



## Post-pyrogenic changes in vegetation cover and biological soil crust in steppe ecosystems

V. V. Shcherbyna\*, I. A. Maltseva\*\*, Y. I. Maltsev\*\*, A. N. Solonenko\*\*

\*Tavria State Agrotechnological University, Melitopol, Ukraine

\*\*Melitopol Bohdan Khmelnytskyi State Pedagogical University, Melitopol, Ukraine

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Tavria State Agrotechnological  
University, B.Khmelnytskyi Ave.,  
18, Melitopol, 72310, Ukraine.

Melitopol Bohdan Khmelnytskyi  
State Pedagogical University,  
Hetmanska str., 20, Melitopol,  
72312, Ukraine.  
Tel.: +38-097-506-25-20.  
E-mail: shcherbyna\_vv@ukr.net

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The study of the processes of restoration of species richness and productivity of steppe ecosystems after fires is an urgent problem that affects not only the conservation of biodiversity but also the maintenance of pasture resources. This article presents the results of a study of post-pyrogenic effects in steppe ecosystems, taking into account changes in the species composition of cyanoprokaryotes and algae that are part of the biological soil crust, which performs ecologically important functions in xerophytic ecosystems. The investigations were carried out in virgin and post-pyrogenic steppe ecosystems of the “Troitsk Clough” reserve (Zaporizhia region, Ukraine). For three years, the dynamics of the projective cover and the height of the vegetation cover in virgin areas of herbs-fescue-feather-grass and fescue-feather-grass steppes was studied as well as within two ecosystems of post-pyrogenic development after fires that occurred in the spring and winter periods. We discovered that restoration of the herbs-fescue-feather-grass and fescue-feather-grass steppes after fires occurs at different rates. The cause of the slow restoration of vegetation cover can be its severe damage by fire at the beginning of the vegetation season and the development of erosion processes. The number of species of cyanoprokaryotes and algae in the biological soil crust of virgin and post-pyrogenic ecosystems is not significantly different. It varies from 35 to 49 species. The greatest diversity is noted for Cyanoprokaryota. Chlorophyta is in the second place. Among the dominants, the filamentous forms of Cyanoprokaryota prevail. *Nostoc edaphicum* was noted as a nitrogen fixing representative. The similarity of the species lists of cyanoprokaryotes and algae of post-pyrogenic and virgin ecosystems, according to the calculated Jaccard coefficient, varies from 49.1% to 55.3%. This indicates a strong specificity of the composition of cyanoprokaryotes and algae in post-pyrogenic biological soil crusts. Changes in their composition reflect different stages of post-pyrogenic succession. In the first year after a fire, there is a slight increase in species richness, which is a consequence of the favorable effect of increasing the amount of mineral substances in the soil after the organic matter has burned out. The “pioneer” group includes: *Phormidium autumnale*, *Ph. dimorphum*, *Ph. retzii*, *Ph. (Leptolyngbya) henningsii*, *Luticola mutica*, *Hantzschia amphioxys*. Gradually this effect is leveled and the species richness of cyanoprokaryotes and algae is stabilized at a level peculiar for this type of ecosystem.

**Keywords:** steppe; fire; algae; cyanoprokaryotes; projective cover; biological soil crust; post-pyrogenic succession

### Introduction

Fires in ecosystems formed by grasses is a fairly common phenomenon associated with the effects of natural and anthropogenic factors (Kolomiets and Burda, 2007; Scheintaub et al., 2009; Clark et al., 2016). The study of the processes of restoration of their species richness and productivity after fires is a relevant problem considering the interests of not only the conservation of biodiversity but also the maintenance of pasture resources.

It is believed that the pyrogenic factor has a significant influence on the formation and evolution of the grass ecosystems, directing the natural selection to increase the fire resistance of biological diversity, the ability to quickly and most effectively use the changed environmental conditions (salinity of the soil cover, hydrothermal and geochemical regimes, etc.) for recovery, growth and development (Lysenko, 2008; Cleary et al., 2010; Buc, 2012). Changes that occur after fires in grass ecosystems have become the basis for working out the models with different scenarios of vegetation burning to control the productivity and

species composition of pasture vegetation (Allen et al., 2011; Strong et al., 2013; Fonseca et al., 2017).

The occurrence and spread of fire leads to changes in all components of ecosystems. Their recovery is realized by successive digressive-demutational changes, the study of which has received considerable attention (Kolomiets and Burda, 2007; Havrylenko, 2011; Buc, 2012). Y. Odum singles out the changes of ecosystems after a fire in a separate group of post-pyrogenic successions, calling them “pulsating stable successions”. Peculiarities of pyrogenic changes and demutational processes are caused both by the specifics of ecosystem components and by the scale, intensity, time of occurrence of fires and other factors (Shcherbina et al., 2014; Savadogo et al., 2017).

In the literature, there is a lot of data on the analysis of postpyrogenic transformations of soil (Vermeire et al., 2011; Rau et al., 2014; Qi et al., 2017), phytocenoses (Tooth and Leishman, 2013; Reed-Dustin et al., 2016), zoocenoses (Mordkovich et al., 2007; Morgun, 2010). The changes that occur in coenoses of soil microorganisms under the influence of fires, including algae communities (Chumacheva, 2001;

Myers and Davis, 2003; Pivovarova and Chumacheva, 2004) are much less studied. The latter are considered as an integral part of biological soil crusts, performing important ecological functions in grass ecosystems and, especially, in their xerophytic variants (Maestre et al., 2002; Belnap, 2002; Dettweiler-Robinson et al., 2013).

Soil algae and cyanoprokaryotes are pioneers of settling intrusions. Therefore, they can be the indicators of processes occurring in ecosystems immediately after fires and reflect the dynamics of their restoration from pyrogenic transformation. The data, obtained during the research presented in this article can be used in subsequent studies of post-pyrogenic territories, working out the scenarios of controlling their productivity and biodiversity processes. The aim of our research was to study post-pyrogenic effects in steppe ecosystems, taking into account the changes in the species composition of cyanoprokaryotes and algae included in the biological soil crust composition.

## Materials and methods

Steppe ecosystems have been preserved in the territory of Ukraine mainly in protected areas. For their protection, a variety of different modes are used: from creation of strict nature reserve creation to the use of natural steppe areas as hayfields and for grazing. Our study of post-pyrogenic changes was conducted on the steppe plots of the local reserve "Troitsk Clough" (Zaporizhia region, Ukraine) under the conditions of herbs-fescue-feather-grass steppe (PP 1) and fescue-feather-grass steppe (PP 2) as well as within two ecosystems of post-pyrogenic development following 2009 (PP 3) and 2010 (PP 4) fires over 3 years in different seasons of the year. To evaluate post-pyrogenic changes, the projective cover and height of vegetation cover of virgin steppe and post-pyrogenic areas were investigated. To study the composition of cyanoprokaryotes and algae in the biological soil crust of steppe ecosystems, soil samples were selected in compliance with all requirements

**Table 1**

Projective cover and height of vegetation cover of etalon and post-pyrogenic ecosystems of the reserve "Troitsk Clough" in the years and seasons of the study ( $M \pm m$ ,  $n = 6$ )

Criteria	2009		2010		2011		
	autumn	spring	summer	autumn	spring	summer	autumn
PP 1. Virgin steppe. Herbs-fescue-feather-grass							
Projective cover, %	71.3 ± 4.1	69.1 ± 3.2	68.6 ± 3.9	72.3 ± 2.5	69.3 ± 2.9	69.2 ± 2.2	70.8 ± 4.2
Height of vegetation cover, cm	80.0 ± 5.9	90.2 ± 11.3	70.2 ± 4.3	95.6 ± 6.8	80.3 ± 5.1	60.7 ± 3.7	82.3 ± 4.1
PP 2. Virgin steppe. Fescue-feather-grass steppe							
Projective cover, %	59.5 ± 3.1	60.6 ± 4.2	62.2 ± 2.2	54.2 ± 3.7	69.3 ± 6.5	54.3 ± 4.2	58.6 ± 4.7
Height of vegetation cover, cm	65.1 ± 5.1	60.9 ± 4.7	73.6 ± 9.6	72.8 ± 4.8	55.3 ± 3.7	68.9 ± 7.8	59.3 ± 3.5
PP 3. Virgin steppe. Post-pyrogenic succession of winter fire in 2009							
Projective cover, %	42.3 ± 6.2	70.3 ± 5.2	68.6 ± 4.7	72.3 ± 4.7	69.3 ± 4.2	69.2 ± 5.7	70.8 ± 6.2
Height of vegetation cover, cm	63.0 ± 3.7	90.3 ± 5.0	70.2 ± 8.4	95.6 ± 9.3	80.3 ± 4.5	60.7 ± 3.6	82.3 ± 7.1
PP 4. Virgin steppe. Post-pyrogenic succession of spring fire in 2010							
Projective cover, %	—*	0	6.2 ± 0.5	10.6 ± 1.8	10.8 ± 1.6	12.3 ± 0.8	10.1 ± 0.7
Height of vegetation cover, cm	—	0	22.3 ± 2.7	26.8 ± 3.1	28.7 ± 2.7	25.3 ± 3.0	24.6 ± 3.7

Note: M – arithmetic mean; m – error of arithmetic mean; n – general sampling; \* – research was not realized.

According to the principle of geobotanical zoning, the researched object of Ukraine's nature reserve fund lies within the Euro-Asian steppe region, the Black Sea steppe province, Priazovsko-Black Sea steppe subprovince in the band of fescue-feather grass steppes. Fescue-feathergrass steppes are characterized by a predominance of xerophilic turf grasses with poor xerophilic grasses of such typical species as *Ferula orientalis* L., *Verbascum phoeniceum* L., *Carduus uncinatus* Bieb., *Tanacetum millefolium* (L.) Tzvel and others.

The higher vegetation flora of "Troitsk Clough" numbers about 450 species. Its territory is dominated by steppe vegetation (class Festuco-Brometea) with domination of *Stipa lessingiana* Trin. et Rupr., *Stipa capillata* L., *Stipa ucrainica* P. Smim, *Agropyron pectinatum* (Beib.) Beauv., *Festuca valesiaca* Gaud. The site is one of the most important localities in Ukraine for *Calophaca wolgarica* (L. fil.) DC, *Cymboschasma borysthena* (Pall. ex Schlecht.) Klok. et Zoz, *Allium pervestitum* Klok., *Elytrigia stipifolia* (Czern. ex Nevski) Nevski, *Caragana scythica* (Kom.) Pojark, *Centaurea talievii* Kleopow, *Astragalus pallescens* Bieb., *Eremogone rigida* (M. Bieb.) Fenzl. Many other rare species

for microbiological studies. The methodology proposed by M. M. Golebch and E. A. Shtyna (1969) was applied. Determining species composition of algae and cyanoprokaryotes was performed by using an optical microscope XSP-128V (lens 4x, 10x, 40x, 100x) involving the following culture methods: method of ground crops with glasses fouling batch culture, method of enrichment cultures on agar nutrient environment and method of pure cultures (Kostikov et al., 2001). Allologically pure cultures were defined by using a stereoscopic microscope MBS 1.

Identifying the species belonging to the algae of the Cyanoprokaryota (Cyanophyta), Chlorophyta, Xanthophyta and Eustigmatophyta groups was realized through the study of living cultures, which helped to determine identifiably significant characteristics of the algae of corresponding groups. Cytochemical reactions were used if needed. The research is based on the system of algae classification, which is proposed in the monograph "Algae of Soils of Ukraine: History and Methods of Research, System, Constellation of Flora" (Kostikov et al., 2001).

On the basis of the cultures with fouling glasses, which are considered to be the closest to natural conditions, the dominants and the subdominants were determined by using a seven-point scale of abundance. The species with abundance score of 7 and 6 were considered to be dominants. The obtained data were analyzed by using the methods of comparative floristics. Mathematical analysis of the study results was conducted in Statistica 6.0 (StatSoft Inc., USA).

## Results

Within the local reserve "Troitsk Clough" the plots of herbs-fescue-feather-grass and fescue-feather-grass steppes two sample plots PP 1 and PP 2 were selected as reference areas. The studied ecosystems differed in composition, projective cover, height of high altitude vegetation and were located at the top part of a slope of the northern exposure (Table 1). There is no step-bed. There is occurrence of water erosion of the soil.

grow there, including endemic ones: *Bellevala sarmatica* (Georgi) Woronow (forms fragments of groupings), *Dianthus carbonatus* Klok, *D. guttatus* Beib, *D. platyodon* Klok, *Minuartia leiosperma* Klok, *Stipa ucrainica*, *Veronica sclerophylla*. Kotov. Significant populations on the steppe part of the clough are formed by *Adonis vernalis* L. (Kolomii-chuk et al., 2012).

Within the territory of the reserve, the strict nature reserve regime has not been introduced, therefore it is used by the local population as a pasture, which, along with fires, creates additional threats to biodiversity and productivity. According to the results of the conducted studies in PP 1 in the composition of biological soil crusts, 38 species of algae and cyanoprokaryotes were identified, belonging to 5 groups: Cyanoprokaryota – 21 (55.3%), Eustigmatophyta – 1 (2.6%), Xanthophyta – 1 (2.6%), Bacillariophyta – 6 (15.8%) and Chlorophyta – 9 species (23.7%).

The leading families are Phormidiaceae (10 species), Pseudanabaenaceae (6) and Bacillariaceae (3), which combine 50.0% of the group. The special attention should be given to the genera: *Phormidium* Kützing ex Gomont (10 species), *Leptolyngbya* Anagnostidis et Komarek

(5), *Nostoc* Vaucher ex Boret et Flahault (3) and *Nitzschia* Hassal (2). Dominant among cyanoprokaryotes and eukaryotic algae in the biological soil crust were: *Phormidium valderiae* (Delp.) Geitler, *Ph. bohneri* Schmidle, *Leptolyngbya foveolarum* (Rabenhorst ex Gomont) Anagnostidis et Komarek, *Nostoc edaphicum* Kondratyeva, *Leptosira terricola* (Bristol) Printz, *Bracteacoccus minor* (Chodat) Petrova and *Heterococcus viridis* Chodat.

In biological soil crust of ecosystem of the fescue-feather grass steppe (PP 2), 35 species of 5 groups were identified: Cyanoprocaryota – 20 (57.1%), Eustigmatophyta – 1 (2.9%), Xanthophyta – 2 (5.7%), Bacillariophyta – 6 (17.1%) and Chlorophyta – 6 species (17.1%). The leading families include Phormidiaceae (11 species), Pseudanabaenaceae (5) and Bacillariaceae (3), which combine 54.3% of the species of the group. The leading genera are: *Phormidium* (11 species), *Leptolyngbya* (5), *Nostoc*, *Chlorococcum* Meneghini and *Nitzschia* (2 species).

The dominants included *Eustigmatos magnus* (Petersen) Hibberd, *Heterococcus viridis*, *Phormidium autumnale* (Agardh) Gomont, *Ph. (Leptolyngbya) henningsii* Lemmermann, *Leptolyngbya foveolarum* (Rabenhorst ex Gomont) Anagnostidis et Komarek, *Nostoc edaphicum*, *Hantzschia amphioxys* (Ehrenberg) Grunow in Celeve et Grunow, *Bracteacoccus minor*.

In total, within the reference geobiocoenosis of the local reserve “Troitsk Clough” in biological soil crusts there were identified 49 species of cyanoprokaryotes and eukaryotic algae that belonged to 5 groups: Cyanoprocaryota – 27 (55.1%), Eustigmatophyta – 2 (4.1%), Xanthophyta – 2 (4.1%), Bacillariophyta – 6 (12.2%) and Chlorophyta – 12 species (24.5%). In the composition of biological soil crusts of etalon ecosystems, about 30% of the species composition is formed by representatives of the family Phormidiaceae. The number of species in the families Pseudanabaenaceae and Bacillariaceae, belonging to the leading ones in the abovementioned biological soil crust is close.

In the local reserve “Troitsk Clough”, the study of two geobiocoenoses of post-pyrogenic development from fires in 2009 (PP 3) and 2010 (PP 4) was conducted. The relevant sites were on the slope of the northern (PP 4) and southern exposure (PP 3). The studied ecosystems differed in composition, projective cover, height of higher vegetation (Table 1). 35 species of algae and cyanoprokaryotes from 5 groups were identified in the biological soil crusts composition on the PP 3, which was laid on the territory of the geobiocoenoses of post-pyrogenic development from the fire in 2009: Cyanoprocaryota – 20 species (57.1%), Eustigmatophyta – 1 (2.9%), Xanthophyta – 1 (2.9%), Bacillariophyta – 5 (14.3%) and Chlorophyta – 8 (22.9%). The leading families include Phormidiaceae (11 species), Pseudanabaenaceae (6), Chlorococaceae and Bacillariaceae (3 species of each), which combine 65.7% of species. Among the leading genera are *Phormidium* (11 species), *Leptolyngbya* (5), *Chlorococcum* and *Nitzschia* (2 species in each). The dominant species of post-pyrogenic biological soil crust among algae and cyanoprokaryotes in this plot were the following: *Heterococcus viridis*, *Phormidium retzii* (Agardh) Gomont, *Phormidium paulsenianum* B. Petersen, *Ph. bohneri*, *Leptolyngbya foveolarum*, *Chlorococcum chlorococcoides* (Korschikov) Philipose, *Eustigmatos magnus*.

On the territory of the ecosystem of post-pyrogenic development from the fire in 2010 (PP 4) 41 species of algae from 5 groups were noted in the composition of biological soil crust: Cyanoprocaryota – 22 (53.7%), Eustigmatophyta – 1 (2.4%), Xanthophyta – 2 (4.9%), Bacillariophyta – 6 (14.6%) and Chlorophyta – 10 (24.4%). The leading families are Phormidiaceae (11 species), Pseudanabaenaceae (6), Bacillariaceae, Naviculaceae (3 species in each) and Chlorosarcinaceae (2) within the area of post-pyrogenic development and combine 61.0% of species. The leading genera are *Phormidium* (11 species), *Leptolyngbya* (4), *Nostoc* (3), *Chlorosarcinopsis* Herndon and *Nitzschia* (2 species in each).

The dominants were represented by the species *Heterococcus viridis*, *Phormidium retzii*, *Ph. (Leptolyngbya) henningsii*, *Leptolyngbya foveolarum*, *Leptolyngbya fragilis* (Gomont) Anagnostidis et Komarek, *Nostoc edaphicum*, *Parietochloris pseudoalveolaris* (Deason et Bold) Watanabe et Floyd in Deason et al., *Eustigmatos magnus*. 51 species of algae and cyanoprokaryotes belonging to five groups: Cyanoprocaryota – 25 (49.1%), Eustigmatophyta – 1 (1.9%), Xanthophyta – 2 (3.9%), Bacillariophyta – 6 (11.8%) and Chlorophyta – 17 (33.3%) were recorded

overall in the biological soil crusts of post-pyrogenic ecosystems of “Troitsk Clough” reserve.

The calculated Jaccard index of commonality for the complete algal species list indicates an average specificity of the algal composition of the studied ecotopes in the post-pyrogenic and etalon ecosystems of the “Troitsk Clough” reserve (Table 2).

**Table 2**

Similarity of species composition of algae groups in different ecosystems according to the community coefficient of Jaccard

Sampling area	PP 1	PP 2	PP 3	PP 4
PP 1	38	52.1	55.3	49.1
PP 2	25	35	52.2	55.1
PP 3	26	24	35	49.0
PP 4	26	27	25	41

Note: diagonally – the number of species in the group, in the upper corner – the value of the community of Jaccard coefficient, in the lower corner – the number of common species in the comparable groups.

## Discussion

The restoration of steppe ecosystems after fires in general occurs according to the scenario typical for other ecosystems formed by grasses. A number of researchers note an increase in the productivity of grass ecosystems after a fire (Limb et al., 2016; Gates et al., 2017). There is information about increasing the participation of perennial grasses and reducing annual grasses, the positive response of legumes (Scheintaub et al., 2009). At the same time, evaluating the consequences of fires for grass ecosystems is not single-valued. The positive effect in post-pyrogenic changes may be absent. In most cases, negative manifestations are limited within a two-year period (Limb et al., 2016; Gates et al., 2017). Fire, combined with subsequent grazing, can lead to the disappearance of the most sensitive plant species (Clark et al., 2016). Therefore, outside well-studied ecosystems, the application of the obtained results should be restricted. This should be taken into account in the case of the planned burning out of grass ecosystems in order to increase their productivity (Scheintaub et al., 2009; Allen et al., 2011; Miller et al., 2017). The consequences of uncontrolled fires for an ecosystem depend on the season of the fire, its scale, intensity, frequency etc. (Ford and Johnson, 2006; Strong et al., 2013; Scherbina et al., 2014).

The investigated post-pyrogenic steppe ecosystems have a different rate of restoration of the projective cover by higher plants (Table 1). If in the plot PP 3 after the winter fire there was a rapid restoration to the virgin steppe indicators, then in PP 4, this process was very slow. The reason for the slow restoration of vegetation cover can be its severe damage by fire at the beginning of vegetation and the development of erosion processes. The high sensitivity of perennial grasses to fires during the growing season is also noted by Ford and Johnson (2006). Restoration processes of vegetation cover after fires occur simultaneously with the renewal of soil functions, vital activity of soil microorganisms and organisms in biological soil crusts (Liu et al., 2010; Limb et al., 2016).

In steppe ecosystems, as well as in other xerophytic ecosystems, biological soil crusts often are created on or below the soil surface (Langhans et al., 2010). They include cyanoprokaryotes, eukaryotic algae, mosses, lichens and fungi that connect soil particles. The thickness of such crusts is usually measured in several millimeters. Some types of filamentous cyanoprokaryotes can permeate the topsoil to a depth of 10 cm (Belnap and Gardner, 1993), increasing the thickness of the crust. It is known that the spread of algae and cyanoprokaryotes in the soil is not limited to this depth. Their living cells have been found at the depth of 120 cm (Maltseva and Pysanets 2004; Shekhovtseva and Maltseva 2015; Maltseva et al., 2017) and more (Gollerbah and Shtina, 1969). They are diffusely dispersed along the soil profile and cannot perform functions peculiar to biological soil crust.

The results of the latest research on algae and cyanoprokaryotes of virgin steppe ecosystems in Ukraine are reported in the works Maltseva (2003), Maltseva and Pysanets (2004), Baranova et al. (2009), Baranova and Maltseva (2009), Shcherbyna (2014, 2015), Maltseva and Shcherbyna (2011), Shcherbyna et al. (2014). This work has contributed to the

preliminary evaluation of the species richness of algae and cyanoprokaryotes of zonal and azonal soils, description of new areas of rare and widespread algae species, updated and supplemented existing data.

Many printed works are devoted to the ecology-coenological direction and contain information about the peculiarities of algae and cyanoprokaryotes of the steppe zone, whose dynamics are observed in accordance with soil conditions, the type of vegetation and other components and elements of ecosystems. In general, the features of the floral composition of algae and cyanoprokaryotes of zonal steppe ecosystems have been defined on the territory of Ukraine (Kostikov et al., 2001; Chumacheva, 2001; Pivovarova and Chumacheva 2004), as well as beyond its borders. One more direction has been presented by the study of algae and cyanoprokaryotes in the composition of biological soil crusts (Belnap, 2002; Ford and Johnson 2006; Langhans et al., 2009). It was found that the formation of biological soil crust on the soil surface of xerophytic ecosystems is carried out in stages (Dettweiler-Robinson et al., 2013). Cyanoprokaryotes and eukaryotic algae appear first, then lichens and mosses do. When destruction occurs, the rate of biological soil crust restoration differs. Crusts are most quickly restored after fires (Myers and Davis, 2003). This is confirmed by our research. On the plot burnt in the spring of 2010, in the summer period the species of Cyanoprokaryota, Bacillariophyta and isolated species of Chlorophyta were already observed. The "pioneer" group includes: *Phormidium autumnale*, *Ph. dimorphum* Lemmermann, *Ph. retzii*, *Ph. (Leptolyngbya) henningsii*, *Luticola mutica* Kutzing Mann in Round et al., *Hantzschia amphioxys*. The appearance of higher plants did not compensate the severe ecotopic conditions and did not contribute to the rapid increase in the diversity of cyanoprokaryotes and algae. The maximum species richness was noted in the spring of the second year after the fire. In general, the diversity of species of algae and cyanoprokaryotes reaches the highest values in the first two years after a fire and then decreases to values peculiar to the virgin steppe. In the initial period after a fire, the active development of algae and cyanoprokaryotes is facilitated by the appearance of easily accessible mineral compounds after the organic mass burning out, by the absence of shading from higher plants and steppe litter. Gradually this effect fades away; the species diversity of algae and cyanoprokaryotes is established in a range typical for this type of ecosystem. In our studies, the most susceptible to soil sod formation were Cyanoprokaryota (the correlation coefficient varied from -0.861 to -0.947).

In the study of biological soil crusts, as Tanja Margrit Langhans and co-authors (2010) note, the species composition analysis of the organisms that make up their composition is very rarely done. This limits the possibility of interpreting the obtained data. In our research the similarity of the algae and cyanoprokaryotes in biological soil crust species lists of post-pyrogenic and etalon ecosystems of the "Troitsk Clough" reserve is 49.0% by the value of the Jaccard coefficient, which confirms the average indicators of their similarity (Table 2).

According to the taxonomic structure of algae and cyanoprokaryotes, the etalon ecosystems are very similar to the post-pyrogenic ones. Cyanoprokaryota prevail in all of them without exception. The share of algae of the groups Eustigmatophyta, Xanthophyta and Bacillariophyta is almost unchanged. Green algae occupy the second place by number of species. Families of Phormidiaceae, Pseudanabaenaceae and Bacillariaceae are among the leading both in virgin areas and in post-pyrogenic geobiocoenoses. The return of the Nostoc genus to the list of leading genera on the area of post-pyrogenic restoration after the 2010 fire is in line with the results of studies by other authors, who during the study of the effects of fires on the state of microbiocoenoses of the soil indicated the increase in the number of microorganisms in the nitrogen cycle: mineral nitrogen immobilizers, oligonitrophils, denitrification agents (Malinovskaia, 2012). They associated it with the entry of mineral substances into the soil after the fire. The results of algae studies of post-pyrogenic areas also indicate the activation of nitrogen-fixing Cyanoprokaryota (Pivovarova and Chumacheva, 2001).

The restoration of biological soil crust in xerophytic ecosystems is of great importance for their functioning. A fire occurring not in the vegetation season has a slight effect on perennial grasses, but maximally destroys the biological soil crusts. Their destruction worsens soil resistance to wind and water erosion (Hu et al., 2002; Bowker et al., 2004;

Zhang et al., 2006; Jimenez-Aguilar et al., 2009), accompanied by loss of C and N due to water erosion (Barger et al., 2006) and a reduction in humus content (Langhans et al., 2010).

The studied ecosystems (both virgin and post-pyrogenic) are located on slopes. The increase in the diversity of algae and cyanoprokaryotes in the early stages of the formation of biological soil crust occurred against the background of overcoming the phenomena of flushing. The main role in fixing the surface of the soil was played by filamentous species of Cyanoprokaryota. Their anti-erosion role is shown in other ecosystems as well (Hu et al., 2002; Bowker et al., 2004; Jimenez-Aguilar et al., 2009).

Another interesting effect of the absence in the first stages of post-pyrogenic successions and the gradual formation of a typical biological soil crust for a particular ecosystem is the influence of biological soil crusts on seed germination and emergence (Langhans et al., 2009). It is indicated that the biological soil crusts can influence the penetration of seeds into deep soil layers, promote emergence by means of increasing moisture, nutrient content (Maestre et al., 2002; Liu et al., 2006). There is also evidence that biological soil crust may act as an inhibitor to higher plants (Escudero et al., 2007). The role of each of the components of biological soil crusts in the manifestation of these effects has not been sufficiently studied. Concerning cyanoprokaryotes that are part of the biological soil crust, it is known that some of them are capable of activating the beneficial and inhibiting the pathogenic microflora, altering the fermentative activity of the soil, etc., thereby stimulating the germination of the seeds of higher plants (Maltsev, 2015; Maltsev et al., 2017).

Taking this into account, it can be assumed that post-pyrogenic successions of higher plants and organisms that make up the biological soil crusts are coordinated and interdependent. Detailed study of this issue will allow us to reach a new level of control of restoration processes in post-pyrogenic ecosystems.

## Conclusions

Restoration of the herbs-fescue-feather-grass and fescue-feather-grass steppes after fire occurs at different rates. The cause of the slow restoration of vegetation cover can be its severe damage by fire at the beginning of the vegetation season and the development of erosion processes.

The surface layer of the soil of virgin and post-pyrogenic steppe ecosystems is populated by cyanoprokaryotes and eukaryotic algae. They are the part of the biological soil crust, which performs important ecological functions in xerophytic steppe ecosystems: it increases the erosion resistance of the soil surface, enriches the soil with organic matter, increases the nitrogen content in the soil due to nitrogen fixation, affects the germination of seeds, etc.

The number of species of cyanoprokaryotes and algae in biological soil crusts of virgin and post-pyrogenic ecosystems is not significantly different. It varies from 35 to 49 species. The greatest diversity is noted for Cyanoprokaryota. Chlorophyta is in the second place. Among the dominants, the filamentous forms of Cyanoprokaryota prevail. *Nostoc edaphicum* was noted as a nitrogen fixing representative.

The similarity of the species lists of cyanoprokaryotes and algae of post-pyrogenic and virgin ecosystems, according to the calculated Jaccard coefficient, varies from 49.1 to 55.3%. This indicates a strong specificity of the composition of cyanoprokaryotes and algae in post-pyrogenic biological soil crust. Changes in their composition reflect different stages of post-pyrogenic succession. In the first year after the fire, there is a slight increase in species richness, which is a consequence of the favorable effect of increasing the amount of mineral substances in the soil after the organic matter has burned out. The "pioneer" group includes: *Phormidium autumnale*, *Ph. dimorphum*, *Ph. retzii*, *Ph. (Leptolyngbya) henningsii*, *Luticola mutica*, *Hantzschia amphioxys*. Gradually this effect is leveled and the species richness of cyanoprokaryotes and algae is stabilized at a level peculiar for this type of ecosystem.

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