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ORIGINAL ARTICLES

AFTERMATH OF FIRES FOR MESOPHYTIC FORESTS' SOILS IN WESTERN CAUCASUS[1]

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Abstract. Every year, vast areas of forests burn down during fires all over the world. The literature contains contradictory data on the effects of fires on individual components of ecosystems, in particular on soils. This necessitates the study of the aftermath of fires in different climatic and soil conditions. The aim of this work is studying the consequences of a ground fire on the properties of phaeozems of the Khamyshinsky district forestry unit of the Adygea Republic 4 years after the impact. The chemical (CEC, hydrolytic acidity, pH, organic carbon and active carbon content) and biological (activity of catalase, dehydrogenases, invertase, urease, phosphatase) properties of post-pyrogenic soils on one fully and two partially burned areas have been studied. The ground fire did not cause significant changes in the composition of the forest stand for burned areas No. 2 (1159 m above sea level) and No. 3 (1359 m above sea level), while the burned area No. 1 (651 m above sea level) was characterised by completely charred trees, abundant growth of pontic rhododendron, and poorly developed herbaceous vegetation. A 51% decrease in catalase activity compared to the control was found in the three areas. The activity of dehydrogenases and urease in post-pyrogenic soils exceeded the control values by an average of 62%. The activity of invertase and phosphatase varied depending on the study area. In general, there was a tendency toward an increase in the activity of these enzymes. At the same time, a high spatial variation in the activity of soil dehydrogenases and invertase was found for burned-out area No. 1. There also was an increase in hydrolytic acidity by an average of 43% compared to the control values. The CEC, the content of organic and active carbon differs to a lesser extent from the control values 4 years after the fire. The acidity index (pH) of the area devoid of grassy vegetation reaches 5.8, with control having pH of 4. Notably, higher values of the CEC correspond to higher pH values. Factor analysis showed that changes in the enzymatic activity of post-pyrogenic phaeozem are associated with the peculiarities of the soils' chemical properties. The activity of hydrolases (urease, phosphatase) is closely related to the content of organic carbon, and the activity of other enzymes – to the CEC, hydrolytic acidity and pH. The content of active carbon changes insignificantly and does not affect the enzymatic activity.

Keywords: *pyrogenic factor, enzymatic activity, chemical properties, phaeozem, bioindication*

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The intensity of forest fires has increased significantly over the last decades. In 2023, according to the data of the Federal Budgetary Institution "Avialesookhrana", the area covered by fire in Russia alone amounted to 11.8 million ha. Forests are the largest carbon sink among terrestrial ecosystems (Sitch et al., 2008). During forest fires, carbon dioxide is released into the atmosphere in large quantities, which is a major contributor to the increase in greenhouse gas concentrations, which in turn leads to climate change (Sommers et al., 2014; Oertel et al., 2016; Kuhar et al., 2019; Mansoor et al., 2022). Further increase in greenhouse gas emissions may force to consider forests not as a carbon sink but as a carbon source (Shvidenko and Shchepashchenko, 2014; Ponomarev et al., 2023; Fan et al., 2023). In the Western Caucasus, xerophytic forests of the Black Sea coast are most vulnerable to fire (Kazeev et al., 2019; Vilkova et al., 2022; Vilkova et al., 2023), while fire risks are lower in mesophytic forests (Baltzer et al., 2021; Bogdanovich et al., 2021).

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Soil is one of the most valuable natural resources involved in nutrient cycling. Degradation of biological, chemical and physical properties of forest soils caused by fires reduces their ability to fully perform ecological functions. Thus, in the study of post-fire soil properties, changes in carbon stock (Akburak et al., 2018), soil media reaction values (Francos et al., 2019; Hinojosa et al, 2021), the sum of exchangeable bases (Gyninova et al., 2018), hydrolytic acidity (Krasnoshchekov, 2018; Gorbunova and Devyatova, 2019), and enzymatic activity (Kazeev et al., 2019; Vilkova et al., 2022; Vilkova et al., 2023). At the same time, the nature of changes largely depends on the type of fire, its duration and intensity, as well as on the terrain features, vegetation type and initial soil properties (Sapozhnikov et al., 2001; Sharagin, 2011; Alcañiz et al., 2018; Lucas-Borja et al., 2020; Vilkova et al., 2024). It is worth noting that fire is a complex factor, so the soil quality is significantly affected not only by the thermal factor, but also by smoke (Nizhelsky et al., 2022).

Despite the large number of studies on this topic, there are contradictory results on the assessment of post-fire changes, and the issues of assessing the impact of fires on soils of different forest zones are still topical. The aim of this work is to assess the effects of lowland fire on the properties of lignite soils in the Western Caucasus 4 years after pyrogenic impact

OBJECTS AND METHODOLOGY

The objects of the study are located in the territory of the Khamyshinsky district forestry (Republic of Adygea). This territory belongs to the Western Mountain Province of the Greater Caucasus. The average annual precipitation is 1200 mm, the average annual temperature is +10.3 °C. The forest belt of the northern macro-slope is represented by mesophytic broad-leaved (beech, oak-hornbeam) and dark coniferous (mainly beech-fir) forests (Akatov, 2014, 2018; Akatov et al., 1990; Litvinskaya, 2020). The soil cover is formed by brown forest soils, Cambisols (WRB, 2014), the litter is sparse. Soils of post-felling successions are the most studied in this area (Lukina et al., 2018; Shevchenko et al., 2019; Kazeev et al., 2021; Shkhapatsev et al., 2022), while post-fire successions remain poorly studied

In June 2022, as a result of field surveys, 3 monitoring plots affected by the fire in 2018 were established in the territory of the Khamyshinsky district forestry. The lowland fire did not cause significant changes in the composition of the stand at the sites of burned areas No. 2, 3; at these sites the forest litter was destroyed, the lower parts of tree trunks up to 15 cm were charred. At the same time, the area of burned area No. 1 was affected to a greater extent, fully charred trees were observed here. On the plateau-shaped areaNo. 1 surrounded by dense thickets of sticky alder (*Alnus glutinosa* L.) undergrowth (up to 4—5 m) with beautiful maple (*Acer laetum* C.A. Mey) and *Rhododendron ponticum* (*Rhododendron ponticum* L.), the vegetation is represented by a fir-beech forest with an understorey of relict shrubs. Caucasian fir (*Abies nordmanniana* (Steven) Spach) forms the basis of the first tree tier A (up to 50 m), it is co-dominated by oriental beech (*Fagus orientalis* Lipsky). The stand formula is 6Px4Bk. The second tree stand B is poorly expressed, and its composition occasionally includes the same tree species: Caucasian fir and Oriental beech. Shrub layer C is moderately pronounced (up to 30—40%). Its basis is *Rhododendron ponticum*, Rhododendron yellow (Rhododendron *luteum* Sweet) and Caucasian bilberry (*Vaccinium arctostaphylos* L.) are sporadically recorded. The shrub layer also includes common undergrowth of tree species: Caucasian fir, sticky alder, beautiful maple, sharp-leaved maple (*Acer platanoides* L.), eastern beech, linden (*Tilia begonifolia* Stev.), and occasionally undergrowth of hooked pine (*Pinus sylvestris* L. subsp. hamata). Herbaceous cover is poorly developed (up to 30%), mainly in more open areas of the site. It is based on mountain fescue (*Festuca drymeja* Mert. & W.D.J. Koch), with scattered occurrences of giant fescue (*Festuca gigintea* (L.) Vill.), oriental goatgrass (*Galega orientalis* Lam.), and golden chyna (*Lathyrus aureus* (Steven) Barandza)

A forest plot unaffected by the pyrogenic factor was selected as a control. The forest type, as well as the soil type of all three plots and the control, is similar: forest — fir-beech-hornbeam, soil — brown earth (Cambisols). Some differences in vegetation are noted only in the site of burned area No. 1, as this site has suffered from pyrogenic impact to a greater extent, herbaceous cover is still poorly developed. Location and description of the study sites are presented in Fig. 1, Table 1.

The sampling sites were laid out randomly in triplicate for each monitoring site under study. Soil samples were collected along the soil profile, but the main attention was paid to the 0—3 cm layer in triplicate for each studied monitoring site. According to literature data, only the surface layer of soil is susceptible to pyrogenic effects (Kazeev et al., 2020; Medvedeva et al., 2020). Soil was air-dried in the shade, organic residues and inclusions were sampled, grinded and sieved through a sieve with a 1 mm hole diameter. Soil enzymatic activity studies were carried out in the first 2 weeks after sampling, the soil was stored air-dry at room temperature.

Analytical studies were performed using methods common in soil science and biology (Kazeev et al., 2016). Soil catalase activity was determined by the volume of released oxygen during decomposition of 3% hydrogen peroxide. Urease activity was determined by the amount of ammonium nitrogen formed during hydrolysis of 3% urea by colorimetric method with Nessler's reagent, invertase activity was determined by modified colorimetric method with Fehling's reagent. Phosphatase activity was determined by the colorimetric method on the account of phosphorus formed by hydrolysis of sodium p-nitrophenylphosphate. The activity of soil enzymes was measured in aqueous solutions without buffers as recommended for biodiagnostic purposes (Galstyan et al., 1978; Kazeev et al., 2016), the soil sample for each enzyme studied was 1 g. Organic carbon content (0.1 g soil sample) was determined by oxidizability by chromium mixture with spectrophotometric termination using the method of I. V. Tyurin modified by B. A. Nikitin (1972). Active carbon (mobile humus) was determined by the modified Blair method with soil treatment (2.5 g sample) with 0.1 n potassium permanganate solution, which gives an idea of the content of the most easily oxidizable substances available for microorganisms (Blair et al., 1995; Moebius-Clune et al., 2016). Determination of soil medium reaction (pH) was carried out by potentiometric method (10 g soil sample) at a soil: KCl 1 n solution ratio of 1:2.5. Hydrolytic acidity was determined by the Kappen method (in modification of CINAO), which is based on measuring the pH of soil suspension based on 1 M sodium acetic acid solution at a soil to solution ratio of 1:2.5 (Agrochemistry Workshop, 2001). The Kappen-Gilkovits method of determining the sum of exchangeable bases is based on displacement of exchangeable

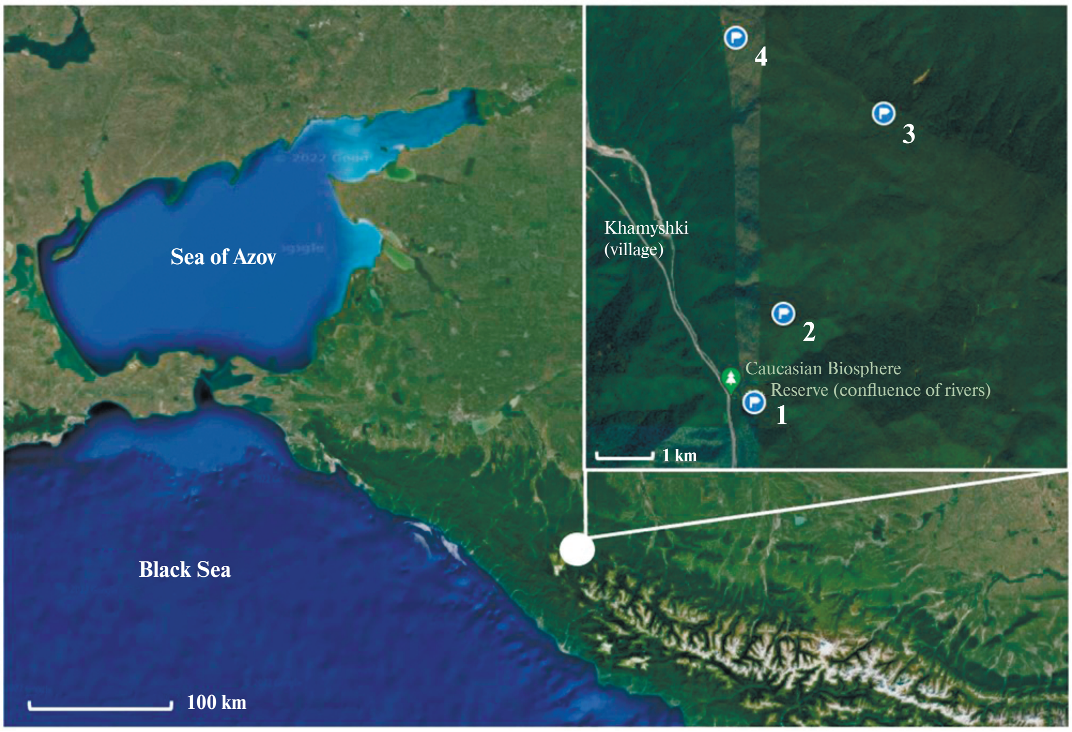

Fig. 1. Location of the study sites on the territory of the Khamyshinsky lesnichestvo (Republic of Adygea), where 1 — control; 2 — burned area No. 1; 3 — burned areaNo. 2; 4 — burned area No. 3.

Table 1. Description of the study sites in the territory of the Khamyshinsky district forestry, Republic of Adygea

Plot	Geographic coordinates	Altitude above sea level, m	Slope steepness, exposure	Vegetation
Control	N44°04.165', E040°10.954'	932	3° SOUTH	Dead-forest, *Fagus orientalis* Lipsky, *Carpinus betulus* L., *Tilia begoniifolia* Stev.
Burn No. 1	N44°03.466' E040°10.600'	651	24° SOUTH	Redina, overgrowth *Rhododendron ponticum* L., *Vaccinium arctostaphylos* L. occurs, rare undergrowth *Alnus glutinosa* L., herbaceous cover is poorly developed
Burn No. 2	N44°06.272' E040°10.470'	1159	3° SOUTH	*Betula pubescens* Ehrh., *Fagus orientalis* Lipsky. Herbaceous-shrub vegetation is represented by *Rubus* sp., *Sambucus* sp., juvenile *Alnus glutinosa* L., cereal herbaceous diversity
Burn No. 3	N44°05.692' E040°12.044'	1359	10° WEST	Redina, *Rubus* sp. overgrowth, juvenile *Carpinus betulus* L., *Alnus glutinosa* L., up to 0.5 m high, *Abies nordmanniana* (Steven) Spach, *Fagus orientalis*

bases by hydrogen ion of 0.1 n hydrochloric acid solution (Agrochemistry Workshop, 2001)

Geobotanical descriptions were carried out according to generally accepted methods in accordance with standard approaches (Mirkin and Naumova, 2012). The species affiliation of plants was determined according to regional identifiers (Kosenko, 1970; Zernov, 2006). Species names are given according to the work “Vascular Plants of Russia and Neighboring States” (Cherepanov, 1995).

Factor analysis was performed to identify the correlation structure within the set of observed variables. Statistical processing of data was performed using Statistica 13.3 and MS Excel. Statistically significant differences with a significance level of 5% ($p < 0.05$) were considered when discussing the results.

RESULTS AND DISCUSSION

In the course of studies of enzymatic activity of postpyrogenic lignite of the Hamyshinsky district forestry 4 years after the fire for average values for each plot, a reliable decrease in catalase activity for soils of burned area No. 1 by 25% relative to control values was established, for soils of burned areas No. 2, 3 by 65% on average (Fig. 2, a).

The aggregate data for all three sites and the control are quite homogeneous, with the coefficient of variation ranging from 9 to 20%. Other works also note prolonged inhibition of enzyme activity from the class of oxidases after fires and anthropogenic disturbances (Kazeev et al., 2021; Vilkova et al., 2023). For dehydrogenases, an increase in enzyme activity relative to control values was noted for soils of burned area No. 1 by 257%, and for burned area No. 3 — by 21% (Fig. 2, b). At the same time, the established differences for the No. 2 burned area are unreliable. The coefficient of variation of the trait for gari No. 1 is 50%, which indicates a large variability of the obtained values, for other sites the coefficient of variation does not exceed 33%. Since dehydrogenases are active only in living cells, the increase in the values of this enzyme indicates the microbiological nature of organic matter decomposition (Kazeev et al., 2016). The activity of invertase was reduced for the soils of burned area No. 1 by 31%, for the other two sites an increase in activity was found on average by 143% relative to the control values (Fig. 2, c). The coefficient of variation of the trait for gari No. 1 is 107%, which indicates a high variability of the indicator values, for other sites the coefficient of variation does not exceed 25%. Urease activity for soils ofNo. 2 burned area is 80% higher relative to control values, for the other two plots the revealed differences are unreliable (Fig. 2, d). Phosphatase activity is significantly decreased for soils of burn site No. 1 by 50%, for No. 2 burn site the enzyme activity is increased by 84%, and for burn site No. 3 — by 24% (Fig. 2, e). The aggregate of urease and phosphatase activity values is absolutely homogeneous, the coefficient of variation does not exceed 22%. Such differences in the nature of changes in the enzymatic activity of soils between sites are related both to the heterogeneity of the burning process itself and to different features of recovery 4 years after exposure. Biological properties of soils are in direct dependence on the depth of burning of organic horizons, as well as on the degree of burning of the root system of trees, which is characteristic of forest phytocenoses (Usenya et al., 2018)

Despite the fact that the established differences in mean values are reliable, the spatial variation of indicators within one site is significant, which can be explained by the peculiarities of soils, hydrothermal conditions and microrelief of the area. The identified differences in enzymatic activity are due to the processes of soil properties recovery after the pyrogenic factor. Indeed, the consequences of the fire are leveled in the first year after exposure to the factor, then a greater contribution is made by the development of the turf process, which in turn reduces the risks of erosion development (Komissarov and Gabbasova, 2017).

The study of chemical properties of post-pyrogenic soils revealed a reliable increase in the average values of the sum of absorbed bases for the soils of Gari No. 1 relative to the average values of the control. The revealed differences for the other sites are unreliable. The average values of hydrolytic acidity are significantly higher by 96% at the site of burned area No. 1, by 32% for burned areasNo. 2, 3. The differences are not reliable. The reaction of soil medium of salt suspension for gari No. 1 increased to 5.8 units, and for No. burned areas 2, 3—4.1 and 4.2 units, respectively. The increase in pH values is associated with ashing of litter and saturation of the absorbing complex of pyrogenic soils with bases (Xue et al., 2014; Zhurkova, Shcherbov, 2016; Maslov et al., 2018). Higher pH values correspond to high values of the sum of absorbed bases, which is consistent with literature data (Sokolova et al., 2012). Despite the fact that changes in chemical indicators do not persist for long (Maksimova et al., 2014), prolonged alkalinization of the soils of Gari No. 1 was noted, which is uncharacteristic of the soils of the other two post-pyrogenic sites. Probably, the impact on Gari No. 1 was more intensive, moreover, this site is still not covered with herbaceous vegetation. Decrease of organic carbon content (C_{org}) by 18% on average values for soils of the site of burned area No. 1 was established, for burned areasNo. 2, 3 the revealed differences from control values are unreliable. A sharp decrease in the humus content and its energy reserves was noted in lignite forest lignites of the Amur region after a fire in larch forest (Purtova et al., 2012). The content of active carbon (C_{act}) was significantly reduced for soils of burned areas No. 1, 3 by 6 and 7%, respectively, compared to the control values, the differences of the indicator for soils of the burned areaNo. 2 are unreliable. After fires there is an increase in mineralization of organic carbon, which leads to a decrease in its content. This is due to the destruction of organogenic horizons, mineralization of root residues, in addition, the organic matter that entered the soil is charred, decomposes slowly and is inaccessible to microorganisms (Dymov et al., 2014; Stavrova et al., 2019; Singh

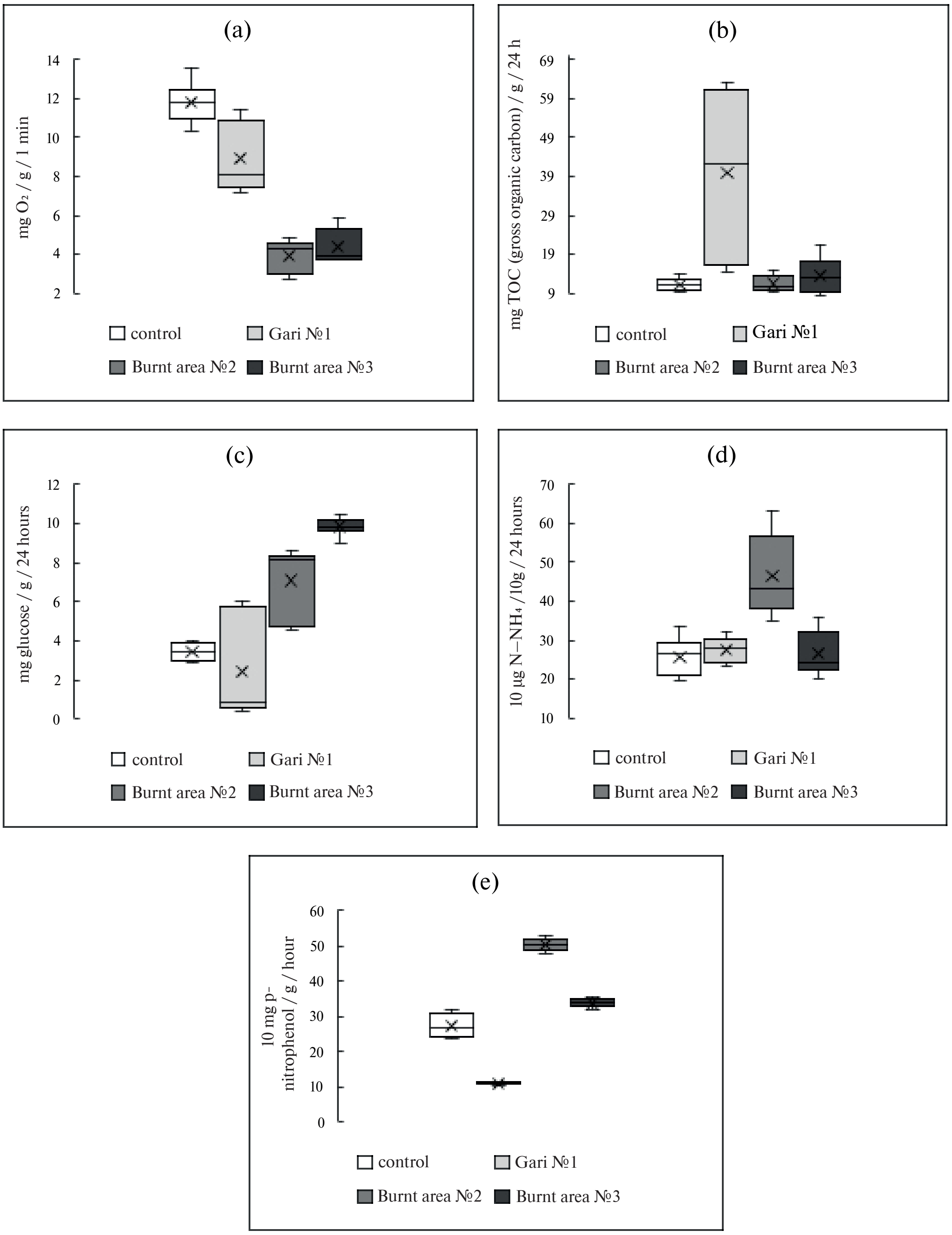

Fig. 2. Enzymatic activity of post-pyrogenic brown soil of the Khamyshinsky lesnichestvo 4 years after the fire: a — catalase activity, b — dehydrogenase activity, c — invertase activity, d — urease activity, e — phosphatase activity.

et al., 2021). Absolute values of soil chemical properties are presented in Table 2.

Correlation analysis was carried out to reveal the nature and closeness of connection of indicators with each other. Between the activity of catalase and invertase, phosphatase a medium negative correlation relationship was noted (r = –0.70). A weak negative correlation relationship was established between dehydrogenase and phosphatase activity (r = –0.50). Invertase is moderately to positively correlated with phosphatase activity (r = 0.70). A weak positive correlation was noted between urease and phosphatase activity (r = 0.47). The sum of absorbed bases of post-pyrogenic lignite is moderately and positively correlated with hydrolytic acidity, pH, and dehydrogenase activity (r = 0.38—0.69), a high positive correlation relationship was noted with catalase activity (r = 0.75). Medium and strong correlations were established between hydrolytic acidity, sum of absorbed bases with invertase activity (r = –0.56 — –0.78). A medium negative correlation was established between the sum of absorbed bases and phosphatase activity (r = –0.60). A medium positive correlation was noted between dehydrogenase activity and pH (0.38), with a medium negative correlation between pH and invertase activity (r = –0.35). Organic carbon content is moderately and positively correlated with urease and phosphatase activity (r = 0.47—0.54).

Fig. 3 shows the graph of factor coordinates based on correlation for all studied indicators of postpyrogenic lignite properties.

Such indicators as the activity of catalase, invertase, dehydrogenases, as well as the content of organic carbon and active carbon, are close enough to the unit circle line, hence, these indicators are well reproducible in the system of coordinates found (Fig. 3). At that, factors 1 and 2 explain 67 % of the total variance. Hydrolytic acidity and the sum of absorbed bases increased with increasing soil pH. The same relationship with invertase, urease and phosphatase activity is opposite. A close relationship between the activity of invertase, urease and phosphatase with organic carbon content and active carbon was found. The relationship of C_{org} with the activity of dehydrogenases is opposite. At the same time, C_{act} has no reliable correlation with any of the studied indicators, so it is far from the circle line in this coordinate system. In the change of enzymatic activity of hydrolases the content of organic carbon plays a major role, and in the change of activity of oxidases — the values of pH, hydrolytic acidity and the sum of absorbed bases.

CONCLUSION

Mesophytic forests of the Western Caucasus are rarely affected by pyrogenic factor. However, even low-intensity fires in this area cause catastrophic damage to the entire ecosystem and soil in particular. Thus, 4 years after a low-intensity fire in the territory of the Khamyshinsky district forestry of the Republic of Adygea, the change in the activity of enzymes of lignite from the class of oxidases (dehydrogenase, catalase) and hydrolases (invertase, urease, phosphatase) was noted. A prolonged decrease in the activity of catalase was established, for the other enzymes a tendency to increase activity relative to control was noted, but this does not indicate a complete restoration of soil properties, but only favorable hydrothermal conditions for the development of soil microorganisms of the reduction succession. The tendency of enzymes to increase their activity can be presented in the series: dehydrogenase > invertase > urease > phosphatase > catalase. In many respects, changes in biological properties of soils are conditioned by peculiarities of chemical properties, which is confirmed by factor analysis

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Table 2. Properties of post-pyrogenic brown soil of the Khamyshinsky district forestry 4 years after the fire

Plot	Sum of absorbed bases, mg*eq/100g	Hydrolytic acidity, mmol/100g	pH, unit.	C_{org}, %	$_{Act}S$, 100 mgC/kg
Control	9.3 ± 0.23	6.5 ± 0.02	4 ± 0.04	3.8 ± 0.10	7.3 ± 0.41
Burn No. 1	19.1 ± 2.45	7.1 ± 0.12	5.8 ± 0.37	3.3 ± 0.15	6.8 ± 0.42
Burn No. 2	9.3 ± 0.37	6.4 ± 0.03	4.1 ± 0.09	4.7 ± 0.27	7.3 ± 0.83
Burn No.3	6.3 ± 1.31	6.5 ± 0.01	4.2 ± 0.13	3.4 ± 0.23	6.8 ± 0.47

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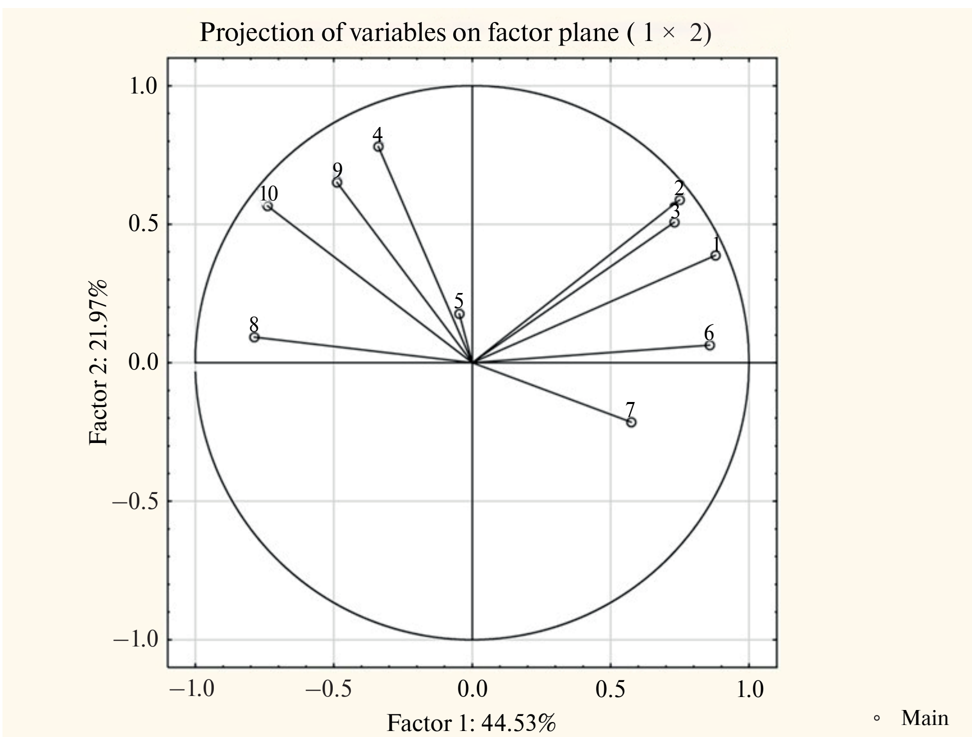

Fig. 3. Projection of variables on the factor plane of the properties of post-pyrogenic brown soil of the Khamyshinsky lesnichestvo 4 years after the fire:
1 — sum of absorbed bases, 2 — hydrolytic acidity, 3 — pH, 4 — C_{org}, 5 — $_{act}C$, 6 — catalase, 7 — dehydrogenases, 8 — invertase, 9 — urease, 10 — phosphatase.

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