, the main aim of this review is to analyze the fires impact on the forest soil. The aim of this work was to characterize disturbances, changes and preservation of post-fire soils morphological characteristics in various forest ecosystems, distributed mainly in Russia; to assess physicochemical soil properties changes; to identify the general patterns of changes in different forms and fractions of soil organic matter (SOM).

Morphological properties of post-pyrogenic soils

Fires alter the soils morphological organizations. Depending on the fire type, the soil litter can burn out completely, forming a well-defined pyrogenic horizon (Fig. 2A, see color insert), or during running ground fires the soils litter can burn out only partly, forming a thin charred layer on its surface (Fig. 2B, see color insert). The focal distribution of organic horizons burnout of is typical for pine forests formed on semi-hydromorphic soils (Fig. 2B, see color insert). Specifics of cryogenic microrelief (the combination of hummocks and troughs) in Northern taiga larch forests of Central Siberia also lead to uneven burning of the ground cover and soil organic horizon [15, 16]. Experimental burning-out in middle taiga pine forests carried out in Krasnoyarsk region showed that in the first year after a high-intensity fire the litter stocks are reduced by more than 3 times, after a low-intensity – by no more than 1.5 times. The litter density increases due to the upper low-density layers combustion and the appearance of heavier components in the form of coal and ash [9, 17]. Part of the combustion products (soot, water-soluble compounds) under the conditions of preferential water flow regime can migrate to the illuvial horizons and geochemically linked drainage network [18]. At the same time, the microreliefs can serve as a refuge for relatively rapid restoration of vegetation cover due to the absence or weak impact of fire (waterlogged and/or frozen state of the organic horizon). Strong ground and especially crown fires lead to the complete destruction of forest litter layer and in most cases cause the death of forest stand [19, 20]. In the first months after the fire, the products of partial pyrogenic decomposition of organic residues can move into mineral horizons (Table 1). The production of pyrogenesis products promotes hydrophobization (due to aliphatic and aromatic organic matter) and cementation (due to ash polyvalent cations and the formation of strong organic-mineral linkages with mineral particles) from the upper soil horizons. At the same time, in soils with partial litter burnout the over-consolidation is less pronounced.

The severity and preservation of soil pyrogenic morphological characteristicis determined by the fire type, its intensity and the original forest type and litter horizons dryness. The fires frequency (fire return interval) in the considered forest types is an important factor of pyrogenic effect on soils. The pyrogenic characters preservation in the forest soil profile varies from days to hundreds of years (Table 1). In most cases, pyrogenic features are

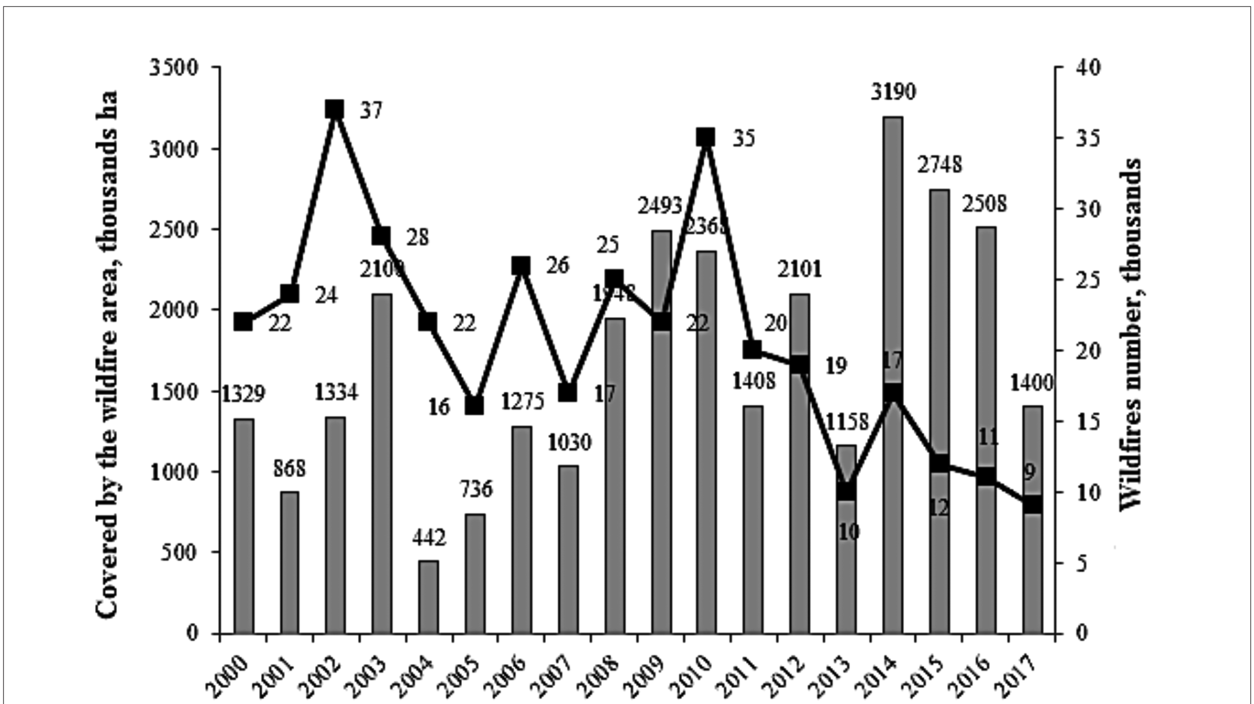

Fig. 1. The statistics of forest fires in Russia, 2000-2017 years. By: [2] with additions from http://wiki-fire.org.

Table 1

Examples of morphological characteristics in forest pyrogenic soils

Time since the moment of exposure	Soil type	Disturbances depth, cm	Litter *	Illusion of pyrogenic organic matter	Upper mineral horizon-sover-consolidation	Carbonaceous inclusions
European North						
Lichen pine forests, middle taiga, ground running fire [24]						
1 year	Albic Podzols (pyrogenic)	up to 10 cm	1	+	+	+
2 years				+	+	+
10 years				–	+	+
16 years				–	+	+
Cowberry-green moss pine forests, middle taiga, ground running fire [25]						
50 days	Albic Podzols (pyrogenic)	up to 2–4 cm	2	+	+	+
83 days				+	+	+
2 years				+	–	+
Bilberry-green moss spruce forests, Northern taiga, ground strong fire [19]						
9 years	Retisols (pyrogenic)	up to 20 cm	2	+	+	+
100 years				+	-	+
154 years				+	-	+
Sphagnum pine forests, Northern taiga, ground running fire [25]						
1 year	Histic Podzols (pyrogenic)	up to 20 cm (foci)	3	+	+	+
3 years				+	+	+
Central Siberia Larchforests, Northern taiga, ground running fire [15, 26]						
1 years	Cryozems and podburs (pyrogenic)	up to 20 cm	1	+	+	+
2 years			1	+	+	+
25 years			2	–	–	+
180 years						+
Forest-steppe Grass pine forests (insulated pine forests), forest-steppe [27]						
8 years (crowning)	Arenosols (pyrogenic)	up to 20 cm	1	–	+	+
8 years (ground)		up to 20 cm		–	+	+

Note: 1– complete litter combustion; 2 – litter top subhorizons combustion; 3 – litter combustion foci (combustion in all litter's subhorizons foci). Dash – not detected.

diagnosed by the presence of carbonaceous inclusions at the boundary of forest litter and mineral horizons. Coal inclusions in the old post-pyrogenic successions soils (over 100 years old) are diagnosed in morphones formed by the dumps of the first post-pyrogenic forest stand generation (Fig. 2G, see color insert). In some cases, this may form soils with a polycyclic profile containing several buried pyrogenic horizons [21]. Fires in mountain regions play a special role in soil cover disturbance. The development of post-fire erosion on the slopes increases tens of times [22].

Fire-affected forest areas of the Central Siberian plateau cryolithozone are characterized by development of solifluction process development along river banks (Fig. 2D, see color insert), which are intensified with increasing precipitation and rapid surface heating in spring [23].

Mesomorphological pyrogenic characteristics are derived from the micro morphology data. The accumulation of Black carbon particles (charcoal), which represent the litter and wood pyrolysis products (Fig. 3, see color insert), as well as the soil pores' filling with combustion products that reduce the pore space and increase subsequent erosion, was detected. Partly combusted detritus accumulates in the pore space of post-pyrogenic soils (Fig. 3), causing the specificity of accumulation and transformation of organic matter in post-pyrogenic ecosystems [28]. Fires promote the appearance of primary minerals grains fracturing since the temperature on the ground cover surface can reach 1000 °C [9]. Common characteristics of pyrogenic soils microstructure are: signs of the active physical weathering process of primary minerals (quartz, feldspar, especially biotite); the formation of humus persistent forms and coal-like particles (the result of incomplete combustion of plant tissues), as well as the inclusion of plant residues.

Pyrogenesis significantly impacts the intensity changes of the podzol-formation process. Homogenization of the upper mineral horizons occurs due to the slopes'erosion processes development; as a result, burozems (Cambisols) and probably non-podzolic soils with the upper brown mineral horizon may form. The authors of [30] have identified independent groups of pyrogenated and pyrogenic burozems that differ from the undisturbed soils by their morphological and physico-chemical properties. "Temporary" Cryosols transfer to Entic Podzols is possible for soils formed cryolithozone.

Indexation of pyrogenic signs is widely discussed currently. Different designations for pyrogenic horizons are used when describing soils: Pr / pr [31]; pir [21, 30, 32]. Most of the proceedings in the morphological soils description detect only the presence of charcoal without pyrogenic horizons indexation. The Field guide for Russian soils [33] recommended a small index "pir" only for peat soils. The carbonaceous inclusions presence and pyrogenic signs are discussed in the framework of the World Soil Classification for Soil Resources [34] and the Canadian Soil Classification System [35]. The most informative one should recognize using of a small index "pyr" (from pyrogenic), as it is convenient for the universality of the features translation into the WRB system [36]. Small index "pyr" should be used in the presence of coal and other pyrogenesis products in individual genetic horizons with subsequent allocation of a universal subtype of soils.

Chemical and physical properties of post-pyrogenic soils

Post-pyrogenic soils differ from natural ones in a number of physicochemical properties. The upper horizons of post-pyrogenic soils in lichen pine forests [24] and cowberry – green moss pine forests [37] are characterized by an acidity decrease (Fig. 4) and an increase in the degree of base saturation in comparison with conditionally mature soils. The similar patterns have been established for post-pyrogenic Podzols of spruce forests [19]. In some cases, a high intensity of fire altered soil acidity greatly [38]. Post-fire acidity reduction in the forest soils organogenic horizons is also typical for the Kola Peninsula soils [39]. The similar

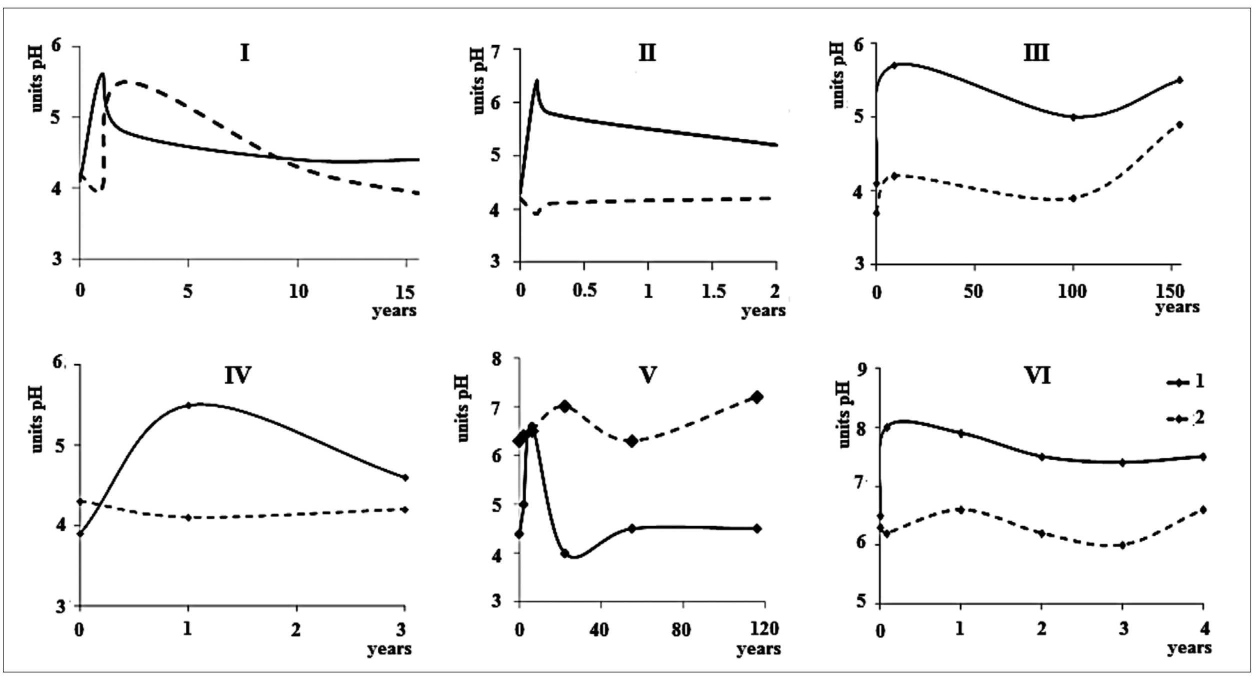

Fig. 4. Acidity changes in the upper genetic soil horizons of lichen pine forests (I), cowberry – green moss pine forests (II), bilberry spruce forests (III), sphagnum pine forests, Komi Republic (IV), green moss larch forests, Krasnoyarsk Region (V) and grassy pine forests, forest-steppe, Samara region, ground fire (VI). 1 – The upper organogenic horizon, 2 – the upper mineral horizon. Zero along the abscissa corresponds to the background plot

changes in soil physicochemical properties have been established for semi-hydromorphic landscapes of Siberia and the European North [25, 26]. The reduction of all forms of acidity in the organic horizons, as well as low increase in the amount of exchange bases and saturation degree of the soil absorption complex is detected in the sandy Podzols of the middle taiga pine forests of Central Siberia a year after a ground fire [9]. The acidity increase in mineral horizons occurs immediately after the fire (Fig. 4II). Soil profile inflow of ash elements and coal after the fire [40] has a significant impact on acidic soils neutralization. In accordance with [31], the litter alkalinization may occur due to coal formed, since a part of the low-molecular organic compounds present in soil solutions of ashes can be sorbed on its surface. The carbon content increase in the upper mineral horizons activates the illuviation of oxalate-extractable iron and aluminum [24, 26]. Thus, postpyrogenic changes in acidity, exchange bases and oxalate-extractable iron and aluminum, have been detected in most studies.

Nitrogen inflow into the upper mineral horizons of the Entic Podzols was detected in the larch forests of Central Evenkia in the initial years after strong ground fire with complete destruction of the forest stand. This is of particular importance for cryogenic ecosystems since nitrogen is one of the factors that limit their productivity [41]. The combustion of live ground cover and litter leads to the dieback of a significant part of the root material and to an increase in organic matter in the upper mineral soil layer [42, 43]. An alteration in nitrogen fraction composition was detected – an increase in the easy hydrolysable fractions by 1.5–2 times. Mineralization processes are activated primarily in organogenic horizons – the total nitrogen content passing into the mineral form increases by 32%. The nitrogen content and itsfraction ratio approach the pre-fire conditions on older burnt-out forests (over 12 years). Nitrogen compounds are sensitive to pyrogenic effects. The Podzols of middle-taiga pine forests of Central Siberia in the initial years after a ground fire are characterized by an increase in total nitrogen by 1.5 times in the litter and by 3–5 times in the mineral soil layer (0–20 cm) [44]. These alterations are due to the very abundant needles' fall in the first post-fire year and its intense mineralization. The concentration of hydrolyzed compounds increases by 1.5–2 times. Mineralization activation and an increase in the proportion of easy hydrolysable nitrogen-containing compounds in the initial post-fire years were previously detected for sod-podzols [32, 45, 46]. Thus, fires increase both the total

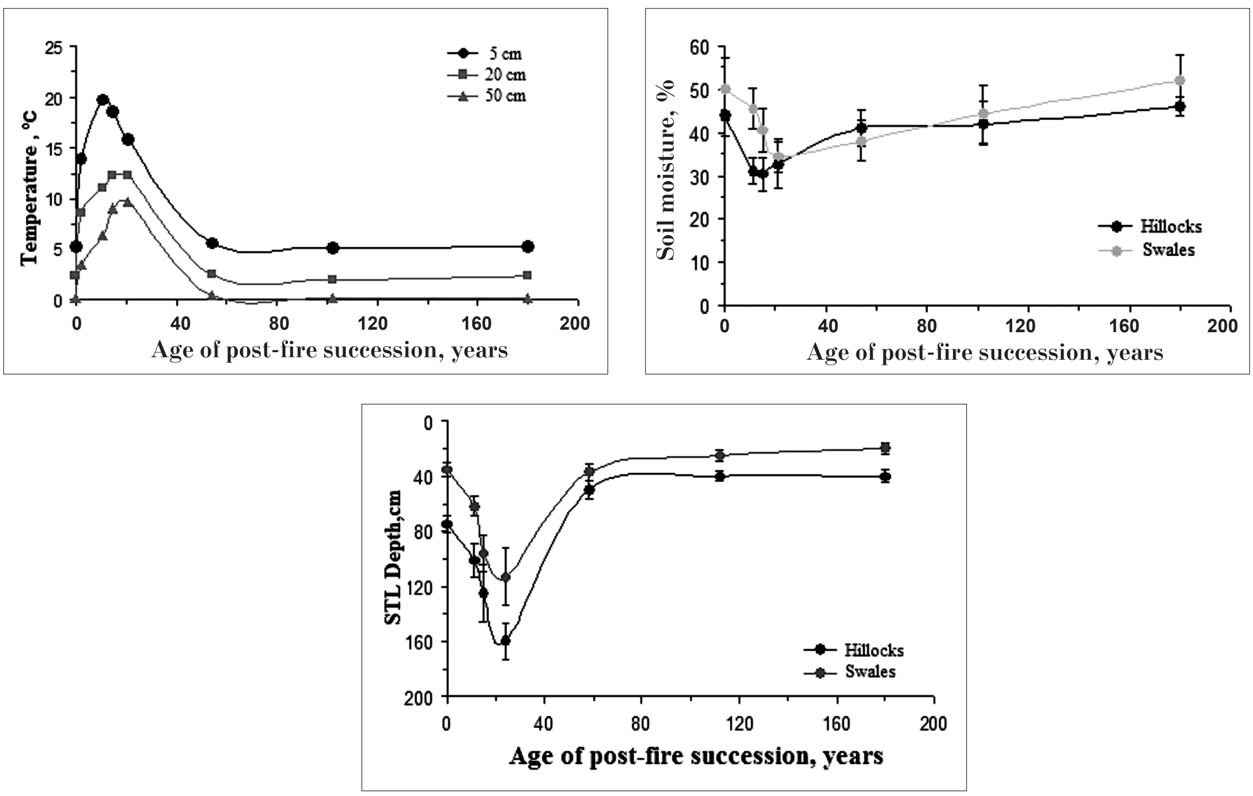

Fig. 5. Changes in temperature, soil moisture and the lactive layer thickness during post-pyrogenic succession, Central Siberia, Evenkia, Krasnoyarsk Region, July 2006 (n = 7, error interval – standard deviation)

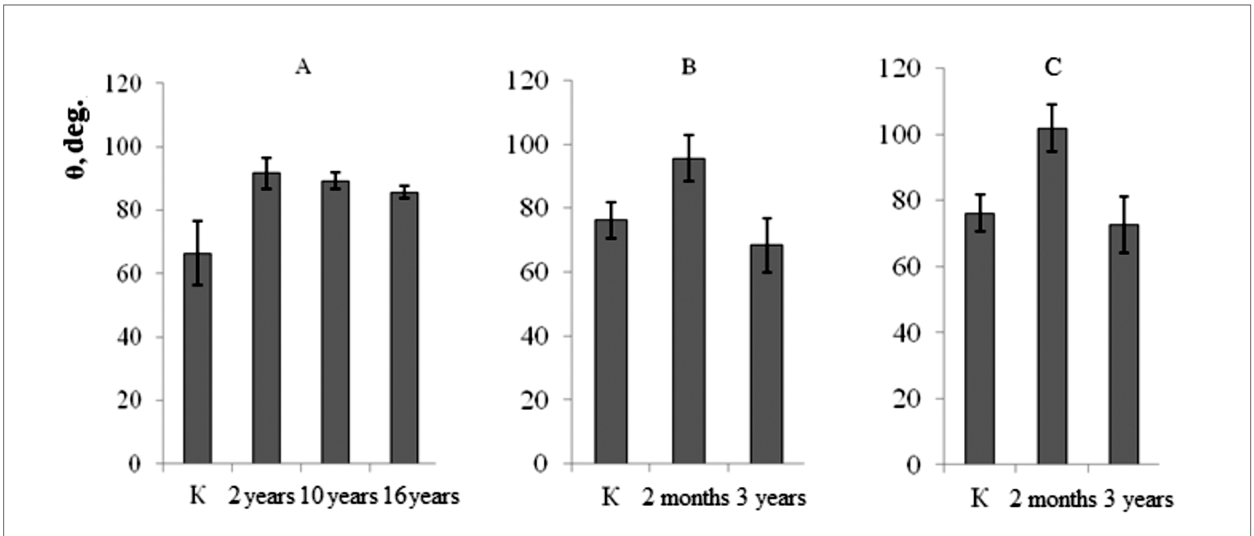

Fig. 6. Hydrophobicity (contact angle) of upper mineral horizons of lichen pine forests soils, middle taiga, Komi Republic (A), soils of grassy pine forests, forest-steppe, Samara region, after ground (B) and crowning fires (C).
K – conditionally background plot (n = 10), error interval – standard deviation

nitrogen and the concentration of easy hydrolysable nitrogen-containing compounds in the soils.

The assessment of the Podzols hydrothermal properties after controlled ground fires in Siberia [47] showed that the temperature regime of burnt places becomes more contrasting in comparison with the original forest. The litter mineralization rate may be observed in the initial post-fire years. The most obvious changes in the hydrothermal regime are observed on the example of soils with a close permafrost underlying (Fig. 5). The increase in average annual temperatures and the improvement of the hydrological regime (caused by the removal of the thermal insulating litter's layer) accelerate soils mineralization process; that provides the improvement of the nutritional regime of larch seedlings and dwarf shrubs rapid growth.

In most cases, low-intensity fires do not affect the texture of the upper mineral horizons [37], but a short-term activation of the cementation processes and aggregates' "cohesion" can be expected [48].

There is an increase in the value of the contact angle (CA) of the upper mineral horizons in most of the studied post-pyrogenic soils (Fig. 6), that indicates their surface hydrophobization in comparison with eluvial horizons of soils of background plots [49]. In soils exposed to fire, the densitometric fractions of free and occluded organic matter proved to be the most hydrophobic [25]. The increased CA values of pyrogenic soils solid phase approach the values of background soils and shift towards hydrophilicity ten years after the fire.

In the course of post-pyrogenic successions the basic physicochemical properties approach the properties of background landscapes' soils already ten years after the fire, but even after a hundred years or more they differ from the original. Forest fires significantly alter the hydrothermal and physical properties of topsoil horizons, increasing hydrophobicity, and thereby contributing to an increase in surface runoff in fire-affected forests.

The carbon content and fractional distribution of its compounds in post-pyrogenic soils

Pyrogenic carbon is considered as one of the most stable pools of carbon sequestration from the atmosphere. According to various estimates [50–52], its contribution varies from 1.6 to 60% of the total soils organic carbon content. Pyrogenic carbon (PyC) or Black carbon is highly resistant and can persist in soils and sediments for a long time. Based to the results of model experiments, the decomposition period of PyC varies from decades [53] to several thousand years [54]. A significant quantities of PyC are concentrated in peat soils [55].

Various pools and fractions within the SOM change differently during pyrogenic exposure. An increase in total carbon content in the upper mineral horizons may occur during the initial post-fire months [37], but in a few years it is usually leveled in conditions of percolation regime of soils. Pyrogenic horizons formed on the mineral and organogenic horizons boundary are enriched with pyrogenic carbon, which is well separated in the light fractions composition during densimetric fractionation (Fig. 2G). An increase in the total content of both humic and fulvic acids with an increase in the fire intensity was detected in pyrogenic burozems (Cambisols) [30].

One of the most sensitive parameters to the pyrogenic effect is the saturation of organic matter with nitrogen. A significant decrease in the C : N ratio (up to 20 units) in pyrogenic horizons of all investigated pyrogenic soils is observed. Subsequently, the C : N ratio gradually increases to the values of background soils during the post-pyrogenic succession. The general pattern of fires after-effects on the carbon balance is the redistribution of carbon stocks between the litter and the upper mineral horizons. In the European North and Siberia soils the litter's carbon stocks decrease with ground high-intensity fires, while no significant alterations in soil carbon stocks occur with ground running fires.

Polycyclic aromatic hydrocarbons (PAHs) perform the diagnostic function of the pyrogenesis effect on soils [24, 37, 57]. A 2–9-fold increase in the total PAHs content in post-pyrogenic soils of the European North is observed, which is mainly due to the accumulation (formation) of light di- and tri-nuclear PAHs. The most water-soluble PAHs can migrate with vertical and lateral streams to geochemically subordinate landscapes and watercourses [19]. Significant accumulation of PAHs in light texture soils of insulated pine forests of the forest steppe was not detected, probably as a result of their intensive migration with clay fraction to accumulative positions. PAH accumulation in the soil after a crowning fire is weaker than after the ground fire. The total PAH concentrations of the upper soils' horizons in the forest-steppe post-pyrogenic soils range from 16 to 24 ng/g [49]. The increase in soils' PAH content is determined by the combustion temperature and the composition of the combusted matter. According to [58], the greatest PAH amount is formed at temperatures of 200–400 °C, which are more typical for running ground fires in the taiga zone [59]. The PAH production is less observed at higher temperatures, that are more typical to crowning and ground independent fires.

Benzenepolycarboxylic acids (BPCA) in the pyrogenic organic matter may serve as markers of pyrogenic effects. Qualitative analysis of the combustion products as BPCA shows their increase in pyrogenic material [60, 61]. Aliphatic and low-molecular compounds are the most mobile, capable of migration. It was detected [62], that the most important biomarkers are an unhydrosugars – products of low-temperature combustion, used to diagnose the fire effects in rivers.

Common patterns in the soils of burned forests consists of a sharp decrease in the water-soluble organic compounds (WSOC) carbon content in the first post-fire months, and the gradual restoration of their concentrations over time. The greatest changes occur in pyrogenic horizons – the WSOC carbon content decreases by 3 to 27 times depending on the phytocenosis, the fire type and the post-fire time [63]. The litter sub horizons not directly exposed to fire retain the WSOC concentrations close to the conditionally background soils.

In accordance with [64], the restoration of the dissolved organic carbon initial concentrations in water streams and its spectral properties is observed approximately after 60 years after the pyrogenic effect. Post-pyrogenic increase in the WSOC carbon content in the cryolithozone is associated with the rise of permafrost water impermeable horizon [65, 66]. This is due to the restoration of vegetation and soil surface organic horizon accumulation, which are the main sources of WSOC.

Changes in the molecular composition of the SOM composition were detected using ^{13}C NMR spectroscopy. An increase in the proportion of free organic matter aromatic structures in the post-pyrogenic soils is the common pattern.

The fire effect on the humic acids molecular fragments of the forest-steppe gray-humus soils consists in increasing their aromatization degree and decreasing oxygen containing functional groups [67]. Pyrogenesis causes a significant transformation of SOM [68, 69], its stability and the individual molecular fragments content. The fire-factor should be taken into account when identifying the specific properties of fractions and groups of soils' organic compounds. At the same time, compounds with a predominance of aromatic fragments accumulate in soils, and with aliphatic ones migrate to river network. Thus, there is a separation of the elements and substances cycles between individual parts of the same landscape or subordinate landscapes.

Fires significantly transform SOM of boreal forests. Plant residues, litter and organic horizons partial combustion increases aromaticity in pyrogenic organic matter, PAHs and BPCA concentrations and reduces the WSOC content. Thus, fires can significantly effect on the formation and functioning of various fractions and groups of SOM.

Conclusion

The fires influence on the forest soils properties has a number of common patterns. Fires determine morphological soil properties (formation of pyrogenic horizons, litter carbonization, pyrogenesis products illuviation, charcoal, coal presence). Pyrogenic soils are characterized by lower acidity, greater saturation of the soil's absorbing complex with exchange bases, surface hydrophobization of the upper mineral horizons. Hydrothermal regime changes and sand available nutrients increase in post-fire soils. Pyrogenic soils are enriched with aromatic polycyclic hydrocarbons. The water-soluble organic compounds content decreases and the aromatic components content increases in the SOM and its individual fractions in post-pyrogenic soils.

Pyrogenic morphological and analytical features are preserved in soils' pyrogenic morphological and analytical signs persist for tens and hundreds of years and reflect the contemporary soils evolution and the specific parameters of SOM. It may be necessary to introduce a universal soil subtype – "pyrogenic" ("pyr") in the presence of pyrogenic characteristics in the soil profile.

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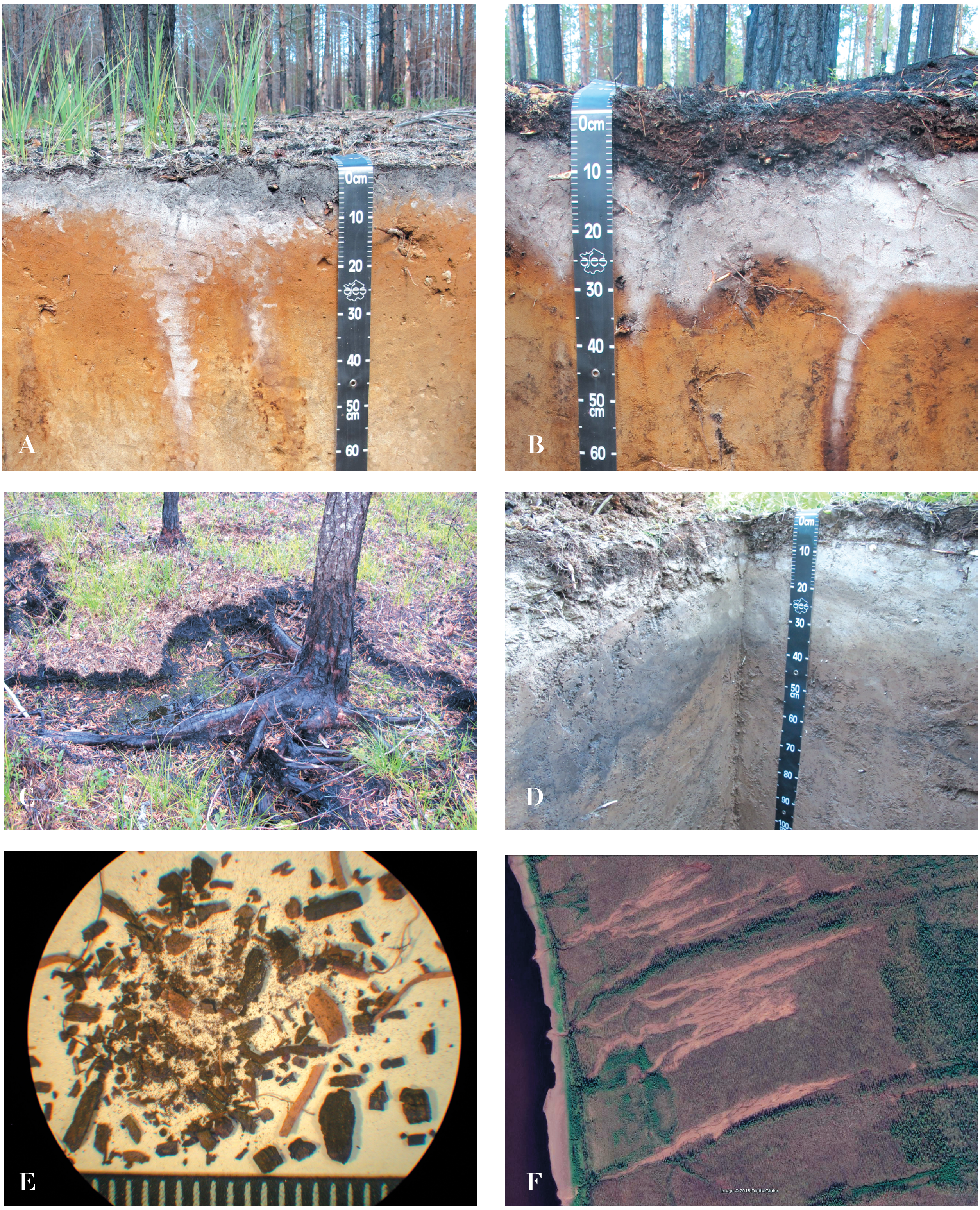

Fig. 2. Examples of pyrogenic soil changes. A – pyrogenic Podzol in the lichen pine forest (2 years after the fire); B – pyrogenic Podzol in the cowberry-green moss pine forest (80 days after the fire); C – focal litter burnout in the sphagnum pine forest (a year after the fire); D – pyrogenic buried horizon (left photo) in the Retisols in the green moss spruce forest (about 150 years after the fire); E – charcoal inclusions, separated by 1.6 g/cm^3 of sodium polytungstate solution; F – post-fire solifluction process development, Central Siberia

A. A. DYMOV, E. V. ABAKUMOV, I. N. BEZKOROVAYNAYA, A. S. PROKUSHKIN, YA. V. KUZYAKOV, E. YU. MILANOVSKY IMPACT OF FOREST FIRE ON SOIL PROPERTIES (REVIEW), P. 13

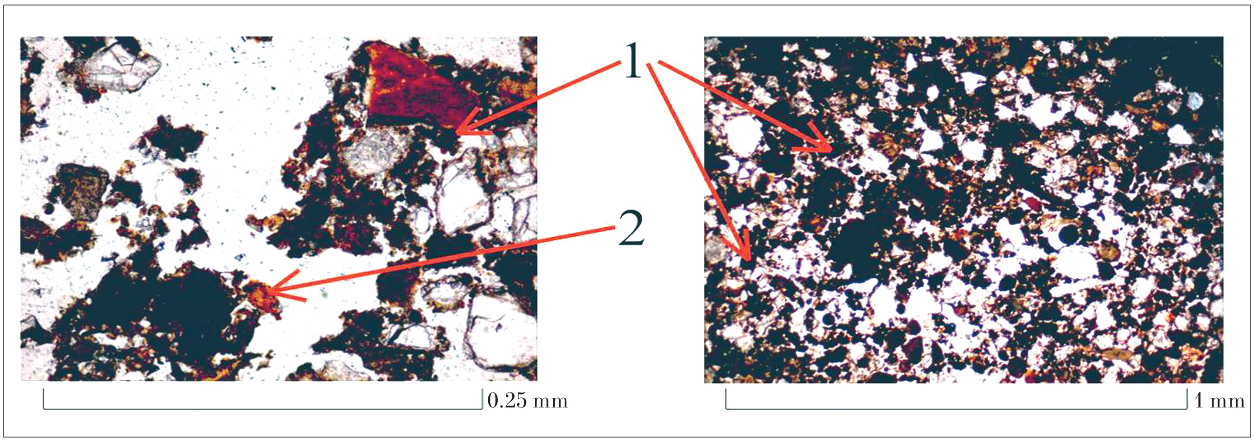

Fig. 3. Microstructure of the upper mineral horizons of postpyrogenic soils in reflected light, where 1 – products of combustion (Black carbon), 2 – particles with unhumified plant residues [29]

В. А. СЫСУЕВ, А. В. АЛЁШКИН, Ю. В. СЫЧУГОВ, А. Ю. ИСУПОВ КОМБИНИРОВАННЫЕ РАСЧЁТНЫЕ СХЕМЫ В МАТЕМАТИЧЕСКИХ МОДЕЛЯХ ПРОЦЕССОВ ФРАКЦИОНИРОВАНИЯ ЗЕРНА, С. 24

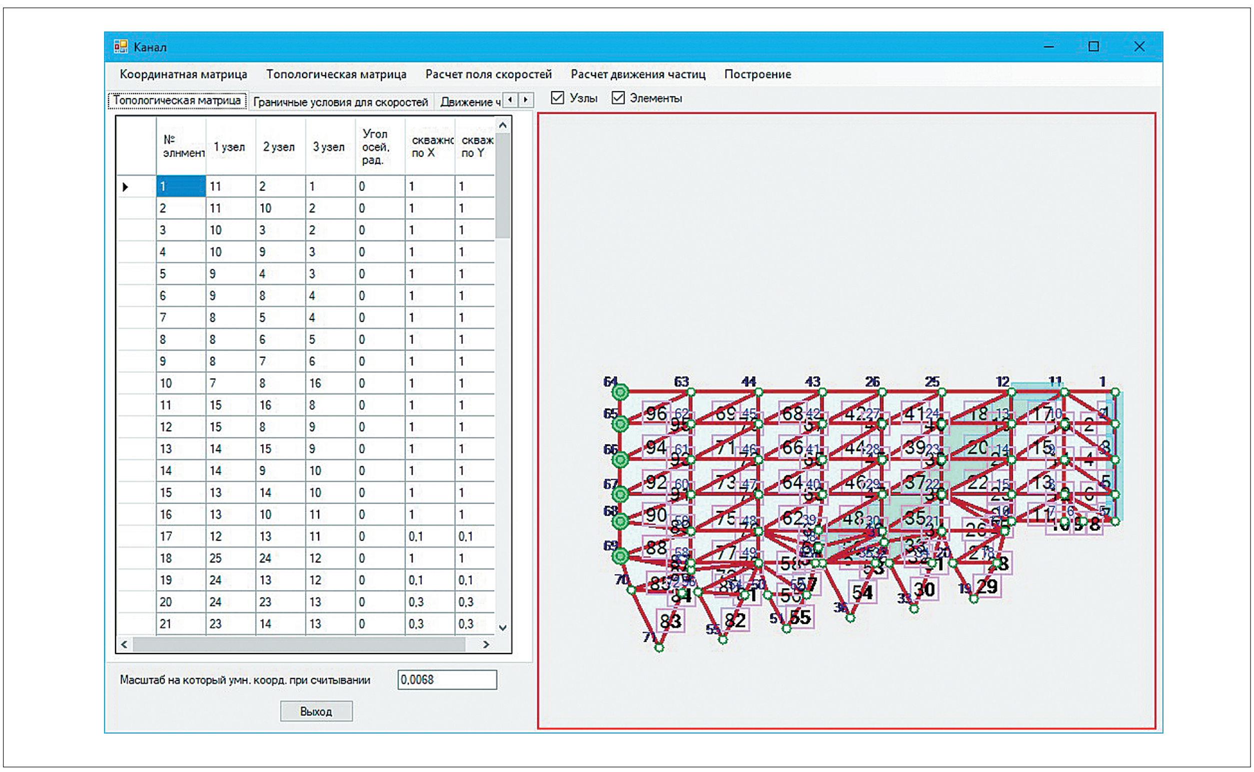

Рис. 2. Расчётная схема разбиения горизонтального канала пневмосепаратора на конечные элементы
Fig. 2. Design scheme of horizontal channel splitting pneumoseparation into finite elements