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Transformation of soil cyanobacterial-algal cenoses affected by urbanization in the South Ural urban areas

© 2025. N. V. Sukhanova[1] ORCID: 0000-0002-6130-6172, A. I. Fazlutdinova[1] ORCID: 0000-0001-7971-6690, A.V. Radygina[1] ORCID: 0000-0003-4696-2128, L. A. Gaysina[1, 2] ORCID: 0000-0002-0920-6449,
[1]M. Akmullah Bashkir State Pedagogical University,
3-a, Okt'yabrskoy revolucii St., Ufa, Russia, 450008,
[2]All-Russian Research Institute of Phytopathology,
5, Institute St., B. Vyazyomy, Odintsovo District, Moscow Region, Russia, 143050,
e-mail: lira.gaisina@gmail.com

The paper presents the results of long-term studies of soil cyanobacterial-algal cenoses (CAC) in urban areas, including 18 South Ural settlements. The studied soil algae and cyanobacteria species diversity includes 487 species with varieties and forms (Chlorophyta – 231 species, Cyanobacteria – 131 species, Ochrophyta – 58, Bacillariophyta – 52, Streptophyta – 13, Euglenophyta – 2). The edaphophototrophs' biodiversity is represented by 6 divisions, 12 classes, 32 orders, 89 families, 176 genera. The CAC flora ratio of the South Ural urban areas is 5.4 for species/family, 2.6 for species/genus, and 2.1 for genus/family. Chlamydomonadaceae, Phormidiaceae, Chlorococcaceae, Nostocaceae, and Pseudanabaenaceae are the top five families by the number of species. They account for 33% of the total number of species. We identified groups of frequently occurring algae and cyanobacteria species in the South Ural soil biotopes exposed to recreational or technogenic stress. The CAC taxonomic structure of the settlements in the South Ural forest, forest-steppe, and steppe zones and their mountain counterparts (while maintaining zonal features), has a significant similarity due to the leveling of soil and climatic conditions in cities and synanthropization effect accompanied by introduction of anthropogenically disturbed habitat species into the CAC. We identify the patterns of CAC formation in urban ecosystems, and develop a scheme of CAC transformation in South Ural urban areas. General patterns are associated with changes in the algae and cyanobacteria species diversity and other CAC characteristics with an increase in anthropogenic pressure, as well as with gradual transformation of zonal CAC into azonal ones with subsequent disappearance of autotrophic microbiota. Particular features result from the predominance of one of the leading anthropogenic factor (technogenic pollution or recreational stress). The persistence of *Hantzschia amphioxys*, *Vischeria magna*, *Botrydiopsis eriensis*, etc. decreases with increasing recreational stress, but the persistence of *Microcoleus autumnalis*, *Leptolyngbya foveolarum*, *Luticola ventricosa*, etc. increases. In other words, when the role of some species is weakened, the importance of others increases.

Keywords: microphototrophs, edaphophototrophs, pollution, urban ecosystems, synantropization, microbiotopes, anthropogenic factors.

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Трансформация почвенных цианобактериально-водорослевых ценозов городов Южно-Уральского региона под воздействием урбанизации

© 2025. Н. В. Суханова[1], д. б. н., доцент, зав. кафедрой, А. И. Фазлутдинова[1], к. б. н., доцент, А. В. Радыгина[1], студент, Л. А. Гайсина[1, 2], д. б. н., доцент, научный руководитель сектора научно-технической интеграции,
[1]Башкирский государственный педагогический университет им. М. Акмуллы,
450008, Россия, г. Уфа, ул. Октябрьской революции, д. 3-а,
[2]Всероссийский научно-исследовательский институт фитопатологии,
143050, Россия, Московская область, Одинцовский район,
р. п. Большие Вяземы, ул. Институт, д. 5,
e-mail: lira.gaisina@gmail.com

В статье представлены результаты многолетних исследований цианобактериально-водорослевых ценозов (ЦВЦ) почв урбанизированных территорий, включающих 18 населённых пунктов Южно-Уральского региона (ЮУР). Видовое разнообразие водорослей и цианобактерий почв изученных территорий включает 487 видов с разновидностями и формами (Chlorophyta – 231 вид, Cyanobacteria – 131 вид, Ochrophyta – 58, Bacillariophyta – 52, Streptophyta – 13, Euglenophyta – 2). Биоразнообразие эдафофототрофов населённых пунктов ЮУР представлено 6 отделами, 12 классами, 32 порядками, 89 семействами, 176 родами. Коэффициент пропорции флор для ЦВЦ урбанизированных территорий ЮУР вид/семейство составляет 5,4; вид/род – 2,6; род/семейство – 2,1. В пятерку ведущих по числу видов семейств входили Chlamydomonadaceae, Phormidiaceae, Chlorococcaceae, Nostocaceae, Pseudanabaenaceae, на них приходится 33% от общего количества видов. Выделены группы часто встречающихся видов водорослей и цианобактерий в почве биотопов ЮУР, подверженных рекреационной нагрузке, либо техногенному загрязнению. Таксономическая структура ЦВЦ населённых мест лесной, лесостепной и степной зон и их горных аналогов ЮУР при сохранении зональных особенностей имеет значительное сходство, обусловленное нивелированием почвенных и климатических условий в городах, влиянием процессов синантропизации, сопровождающихся внедрением в ЦВЦ видов антропогенно-нарушенных местообитаний. Выявлены закономерности формирования ЦВЦ в городских экосистемах, разработана схема трансформации ЦВЦ урбанизированных территорий ЮУР. Общие закономерности связаны с изменением видового разнообразия водорослей и цианобактерий и других характеристик ЦВЦ при возрастании антропогенной нагрузки и постепенной трансформации зональных ЦВЦ в азональные с последующим исчезновением автотрофной микробиоты. Частные особенности возникают в результате преобладания одного из ведущих антропогенных факторов (техногенного загрязнения или рекреационной нагрузки). При увеличении рекреационной нагрузки уменьшается постоянство *Hantzschia amphioxys, Vischeria magna, Botrydiopsis eriensis* и др., но увеличивается постоянство *Microcoleus autumnalis, Leptolyngbya foveolarum, Luticola ventricosa* и др., то есть при ослаблении роли одних видов увеличивается значение других.

Ключевые слова: микрофототрофы, эдафофототрофы, загрязнение, городские экосистемы, синантропизация, микробиотопы, антропогенные факторы.

As a result of long-term anthropogenic stress observed over many centuries, the natural environment in cities is transformed into an urbanized one. Large and small cities, as well as other settlements, affect all components of the biota, including in the soil [1]. An integral component of terrestrial ecosystems – microscopic algae and cyanobacteria – play a significant role in maintaining the stability of anthropogenically disturbed ecosystems, which are characterized by technogenic pollution, as well as a significant degree of disturbance of the soil and vegetation cover. Urban soils (urbozems) are mostly compacted due to high recreational stress, soil horizons are mixed with household and construction waste. There is an increased content of heavy metals, oil products, reagents used to clear roads and sidewalks from snow and ice. The fertility of urbozems is reduced due to regular removal of plant residues; the acid-base balance of these soils changes towards alkalization. However, a short life cycle, microscopic size, autotrophic nutrition, the ability of cyanobacteria to fix nitrogen and many other features of microphototrophs allow them to exist in heavily transformed urban soils. They form the primary production, stimulate the soil self-purification and the vital activity of other soil microorganisms, and also prevent erosion.

Recently, there has been an increased interest in the study of soil algae and cyanobacteria in cities. The biodiversity of terrestrial algal flora of cities and their environs in the Russian Federation and neighboring countries was analyzed in Ufa [2–4], Izhevsk [5], Novosibirsk [6, 7], Krasnoyarsk [8], Kirov [9, 10, 11], Sterlitamak [12], Ishimbay [13], Neftekamsk [14], Apatity [15], Usolye-Sibirskoye [16], Kiev [17], Magnitogorsk [18] and Gomel [19]. Cyanobacterial-algal floras were used to assess the structural and functional changes in soils under anthropogenic stress [20, 21]. Microphototrophs were used as bioindicators of the sanitary and hygienic status of the soil cover [22], as test objects in assessing the toxicity of soil and snow, as well as the atmosphere status in cities [23–26]. At the same time, information on the biodiversity of algae and cyanobacteria in the soils of urban areas of the South Ural Region (SUR) is insufficient and requires further study.

The aim of this work was to analyze the patterns of cyanobacterial-algal cenoses (CAC) forming in urban ecosystems and to develop a scheme of the CAC in urban territories of the SUR.

Research materials and methods

The study is a summary of the results of a 25-year study of the CACs in the cities of the South Urals. The work is based on the analysis of more than 700 soil samples collected in 18 cities and other settlements and in areas of zonal vegetation in their vicinity (Fig. 1). The studied urban territories were located in different natural and climatic zones: forest, forest-steppe and steppe. According to the longitudinal gradient, the studied areas belonged to the Southern Cis-Urals, Southern Urals, and Southern Trans-Urals.

The urban environment is a mosaic space. The typification of urban biotopes is diverse and largely depends on the object of study. In order to obtain a more complete picture of the CAC formation in urban ecosystems, we collected samples in the following habitats (biotopes) (Table 1):

1. Roadsides and lawns along highways. These areas were characterized by varying degrees of pollution, which depended on ventilation conditions, terrain, traffic intensity, and age of the lawn.

2. Parks, squares, and forest parks exposed to anthropogenic stress. They were characterized by a moderate degree of persistent pollution.

3. Railway embankments approaching and inside cities, as well as at enterprises, and tram tracks. These areas were characterized by a high level of persistent pollution.

4. Yards, vacant lots, school grounds, kindergartens, playgrounds, and sports grounds. These habitats were characterized by a high level of recreational stress and a variety of microbiotopes with different physicochemical and hydrothermal properties.

5. Areas of industrial enterprises, industrial sedimentation tanks, and landfills were characterized by a high level of persistent pollution.

6. Industrial waste dumps of the Sibay Branch of JSC Uchalinsky Mining and Processing Plant (UMPPSB) were characterized by a toxic mineral substrate, constant release of pollutants during blasting operations with subsequent concentration in soils in the surrounding area.

7. Salt marshes in the vicinity of Sibay were characterized by a chloride-sulphate type of salinization and neutral pH values.

8. Zonal forest, forest-steppe and steppe areas near settlements. These areas were subject to limited impact of emissions from urban industrial enterprises, however, the level of pasture and recreational load could vary.

These habitats were combined into zones that are usually distinguished in the city:

– residential zone – place of residence of the population (habitat 4);

– industrial zone – territories where the main industrial enterprises are located (5, 6);

– recreational zone – place of concentration of natural objects (2, 7, 8);

– transport zone – this is the place of unification of all types of transport (automobile, railway and electric transport) within the city limits (1, 3).

The work used traditional geobotanical and soil-algal methods. The species were determined by the methods of soil cultures with fouling glasses [27, 28], aquatic cultures using soil extract, sowing fine soil (melkozem) on moistened agarized Bold medium in Petri dishes.

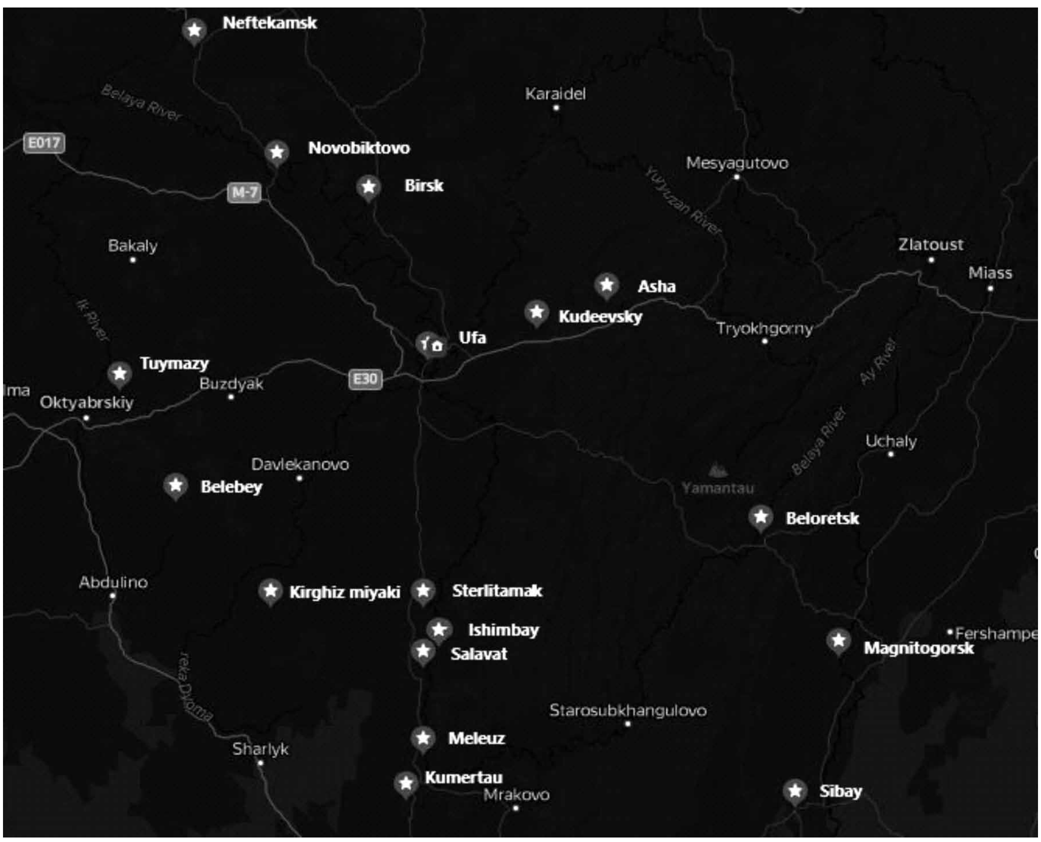

Fig. 1. Soil sampling sites (marked with an asterisk)

Table 1

Representation of biotopes in the studied settlements of the South Ural region

Locality	Biotope							
	1	2	3	4	5	6	7	8
Neftekamsk	+	+	–	+	–	–	–	+
Birsk	+	+	–	+	–	–	–	+
Novobiktovo	+	–	–	+	–	–	–	+
Beloretsk	+	+	–	–	–	–	–	+
Asha	+	+	+	+	+	–	–	+
Ufa	+	+	+	+	+	–	–	+
Tuymazy	+	+	–	–	–	–	–	+
Belebey	+	+	–	+	–	–	–	+
Kudeevsky	+	+	–	+	–	–	–	+
Oktyabrskaya	+	–	–	+	–	–	–	+
Sterlitamak	+	+	–	+	–	–	–	+
Ishimbay	+	+	–	–	–	–	–	+
Salavat	+	+	–	–	–	–	–	+
Kyrgyz-Miyaki	+	+	–	–	–	–	–	+
Meleuz	+	+	–	–	–	–	–	+
Magnitogorsk	+	+	+	+	+	–	–	+
Sibay	+	+	+	+	+	+	+	+
Kumertau	+	+	–	–	–	–	–	+

Note. Biotopes 1–8 – designations are given in the text. A dash indicates the absence of a biotope.

To identify the species of algae and cyanobacteria, we used modern summaries and identification guides [29–36]. The structure of taxa and names of algae and cyanobacteria species, the system of higher taxonomic units at the division level are presented according to the AlgaeBase (http://www.algaebase.org/) as of August 2022. We accepted the names of the taxa Streptophyta and Charophyta, Euglenozoa and Euglenophyta as synonyms.

The abundance of algae and cyanobacteria was assessed on fouling glasses according to a 15-point scale [37]. During the syntaxonomic analysis, to each species it was assigned its own rank by transforming the abundance scale of R.R. Kabirov into the abundance scale of Braun-Blanquet: r – the sum of the abundance points on the fouling glass was equal to 1; + – 2 points; 1 – 3–6 points; 2 – 7–11 points; 3 – 12–13 points; 4 – 14 points; 5 – 15 points. When conducting the syntaxonomic analysis, the results were processed using the traditional method of phytosociological tables [38–40].

The rank of leading family was assigned to those families that included a number of species above average.

Results and discussion

During the study, 487 species of microphototrophs (including varieties and forms) were found in the soils of the studied settlements and their environs of the SUR: 231 species of Chlorophyta (170 – Chlorophyceae, 1 – Pedinophyceae, 55 – Trebouxiophyceae, 5 – Ulvophyceae), 131 species of Cyanobacteria (131 – Cyanophyceae), 13 species of Streptophyta (1 – Chlorokybophyceae, 5 – Zygnematophyceae, 7 – Klebsormidiophyceae), 58 species of Ochrophyta (48 – Xanthophyceae and 10 – Eustigmatophyceae), 52 Bacillariophyta (52 – Bacillariophyceae), 2 species of Euglenophyta (2 – Euglenophyceae).

The biological diversity of microphototrophs in the SUR urbanized areas include 6 divisions, 12 classes, 32 orders, 89 families, and 176 genera. The flora proportion coefficient for the CACs of SUR urban area was: species/family – 5.4; species/genus – 2.6; genus/family – 2.1. The ratio of Cyanobacteria/Chlorophyta+Streptophyta was 0.54, Cyanobacteria/Ochrophyta – 2.28. The family Chlamydomonadaceae was the leader in the number of species. The leading families also included four families of Cyanobacteria, three families of Chlorophyta, one family of Ochrophyta, and one family of Bacillariophyta (Table 2).

The analysis of the CAC species composition in the SUR settlements showed a significant diversity of soil microscopic phototrophs with a significant predominance of Chloriphyta and

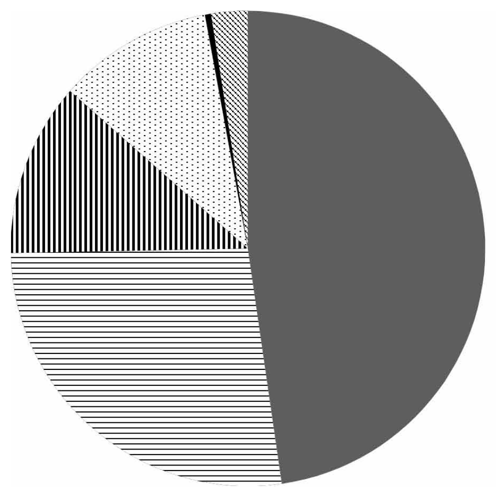

Fig. 2. Representation of different systematic groups of soil phototrophs in the South Ural settlements and their surroundings

Table 2

Families leading by the number of species in the flora of edaphophototrophs of the South Ural studied settlements

Rank	Families	Number of species
1	Chlamydomonadaceae	54
2	Phormidiaceae	33
3	Chlorococcaceae	28
4	Nostocaceae	27
5	Pseudanabaenaceae	21
6	Pleurochloridaceae	17
7	Oscillatoriaceae	16
7	Naviculaceae	16
8	Chlorellaceae	14
9	Prasiolaceae	13

Cyanobacteria. A similar picture is characteristic of the soils of a significant number of cities in the Republic of Bashkortostan [2, 12, 41, 42]. In accordance with the data of the review of zonal soil algae of the steppe and forest-steppe Bashkir Cis-Urals [43], in the composition of the CAC soil phototrophs of the SUR urban territories, as well as in zonal soils, Chlorophyta was the most numerous group (Fig. 3). At the same time, their share in the soils of urban territories was noticeably higher compared to zonal soils (increased from 37.8% (zonal soils) to 41.7%, respectively).

The biodiversity of microphototrophs in urbanozem was significantly higher than the diversity of zonal soils [43]. This is probably due to the increase in the those for habitats with a certain set of environmental conditions as a result of human activity and the formation of new biotopes for algae and cyanobacteria.

The Cyanobacteria/(Chlorophyta+Streptophyta) ratio for the CAC of settlements was 0.54, while for virgin soils of the steppe and forest-steppe zones of the Cis-Urals this indicator was 1.06 [43]. In the flora of soil phototrophs of anthropogenically disturbed areas, a decrease in the proportion of Ochrophyta (a combination of Xanthophyceae and Eustigmatophyceae) and Cyanobacteria was noted, relative to zonal soils. Thus, the flora of edaphophototrophs of urban areas underwent significant changes, while remaining zonally determined. These changes were reflected in the number of individual systematic groups of the studied soil microorganisms in the cities and other settlements.

In the soil samples of urban areas, the proportion of species found in only one sample was twice as high as in zonal soils [43] and amounted to 141 species together with intraspecific taxa. For the SUR settlements, the indicators of flora proportion were noticeably lower as compared to zonal soils. In particular, for zonal soils, the species/family ratio was 7.0 [43], while for urban areas this indicator was 5.4.

A study of local CACs of a separate settlement (Magnitogorsk, Chelyabinsk Region) showed that a large variety of CACs is formed on its territory, in which individual taxa of algae and cyanobacteria play a certain role in urban ecosystems (Fig. 4). With pollution by heavy metals, Chlorophyta prevailed in biotopes, while with soil compaction or alkalization, the diversity of Cyanobacteria increased.

The composition of multi-species families in urban areas changed significantly. If in the zonal soils of the Bashkir Cis-Urals the Oscillatoriaceae was characterized by the greatest diversity [43], then in urban soils it was the Chlamydomonadaceae. Of the five leading families for virgin soils, Pleurochloridaceae and Naviculaceae dropped out, and the Nostocaceae and Pseudanabaenaceae ppeared instead. The ten leading families of edaphophototrophs in the settlements of the South Urals united almost half of the identified species (49.6%) (Table 2). The first five families included 33% of the total number of species. In addition to the families of Cyanobacteria and Chlorophyta, the list of leading families also included the families of Ochrophyta and Bacillariophyta.

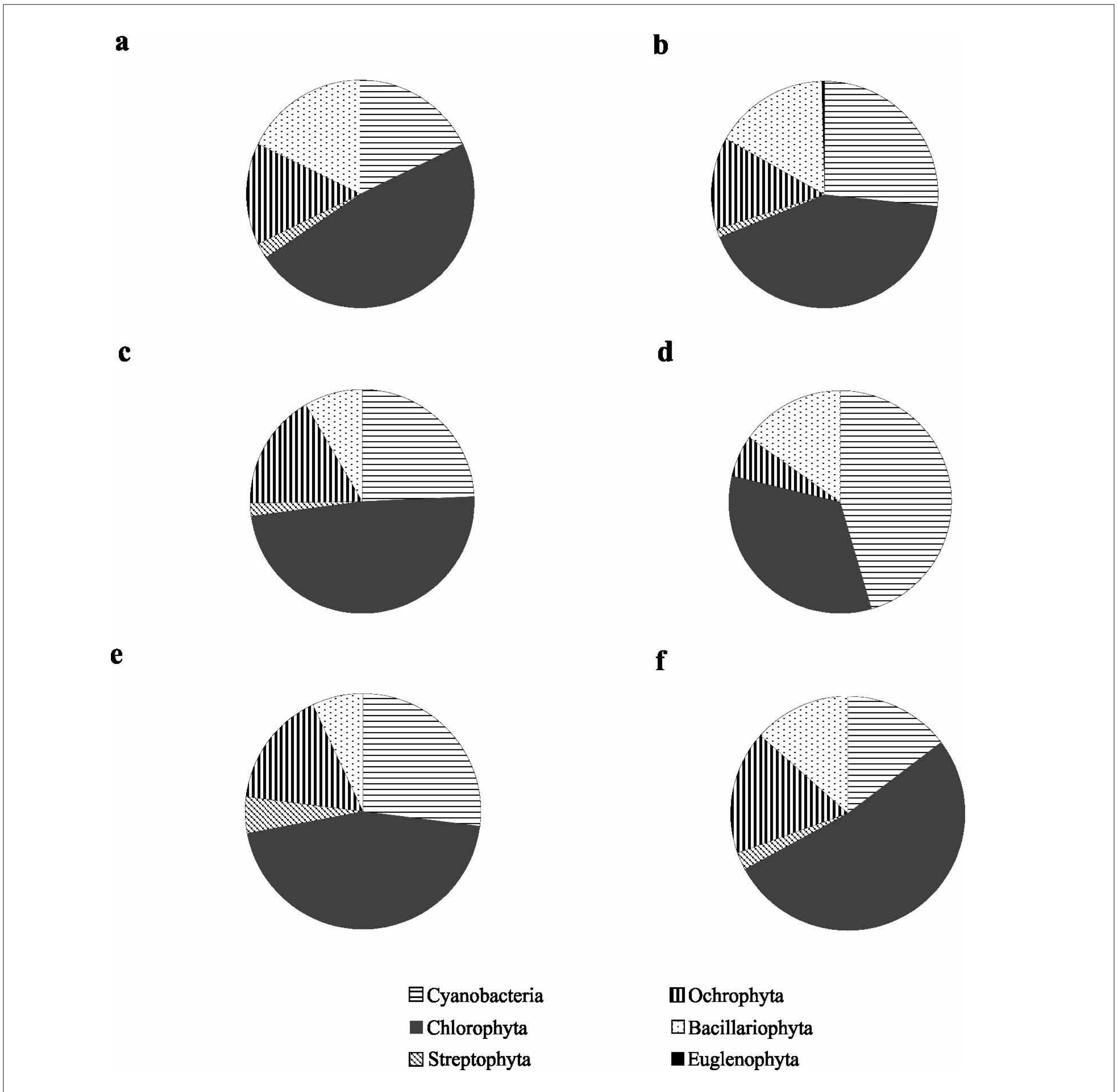

Fig. 3. The ratio of species by divisions in the soil of the South Ural studied cities: a – Neftekamsk, b – Ufa, c – Kumertau, d – Magnitogorsk, e – Sibay, f – Beloretsk

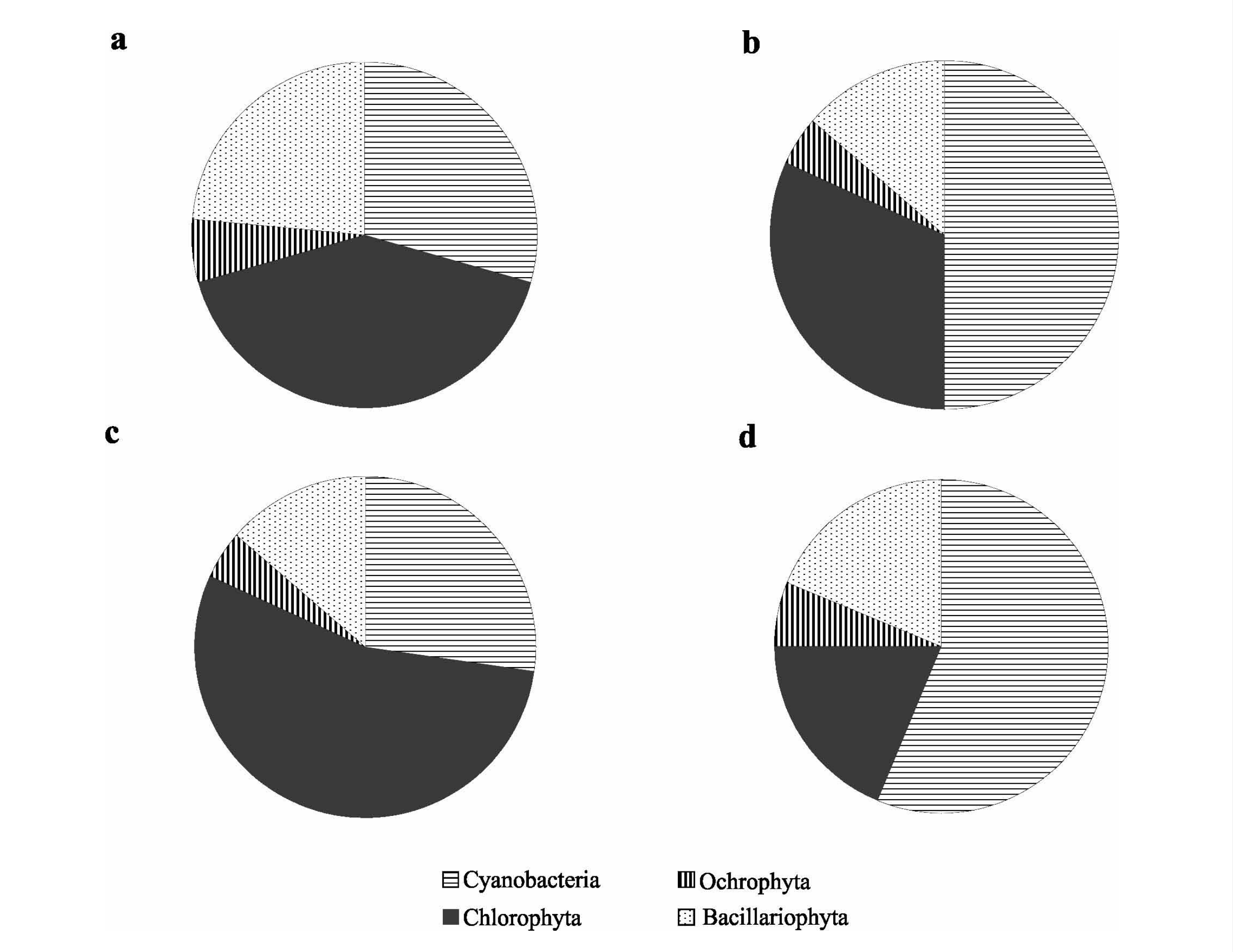

Fig. 4. Distribution of species by divisions in the soil of Magnitogorsk: a – Roadside lawns, b – Veterans Park, c – Magnitogorsk Iron and Steel Works, d – Magnitogorsk Cement Plant

Table 3

The leading families by number of species in the soil of South Ural biotopes, exposed to recreational stress

Leading families	Zonal sites of the vicinity of studied settlements			Forest parks, parks, public gardens			Biotopes of the residential area		
	F	F/s	S	F	F/s	S	F	F/s	S
Chlamydomonadaceae	1	1	1	1	1	2	2	2	1
Phormidiaceae	4	2	1	4	2	1	1	1	2
Chlorococcaceae	3	3	2	3	5	3	–	5	3
Pseudanabaenaceae	4	5	6	–	4	5	–	4	–
Prasiolaceae	4	–	5	4	–	5	2	–	1
Nostocaceae	–	1	4	2	3	6	–	2	–
Pleurochloridaceae	2	4	3	–	6	4	–	–	–
Bracteacoccaceae	4	–	–	5	–	–	–	–	–
Trebouxiaceae	4	–	–	5	–	–	–	–	–
Chlorellaceae	–	–	–	5	–	–	–	–	–
Bacillariaceae	–	–	–	5	–	–	–	–	–
Diadesmidaceae	4	–	–	5	–	–	2	5	5
Naviculaceae	–	6	–	–	5	–	2	3	4
Microcoleaceae*	–	–	–	–	–	–	–	5	5

Note for Tables 3 and 5: F – forest zone, F/s – forest-steppe zone, S – steppe zone, * *– the family is leading only for these types of biotopes; a dash means – not detected.*

Table 4

Group of soil algae and cyanobacteria species frequently occurring in South Ural biotopes affected by recreational stress

Taxa	City vicinities	Forest parks and parks	Residential area biotopes
Hantzschia amphioxys (Ehrenberg) Grunow	V^5	IV^5	III^4
Microcoleus autumnalis (Gomont) Strunecky, Komárek & J.R.Johansen	III^4	III^5	III^5
Bracteacoccus minor (Schmidle ex Chodat) Petrov	IV^5	V^5	I
Vischeria magna (J.B.Petersen) Kryvenda, Rybalka, Wolf & Friedl	IV^5	III^5	I^3
Klebsormidium flaccidum (Kützing) P.C. Silva, K.R.Mattox & W.H.Blackwell	III^3	III^4	II^4
Luticola mutica (Kützing) D.G.Mann	III^4	III^5	III^5
Microcoleus autumnalis (Gomont) Strunecky, Komárek & J.R.Johansen	I^3	III^4	III^5
Leptolyngbya foveolarum (Gomont) Anagnostidis & Komárek	I^4	III^5	III^5
Myrmecia bisecta Reisigl	III^3	I^3	III^3
Botrydiopsis eriensis J.W.Snow	IV^5	III^5	I^3
Dictyococcus varians Gerneck	IV^4	III^4	III^3
Chlorella vulgaris Beijerinck	I	III^5	III^4
Fistulifera pelliculosa (Kützing) Lange-Bertalot	I^5	III^5	III^4
Luticola ventricosa (Kützing) D.G.Mann	I	II^5	III^5
Desmonostoc muscorum (Bornet & Flahault) Hrouzek & Ventura	I	II^4	III
Pseudophormidium hollerbachianum (Elenkin) Anagnostidis	I^4	I^5	III^5
Pleurastrum terricola (Bristol) D.M.John	I	I^3	III^5
Chlorococcum infusionum (Schrank) Meneghini	III^5	II^5	I^5
Xanthonema exile (Klebs) P.C.Silva	II	III^5	I
Chlamydomonas gloeogama Korshikov	III^4	II^5	I
Chl. elliptica Korshikov	III^5	II^5	I
Chl. oblongella J.W.G.Lund	III^5	I^5	I

Note for Tables 4 and 6: Roman numerals indicate persistence classes; Arabic numerals indicate maximum abundance on the Brown-Blanquet scale. Color indicates groups of species of high constancy and abundance.

The largest share of species diversity fell on Cyanobacteria (20.1%) and Chlorophyta (22.6%). The total contribution of Ochropyta (3.5%) and Bacillariophyta (3.3%) was 6.8%.

The studied biotopes of the SUR settlements can be divided into two groups according to the most significant anthropogenic factor affecting the CAC forming.

1. The leading factor is the recreational stress (Table 3, 5).

2. The leading factor is the technogenic stress (Table 4, 6).

According to Table 3, Chlamydomonadaceae and Phormidiaceae were the leading families in terms of number of species in biotopes affected by recreational stress. The exception were zonal areas in the vicinity of urban areas and parks of cities in the forest zone, where the Phormidiaceae was in fourth place. In the biotopes of the residential zone, the leading family was Microcoleaceae, whose representatives play a major anti-erosion role in soils [44]. With an increase in the recreational load, the constancy of *Hantzschia amphioxys*, *Vischeria magna*, *Botrydiopsis eriensis* and others decreased, but the constancy of *Microcoleus autumnalis*, *Leptolyngbya foveolarum*, *Luticola ventricosa* and others increased (Table 4); that is, with a decrease in the importance of some species, the role of others increased.

The species *Fistulifera pelliculosa*, *Myrmecia bisecta*, *Chlamydomonas gloeogama*, and *C. elliptica* were resistant to recreational pres-

Table 5

The leading families by number of species in the soil of the South Ural biotopes affected by technogenic pollution

Family	Lawns and roadsides			Tramway embankments	Railway embankments	MSW container sites	Landfill	Dumps of UMPPSB	Industrial sites
	F	F/s	S						
Chlamydomonadaceae	1	1	1	3	1	1	–	–	1
Phormidiaceae	2	3	2	1	1	2	1	–	1
Chlorococcaceae	2	6	3	4	–	3	2	2	3
Pseudanabaenaceae	4	4	5	4	2	3	–	–	2
Nostocaceae	2	2	4	2	–	–	3	–	3
Naviculaceae	3	5	7	–	–	–	–	–	–
Bacillariaceae	4	–	–	–	–	–	–	3	–
Diadesmidaceae	4	–	–	–	–	–	–	–	–
Pleurochloridaceae	–	6	–	–	–	–	–	–	–
Prasiolaceae	–	–	6	4	–	–	–	2	–
Chlorellaceae	–	–	–	–	2	–	–	1	–
Trebouxiaceae	–	–	–	–	2	3	–	–	3
Diadesmidaceae	–	–	–	–	2	3	2	–	3
Bracteacoccaceae	–	–	–	–	–	–	3	–	–
Klebsormidiaceae*	–	–	–	–	–	–	–	1	–

Note for Tables 5 and 6: UMPPSB – Uchalinsky Mining and Processing Plant JSC (Sibay branch).

sure, but responded to technogenic pollution.

In the soils of biotopes with a high degree of technogenic pollution, the positions of the leading families changed. The Chlamydomonadaceae was not among the leading families in two types of biotopes (in the overburden dumps of the UMPPSB and in solid waste landfills), and on tramway embankments this family was only the third. Cyanobacteria families – Phormidiaceae, Pseudanabaenaceae, and Nostocaceae – ranked higher compared to habitats affected by recreational stress (Table 5). Of particular interest is the high species diversity of the Klebsormidiaceae on the UMPPSB dumps. Unlike the group of sites affected by recreational load, the Microcoleaceae in this case was not among the leading ones.

Hantzschia amphioxys, Microcoleus vaginatus, M. autumnalis, Leptolyngbya foveolarum, Bracteacoccus minor and other species formed the CAC core of habitats with a high degree of technogenic stress (Table 6). These species were resistant to both recreational load and technogenic pollution.

A comparison of the CACs in the SUR settlements with similar CACs of other natural and climatic zones showed that they were mainly characterized by a relatively high species diversity, the predominance of Chlorophyta and the important role of Cyanobacteria [5, 19, 45]. At the same time, in a number of cities, the CACs were dominated by Cyanobacteria and had a significant diversity of Chlorophyta, for example, in the city of Kirov [46].

Based on the comparison of a group of edaphophototrophic species that have a high constancy and dominate in urban areas in the SUR and other cities [5, 18, 19, 46], we propose to distinguish a separate group of synanthropic species. Synanthropic organisms in a broad sense include plants and animals whose way of life is associated with humans, their homes, and the landscape created or modified by them [47]. Cyanobacteria *Microcoleus vaginatus, M. autumnalis, Leptolyngbya foveolarum, Nostoc punctiforme, Phormidium animale, Ph. breve, Ph. ambiguum* can be considered as synanthropic species. Among Chlorophyta we included *Bracteacoccus minor, Dictyococcus varians, Chlorella vulgaris, Chlamydomonas gloeogama, Stichococcus bacillaris* in the group of synanthropic species; among Streptophyta – *Klebsormidium flaccidum*; among Ochrophyta – *Botrydiopsis eriensis* and *Vischeria magna*; among Bacillariophyta – *Hantzschia amphioxys, Luticola mutica, L. nivalis, L. ventricosa*. These species are cosmopolitan and highly resist to a number of environmental factors, including anthropogenic ones. For example, species of the genera *Microcoleus* and *Phormidium* are typical in technogenic habitats and are noted in samples with a high content of heavy metals near waste heaps in the south of Poland. They were isolated from the tailings of the Valenciana mine (Guanajuato, Mexico), and reclaimed soils of the brown coal and lignite mines of Sokolov (Czech Republic) and Cottbus (Germany). They dominanted in the early waste heaps of the Kansk-Achinsk coal deposit (Russia), and were a part of the "crusts" of the mine waste heaps of the Sibay branch of the Uchalinsky mine (Russia) [48].

When comparing the biodiversity of microphototrophs of settlements and zonal areas of their environs with each other, it was found that CACs significantly change under anthropogenic stress. This was reflected in the overall species diversity of soil phototrophs, the taxonomic structure of CACs, the list of leading families and other characteristics. The features of CACs of various biotopes largely depended on the type of natural and climatic zone, the localization of settlements relative to the Ural Mountains, the features of industrial development of cities, the type of plant community, the intensity of anthropogenic stress, successional changes, etc. Based on the generalization of the data obtained during the analysis of CACs species composition, we developed a scheme for the transformation of CACs under urbanization (Fig. 5).

Conclusions

1. The biodiversity of algae and cyanobacteria in the soils of urbanized areas of the South Ural Republic was represented by 487 species with varieties and forms (Chlorophyta – 231 species, Cyanobacteria – 131 species, Ochrophyta – 58, Bacillariophyta – 52, Streptophyta – 13, Euglenophyta – 2). The CACs taxonomic structure of urban areas of the forest, forest-steppe and steppe zones and their mountain analogues of the South Ural region, while maintaining zonal features, had significant similarities due to the smoothing of soil and climatic conditions in cities, the synanthropization effect, accompanied by the introduction of species of anthropogenically disturbed habitats into the CAC.

Table 6

Group of frequently occurring algae and cyanobacteria species in the soil of the South Ural biotopes affected by technogenic pollution

Taxa	Roadside lawns	MSW container sites	Landfill	Industrial sites	Tramway and railway embankments	Dumps of UMPPSB
Hantzschia amphioxys	IV^5	IV^5	III^5	I	IV^4	III
Microcoleus vaginatus Gomont	III^5	III^4	III^4	IV	I^5	I
Bracteacoccus minor	III^4	V^5	III^5	I^4	III	I
Klebsormidium flaccidum	II^5	III^5	I	III^5	III^5	I
Luticola mutica	III^5	IV^5	I^5	II^4	I	I
Microcoleus autumnalis	III^5	III^5	III^4	III^5	IV^5	I
Leptolyngbya foveolarum	III^5	IV^4	III^4	III^5	IV^4	I
Vischeria magna	I^4	III	III	III^4	I	
Botrydiopsis eriensis	III^4	I	III	II	I	I
Dictyococcus varians	III^5	I	I^3	II	II	I
Chlorella vulgaris	III^5	I	III^3	III^4	I	I
Luticola ventricosa	III^5	I	I	I	I^4	I
Luticola nivalis (Ehrenberg) D.G.Mann	II^5	III		III^5	II^5	
Pseudophormidium hollerbachianum	II^5	IV^4	I	I^3	II	II
Desmonostoc muscorum	II^5	III^3	I^3	III^4	II	
Phormidium breve (Kützing ex Gomont) Anagnostidis & Komárek	I	IV^5	I^3	I	I	
Chlorococcum infusionum	I^5	IV	III	I		
Trichocoleus cf. *hospita*				I		III
Leptolyngbya vorochiniana Anagnostidis & Komárek	I^4			I	I	III

Cyanobacterial-algal cenoses (CAC) of zonal ecosystems in the settlement environs

Characterized by the predominance of Chlorophyta and Ochrophyta, with Cyanobacteria (CB) and Bacillariophyta being less represented. The composition of the CAC depends on the type of soil, natural and climatic conditions, and zonal vegetation. Species with high frequency: *Chlamydomonas oblongella, Chl. elliptica, Chlorococcum infusionum, Bracteacoccus minor, Dictyococcus varians, Myrmecia bisecta, Desmococcus olivaceus, Klebsormidium flaccidum, K. nitens, Botrydiopsis eriensis, B. arhiza, Heterococcus viridis, Xanthonema exile, Vischeria magna, V. helvetica, Hantzschia amphioxys, Luticola mutica, Microcoleus vaginatus*. The average number of species per sample (NS) is 28, the average sum of species abundance scores (SAS) on fouling glasses is 152

↓

Soil CAC of settlements

The proportion of Bacillariophyta and CB increases, the diversity of Ochrophyta decreases. The mosaic nature of biotopes and the diversity of CACs increase

↓ ↓

CAC of rural settlements

Characterized by an increase in the species diversity and abundance of soil algae and CB. Species with high frequency: *Calothrix elenkinii, Desmococcus olivaceus, Gongrosira debaryana, Fistulifera pelliculosa, Leptolyngbya tenuis, Coleofasciculus chthonoplastes*. NS=47, SAS=170

CAC of urban areas

Environmental pollution by vehicle and industrial emissions, household waste, deterioration of hydrothermal conditions of soil in populated areas leads to a decrease in the share of Ochrophyta in the CACs, as they are less resistant to extreme factors. Species resistant to anthropogenic load: *Mayamaea atomus, Nostoc punctiforme, Phormidium animale, Ph. breve, Ph. ambiguum*. NS=18, SAS=104

↓ ↓

CAC of biotopes affected by recreational stress

CB predominate. Ubiquitous species predominate among Chlorophyta. With sufficient moisture in areas without higher vegetation, the role of Bacillariophyta increases. Species resistant to soil compaction: *Microcoleus vaginatus, M. autumnalis, Leptolyngbya foveolarum, L. gracillima, Desmonostoc muscorum, Phormidium breve, Pseudophormidium hollerbachianum, Bracteacoccus minor, Dictyococcus varians, Chlorella vulgaris, Botrydiopsis eriensis, Vischeria magna, Hantzschia amphioxys, Fistulifera pelliculosa, Luticola ventricosa, L. mutica*. NS=23, SAS=139

CAC of biotopes affected by technogenic stress

Unique CACs of relatively poor species composition are formed, including *Hantzschia amphioxys, Microcoleus vaginatus, M. autumnalis, Leptolyngbya foveolarum, Bracteacoccus minor, Chlorococcum infusionum, Klebsormidium flaccidum, Luticola mutica, L. ventricosa, L. cohnii, L. nivalis, Vischeria magna*. NS=14, SAS=83. With prolonged soil pollution, further depletion of CACs species composition is observed

↓ ↓

CAC are represented mainly by a small number of unicellular Chlorophyta. CACs are found on tram and railway embankments, areas of metallurgical and chemical plants contaminated with heavy metals. Species with high frequency: *Bracteacoccus minor, Dictyococcus varians, Chlorella vulgaris, Pseudococcomyxa simplex*. NS=7, SAS=17

The CACs composition is very poor and is represented mainly by filamentous CB. CACs are confined to old roadside lawns, industrial sites, often characterized by alkalization or salinization of the soil. Species with high occurrence: *Trichocoleus* cf. *hospita, Leptolyngbya vorochiniana, L. foveolarum, Microcoleus vaginatus, M. autumnalis*. NS=6, SAS=33

↓ ↓

Communities of single algae or CB with deformed cells, the species of which cannot be determined by microscopy

↓

Termination of development of photosynthetic biota in the soil

Fig. 5. Scheme of cyanobacterial-algal cenoses' (CAC) transformation under urbanization on the example of the South Ural biotopes

2. A scheme for the transformation of the CAC of populated areas was developed, including general and specific patterns of change in the CAC under anthropogenic stress. General patterns were associated with changes in algae and cyanobacteria species diversity and other CACs' features under increasing anthropogenic load and gradual transformation of zonal CACs into azonal ones with subsequent disappearance of autotrophic microbiota. Particular CACs' patterns were associated with the predominance of one of the leading anthropogenic factors (technogenic pollution or recreational stress).

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