Assessing Environmental Condition of Urban Areas from Soil Monitoring Data: Case Studies of Saratov and Engels

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Abstract: We conducted ecological and microbiological assessment of soil cover in different functional zones within the Saratov-Engels agglomeration. We analyzed functional zoning of the area under study identifying the industrial zone, road network, low-rise residential area and high-rise apartment buildings. Microbiological analysis was carried out for the following groups of microorganisms: heterotrophs, actinomycetes, micromycetes, nitrogen-fixing and cellulolytic microorganisms. We revealed the differences in physiological groups of microorganisms and soil enzymatic activity among various urban functional zones. We propose constructing schematic maps of environmental condition in urban areas on the basis of integrated indicators, taking into account geographical features, as well as developing maps of urban soil degradation based on obtained values of microbiological and biochemical indicators.

Keywords: environmental monitoring, microbiological analysis, enzymatic activity, soil respiration, soil degradation grading scale, integrated soil biological condition index, urban functional zoning, urban terrain features, ravine system, flat terrain.

Introduction

Currently, urban areas have soil cover, the composition of which undergoes drastic changes. With industrial growth and noncompliance with environmental protection laws, emissions from vehicles and industrial enterprises, as well as anthropogenic impact on soil structure, the latter changes to such extent that many authors used in their publications the term *urban soil*, rather than just *soil*, thereby emphasizing the ultimate degree of change in the composition of urban areas.

The need of improving the ecological condition of urban soils is among many important problems that must be solved to ensure high-quality living standards in the city. The level of anthropogenic impact is already so high, that, comparing monitored urban soils with natural areas, we can see extremely significant differences in various indicators.

This issue can be resolved solely via continuous monitoring and effective management of the urban environment quality.

Environmental monitoring is an important means of controlling the state of the environment; it also allows tracking changes occurring in it, which makes it possible to evaluate the quality of applying certain measures to increase soil fertility. Monitoring constitutes an initial stage in any project on quality improvement of the urban environment.

The quantitative structure of microbial communities in soil is a reliable biological indicator characterizing the state of urban ecosystems and of important biochemical processes in it, associated with microorganisms. An essential enzymatic activity in soils is closely related to the functional activity of microorganisms. Values of these indicators should be determined for overall biological characterization of soils, as well as for calculating the integral indicator of their biological condition – integrated soil biological condition index (ISBCI) [1].

Currently, use of geoinformation technologies in the environmental monitoring of urban soils can make it possible to more quickly and accurately analyze the biological indicators of the environment and, therefore, make more accurate forecasts and calculations of environmental risks [2, 3]. This approach makes facilitates analyzing large volumes of essential information, on the basis of which, scientifically grounded and effective solutions in the field of environmental remediation of contaminated media are further developed.

Anthropogenic impact on the soil deteriorates its biological quality; consistent environmental monitoring allows tracking the extent, to which the soil cover of urban systems with varying degrees of human impact is affected, and to draw sensible conclusions to find convenient and reliable systems for monitoring the state of the environment for timely management decisions on improving the ecological well-being of urban soils.

The goal of our study was to investigate the ecological condition of urban soils using a complex of microbiological and biochemical indicators and to determine the degree of anthropogenic impact on various urban functional zones, taking into account geographical features of the Saratov-Engels agglomeration.

To achieve the goal, the following tasks were fulfilled:

1. To monitor the state of soils in various functional zones in the cities of the agglomeration under study: sanitary protection zone, road network zone and residential area) over the period of 2010–2020;

2. To assess the qualitative and quantitative composition of soil microbial communities, their enzymatic activity and soil respiration in various functional zones, taking into account geographical features of the agglomeration;

3. To construct the series of soil degradation grades based upon the data on the integrated soil biological condition index;

4. To conduct a comparative assessment of the soil cover state between different functional zones of Saratov and Engels, taking into account geographical features and urban functional zoning;

5. To compile the maps of urban soil ecological condition using up-to-date GIS technology, and to determine the degree of anthropogenic impact on various functional zones, taking into account geographical features of the agglomeration.

Our study subjects included ecological and physiological groups of soil microorganisms in Saratov and Engels. We investigated their enzymatic activity and soil respiration.

Our study objects were soil samples collected at closely located satellite cities of Saratov and Engels with different features of terrain structure.

Materials and Methods

The selection of soil samples was carried out in accordance with Russian National Standard 17.4.3.01-83, General Requirements for Sampling, over the period from 2010 through 2020. All laboratory studies were conducted on the basis of the Science and Education Center for Industrial Ecology at the Department of Ecology, Yuri Gagarin State Technical University (SSTU); and at the accredited testing laboratory *EcoOS*, SSTU, on preliminarily tested equipment, using standard and certified techniques and repeated in triplicate.

We investigated the qualitative and quantitative composition of major groups of microorganisms, their enzymatic activity, as well as the amount of carbon dioxide released from the soil sensu conventional methods [1, 4, 5, 6].

The dilutions of soil suspensions were plated on selective and differential diagnostic nutrient media. We investigated the growth of heterotrophic bacteria on GRM nutrient medium, of actinomycetes on starch-and-ammonia agar, of micromycetes on Czapek medium. Nitrogen-fixing microorganisms were counted by the method of overgrowing soil lumps on Ashby's mannitol agar, and cellulolytic microorganisms were determined sensu Vinogradsky on Hutchinson's nutrient medium [4, 1].

We estimated the activity of soil enzymes of different classes, including oxidoreductases (catalase, sulfite oxidase, and dehydrogenase), hydrolases (cellulase representing glycosyl hydrolases), urease (representing amidohydrolases), invertase (representing β-fructofuranosidases), and phosphatase (representing phosphohydrolases) [1, 5]. The activity of catalase was investigated via the gasometric method; of dehydrogenase, invertase and phosphatase by the colorimetric method; of sulfite oxidase by the titrimetric method; and of cellulase by the field application technique.

The level of soil respiration was determined via the integrated indicator of soil biological activity sensu via the conventional technique of Galstyan [1].

For the parameters under study, the ISBCI was determined [7].

For the cartographic representation of urban soils in different conditions, a geoinformation program (MapInfo) and geoinformation technology were used: vectorization of raster maps for studied territories; overlay of raster maps on terrain for visual presentation of cartographic information.

All obtained results were processed using standard statistical methods for environmental and biological data.

For the city of Saratov, solving the problem of improving environmental monitoring of soils is of particular importance, since it is one of the largest cities in the Lower Volga region. On the territory of the city, there are many large enterprises of chemical, petrochemical, oil refining, mechanical engineering, construction and power engineering industries, all of which are of federal importance. At the same time, in terms of landscape and geographical features, Saratov belongs to the typical right-bank cities of the Volga region with a predominance of a ravine network, with a characteristic wind potential and the formation of the so-called *heat islands* [8, 9], which, in turn, stimulates the formation of local air currents moving from the city suburbs towards its center, thereby forming another network of pollution.

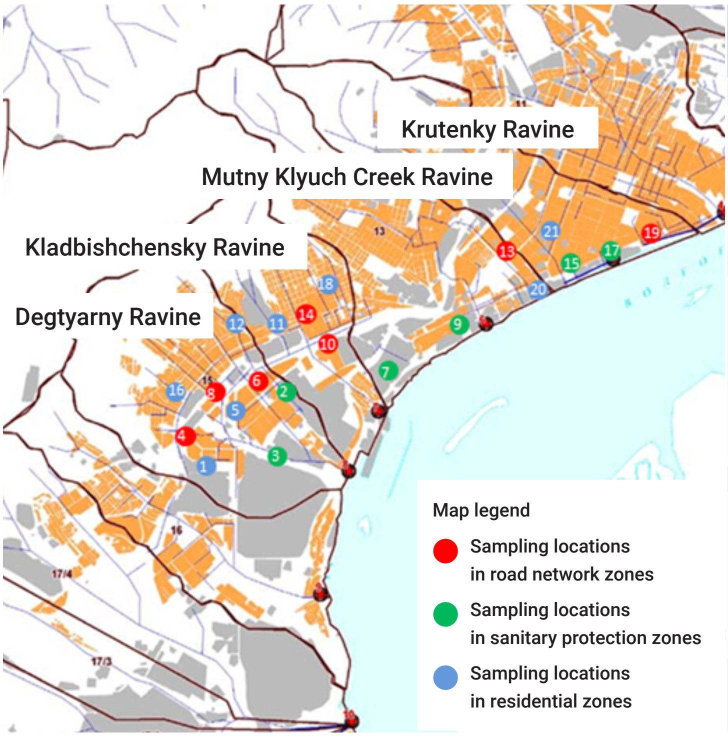
The architectural and planning composition and the geomorphological structure of Saratov determined the conglomerate of various functional zones, depending on the structure of the ravine network. The accumulation of various pollutants in the soils of the city occurs for various reasons: intensive development of the slope and coastal area, perpendicular to the direction of the wind rose; absence of natural ventilation corridors in the downtown area, as well as a small number of wide streets; and critically low proportion of green areas.

For these reasons, the selection of soil sampling points was made, taking into account the peculiarities of the ravine network in the city, the microforms of the terrain, climatic features, and the variety of urban functional zones. Sampling points were located within the Krutenky Ravine, Mutny Klyuch Creek Ravine, Kladbishchensky Ravine, and Degtyarny Ravine (Figure 1).

The terrain is cut through by ravines and gullies, which are completely or partially covered with soils, fine earth and debris. The process of urbanization caused a degradation in natural ecosystems throughout the city in favor of buildings-and-asphalt landscape in combination with a minimum number of open areas.

The city of Saratov is characterized by the predominance of anthropogenic impact over the factors of natural soil formation. This specific feature leads to the formation of novel soil types under these environmental conditions [10].

The problem of soil modification in Engels is associated with a large number of industrial enterprises of various types, which actively developed and grew in the 1980s and 1990s. Currently, their numbers declined, but the cumulative effect would still affect the condition of the soil cover for a long period of time. The second problem is the large number of vehicles and heavy congestion of the major



Sample coding numbers	Cartographic position of sampling locations
	Sanitary protection zones
2	Intersection of Penzenskaya St. and Tomskaya St. (Aircraft Plant)
3	79 New Nineth Line (New Port, OJSC)
7	2b Ordzhonikidze St. (Aircraft Plant)
9	5 Fabrichnaya St. (New Port, OJSC)
15	1 Chernyshevsky St. (Gazprommash LLC)
17	131 Ordzhonikidze St. (Gazprommash LLC)
	Residential zones
1	4 Krymskaya St.: Kindergarten No. 66
5	Intersection of Kavkazskaya St. and Ponomareva St.: Secondary School No. 43
11	11 Ordzhonikidze St.: Kindergarten No. 227
12	196 Ogorodnaya St.: Secondary School No. 5
16	23 Millerovskaya St.: Kindergarten No. 147
18	Intersection of Usievicha St. and Rostovskaya St.: Secondary School No. 22
20	Territory of Saratov City Park (Chernyshevsky St.)
21	Territory of Saratov City Park (Children's School for Music No. 6)
	Road network zones
4	Novoastrakhanskoye Hwy, Torpedo Stadium
6	Intersection of Penzenskaya St. and Tomskaya St.
8	Intersection of Enthusiast Prospect and Penzenskaya St.
10	Volga Stadium (terminus of tramway routes 2, 7, 8)
13	1 Ordzhonikidze St., Cogeneration Plant No. 1
14	Kievsky Ln. (next to railway tracks)
19	Intersection of Chernyshevsky St. and Melnichny Proezd St.
Control location (K)	Village of Aleksandrovka, 10 km away from Saratov

Figure 1. **Map of the location of soil sampling points in different functional zones within the ravine network of Saratov**

road leading across the bridge to the city of Saratov, where most of the Engels population works and, accordingly, travels there on a daily basis. The third problem is the disordered and dense construction of houses, which violates the natural ventilation of the urban area. There are also some positive factors that may have a future positive effect on the state of the soil cover in the city: improvement of the territories by the residents and the city administration (the latter is actively involved in cultural and environmental events throughout the city).

The geographic features of Engels differ from those of Saratov: the territory of the former is represented by a flat terrain. The sampling points were selected taking into account the variety of functional areas (Figure 2): Nos. 4, 14, 16, 17 in road network zones, Nos. 1, 2, 3, 7, 8, 9, 11, 12, 13, 15 in in parks and residential areas, Nos. 5, 6 and 10 in sanitary protection zones.

The cities of Saratov and Engels are large centers of the chemical, oil refining, defense and construction industries. Growth in production, heavy industrial impact on the environment, high population density – all these factors predetermined the growing environmental stress in these cities [11].

As a control, the soil from the territory of the Village of Aleksandrovka near Saratov was studied. That area is close to both cities, but is characterized by a low degree of anthropogenic pressure.

In residential areas, soil samples were taken in the courtyards of schools, kindergartens and residential buildings, as well as within the territory of city parks (for comparison).

In the sanitary protection zones, sampling was carried out around operating or non-operating industrial enterprises.

In road network zones, soils were examined along the major city highways.

Each of the considered functional zones differs in its own characteristics and the degree of an impact on the environment. Therefore, it was of scientific and practical interest to carry out a comparative analysis of the condition of urban soils within the zones, depending on the terrain microforms, and to assess self-cleaning capability of soils via a set of biological indicators. For this purpose, we constructed the series of soils in accordance with the degree of their degradation, depending on the functional zones of the urban area.

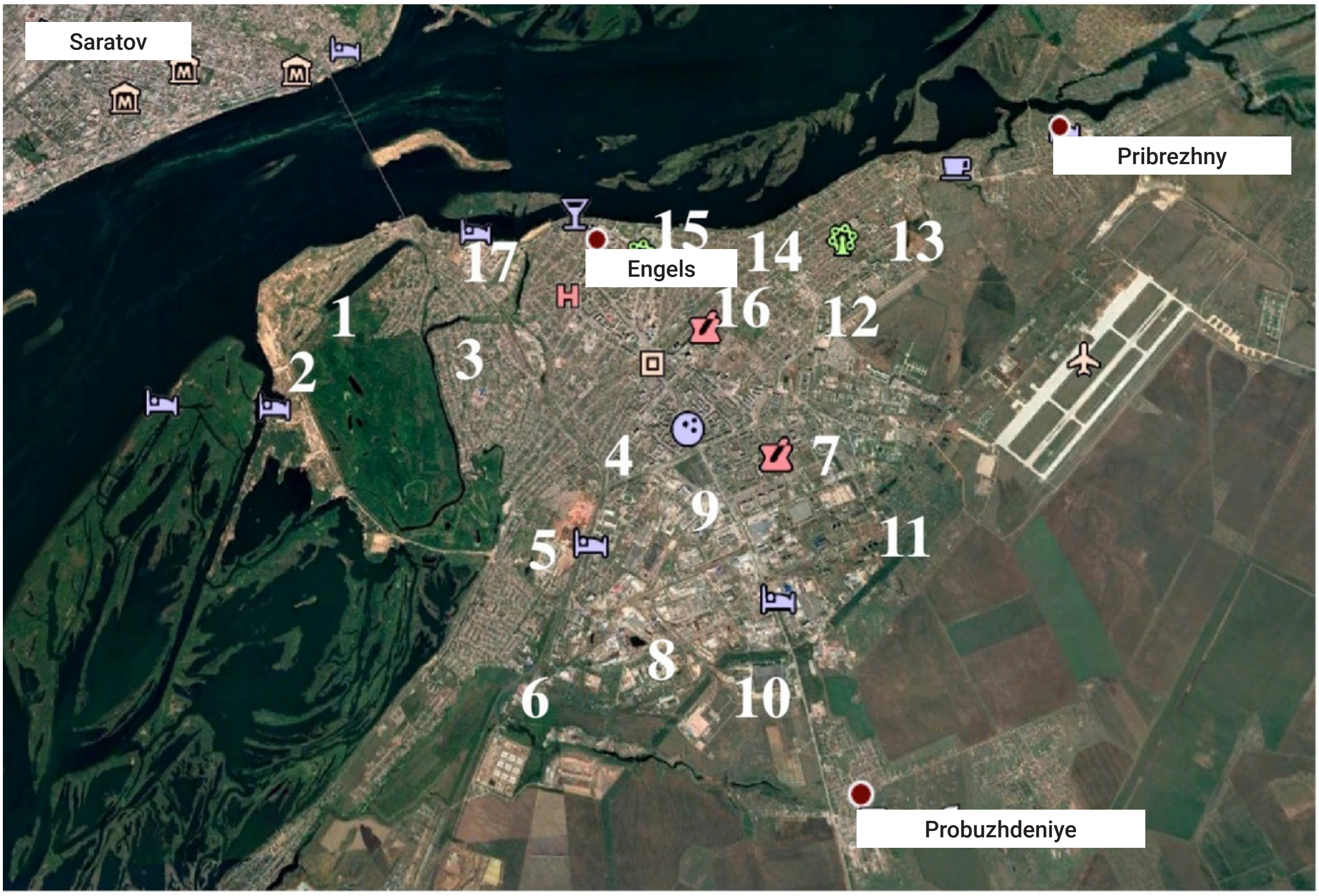


Figure 2. **Map of the location of soil sampling points in different functional zones within flat terrain in Engels.**
1 – Peschanaya St.; **2** – Rybnaya St. (near Pioneer Lake); **3** – 19 Sportivnaya St.; **4** – 171 Mayakovskogo St.; **5** – 285 Mayakovskogo St.; **6** – 24 Volzhsky Prospect; **7** – 152 Telman St.; **8** – 157a Engels Prospect; **9** – 58 Pervy Mikrorayon Uritskogo; **10** – 7 Mendeleev St.; **11** – 59 Marina Raskova St.; **12** – 10 Poligraficheskaya St.; **13** – 21 Demyan Bedny St.; **14** – 7 Pushkin St.; **15** – 28 Berezhnaya St.; **16** – 15 Ostrovsky St.; **17** – 6 Vodnaya St.

Results and Discussion

In all investigated soil samples, all studied groups of microorganisms and enzymes were identified (Tables 1 and 2). Their maximum numbers were discovered in soil samples collected in green areas (parks) and in residential areas of Saratov and Engels. The numbers for Engels were higher than for Saratov. The minimum values were characteristic for soil samples from Saratov, collected on the territory of the city quay, at highways with heavy traffic, in residential areas, and on the territory of the industrial zone of an aircraft plant.

Contrary to Saratov, in Engels, the minimum values of biological activity of urban soils were found only in the city center: within the boundaries of the busiest highway (near the Saratov-Engels bridge).

Based on the obtained data, we carried out an assessment of ISBCI in Saratov and Engels over the period of 2010–2020 in order to compare the ecological condition of urban soils between two cities (Tables 1 and 2).

Contrary to Saratov, in the city of Engels, there are practically no territories with an increased degree of anthropogenic impact. Table 2 highlights the ISBCI values below 50 % in bold. There is just a single location like that in Engels, in contrast to the city of Saratov, where almost half of such values are in the parks and residential areas, as well as in the road network zones.

On the basis of the obtained results of ISBCI assessment within the Saratov-Engels agglomeration, we

TABLE 1.
Assessment of the Integrated Soil Biological Condition Index (ISBCI) Sensu [1] Based on Microbiological and Biochemical Indicators in the City of Saratov Over the Period of 2010–2020 (mean values, %)

Sample No.	Heterotrophs	Actinomycetes	Micromycetes	Nitrogen-fixing microorganisms	Catalase	Dehydrogenase	Invertase	Cellulolytic microorganisms	Urease	Sulfite oxidase	Phosphatase	Soil respiration	ISBCI
Saratov													
FZ	100	100	100	100	100	100	100	100	100	100	100	100	100
Sanitary Protection Zones													
6	116	32	31	105	20	51	72	58	58	75	53	5	57
7	85	46	107	137	5	90	60	87	88	87	71	7	73
11	13	57	19	106	25	151	14	86	75	87	78	2	59
13	27	79	62	78	35	454	62	72	58	62	78	0	90
19	97	85	108	62	45	90	39	100	54	62	31	17	66
21	12	122	18	66	45	84	14	98	60	8	12	3	51
Parks and Residential Zones													
5	22	12	22	37	10	36	72	67	64	87	93	5	44
9	79	72	92	9	5	339	18	75	60	62	7	2	67
15	28	73	44	91	20	48	72	79	75	87	31	1	54
16	21	79	40	19	45	51	31	95	50	75	21	23	45
20	13	95	25	28	45	151	10	76	60	75	28	2	50
22	14	149	22	34	15	84	31	98	60	62	12	1	48
24	73	76	73	128	50	151	33	92	40	50	40	2	66
25	15	91	19	21	50	48	72	64	45	62	59	19	47
Road Network Zones													
8	24	23	32	36	10	57	41	65	79	100	246	12	60
10	18	59	34	52	55	48	18	68	62	75	21	7	43
12	84	77	82	101	35	163	45	73	76	75	309	2	93
14	44	41	62	70	5	48	64	96	59	50	46	1	48
17	63	51	115	34	35	90	60	100	56	62	46	21	61
18	30	66	35	35	25	84	27	82	52	62	15	21	45
23	14	68	17	105	30	81	31	67	55	75	15	25	48

Note: FZ – functional zones.

constructed the series of functional zones from less disturbed to more changed in terms of anthropogenic impact:

- Saratov: Sanitary protection zones > Road network zones > Residential areas
- Engels: Sanitary protection zones > Residential areas > Road network zones.

The obtained results made it possible to draw a conclusion about the direct influence of geographical features in the urban areas on spatial distribution of anthropogenic impact.

On the basis of ISBCI data, which, in turn, was based on microbiological and biochemical analysis of the city of Saratov, a map of ecological condition of Saratov soils was constructed, taking into account

TABLE 2.
Assessment of the Integrated Soil Biological Condition Index (ISBCI) sensu [1] Based on Microbiological and Biochemical Indicators in the City of Engels Over the Period of 2010–2020 (mean values, %)

Sample No.	Heterotrophs	Actinomycetes	Micromycetes	Nitrogen-fixing microorganisms	Catalase	Dehydrogenase	Invertase	Cellulolytic microorganisms	Urease	Sulfite oxidase	Phosphatase	Soil respiration	ISBCI
Engels													
FZ	100	100	100	100	100	100	100	100	100	100	100	100	100
Sanitary Protection Zones													
5	95	65	95	75	66	76	67	82	35	85	223	35	83
6	100	76	111	76	83	92	84	97	44	100	233	35	93
10	97	70	142	59	50	81	49	82	37	85	147	28	81
Parks and Residential Zones													
1	39	45	49	33	22	50	49	73	30	100	90	0	47
2	59	39	58	37	27	59	54	73	43	100	185	28	60
3	64	38	68	41	72	71	60	92	31	100	180	28	65
7	98	47	106	56	88	85	92	100	48	142	152	28,	84
8	68	62	92	41	55	71	47	82	41	85	142	28	67
9	65	39	64	42	66	79	50	82	50	100	142	28	64
11	95	79	127	75	55	67	39	82	53	114	171	35	87
12	67	36	79	53	94	90	64	97	62	100	119	28	70
13	71	27	74	43	61	60	62	82	48	142	138	28	66
15	92	45	112	68	94	89	81	97	43	85	228	35	86
Road Network Zones													
4	50	52	67	64	55	70	62	82	34	114	166	28	67
14	98	52	118	70	55	75	56	82	76	85	185	35	83
16	62	21	63	44	88	92	94	95	50	85	152	28	66
17	42	25	56	40	72	73	73	92	55	71	266	28	65

Note: FZ – functional zones.

the peculiarities of the urban landscape (Figure 3). On the map, zones are highlighted, where the values of the ISBCI of urban soils in Saratov are above 50 %: these are the sanitary protection zones of industrial enterprises. These zones are characterized by the average degree of deterioration, in terms of ecological condition of urban soils. For their restoration, the measures are required, as a result of which, the number of the main groups of soil microorganisms would increase and, as a result, soil enzymatic activity would increase.

The zones where the ISBCI values of Saratov soils are below 50 % are the zones with the maximum degree of degradation of their ecological condition: residential and road network zones, which are primarily subject to restoration using high tech methods of soil cleaning.

The highest values of investigated indicators were in soil samples taken around the territory of Saratov City Park, which were typical cultural soils with green spaces, where agrotechnical measures are periodically carried out.

According to the map shown in Figure 4, it is possible to trace the dependence of the values of biological indicators on their distribution over the basins

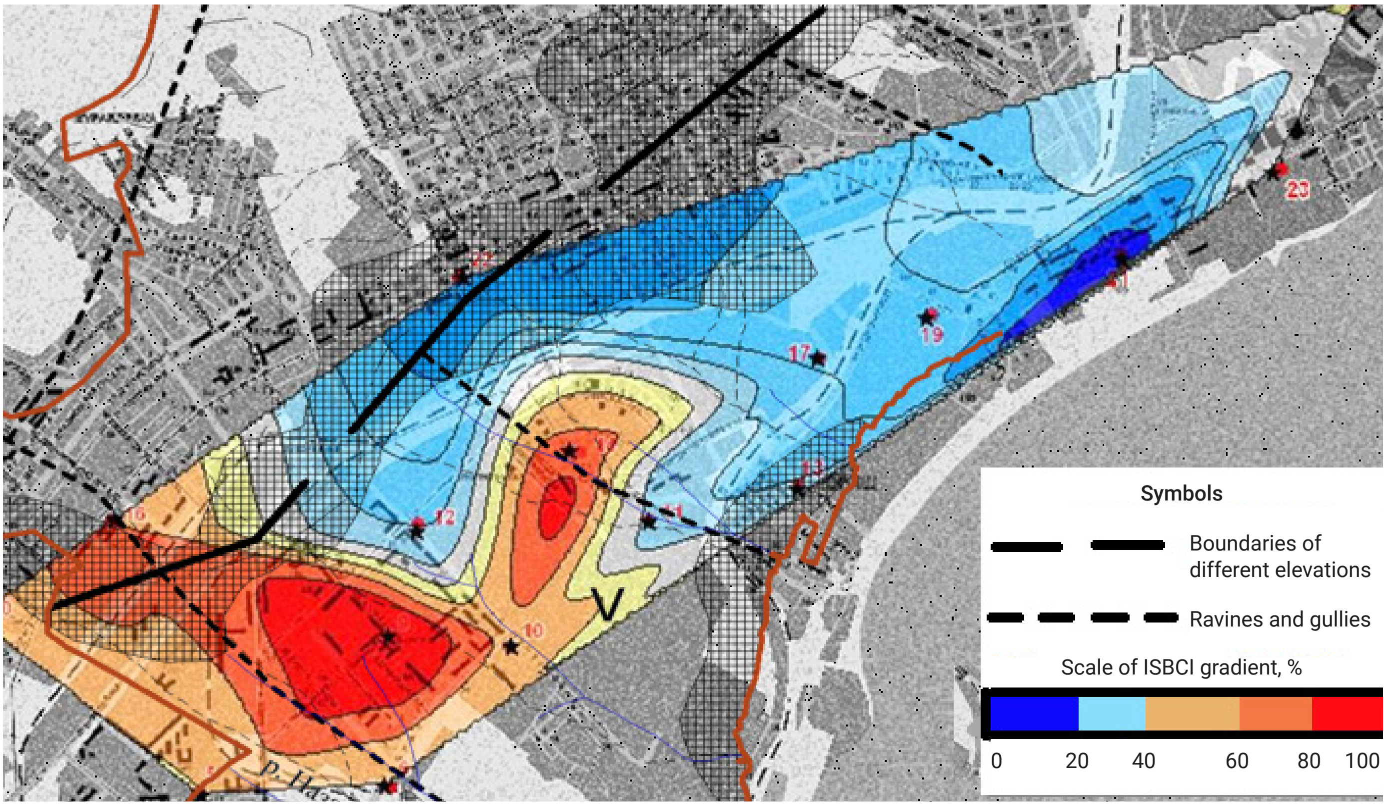


Figure 3. **Map of ecological conditions of soils in the gully-ravine network of Saratov based on the integrated soil biological condition index values**

of ravines, which have been greatly transformed over many years, however, retaining their original properties, especially in a part of the old city (Kladbischensky and Degtyarny ravines).

In these ravines, the distribution of the studied indicators is strictly unvarying along their entire length, from the Volga River to the beginning of the ravine. At present, the landforms of these ravines are not clearly expressed by their original characteristic features and do not differ in the features of the gully-and-ravine network, because here, there is a complete transformation and replacement of the original natural soil with soil brought from elsewhere.

This territory does not have many industrial enterprises; it is occupied by high-rise and medium-rise buildings, located in a way facilitating the processes of street ventilation. Taking into account all these features, we can say that the landforms on a micro scale are best manifested in this area of the ravines.

In the basins of the Krutenky and Mutny Klyuch Creek ravines, the distribution of the ISBCI values has no direct dependence on the length of the ravine. On this territory, it is necessary to take into account not only the features of the gully-and-ravine network, but also the type of functional zones, as well as the characteristic features of residential development: in these zones, there is a large number of high-rise buildings, dense development of which, as well as the difference in terrain elevations, favor the effect of accumulating pollution, which is reflected in the investigated indicators.

The geographic features of the urban area strongly influence the distribution of the anthropogenic pressure effect. For instance, the ISBCI values for urban soils in the city of Saratov above 50 % are characteristic for the sanitary protection zones of industrial enterprises, just as in the city of Engels. The areas in Saratov, where ISBCI values for the soils are below 50% are residential zones with the maximum degree of disturbance to their ecological condition, and they are subject to restoration practices in the first place; whereas in Engels, such values are characteristic for the road network zones.

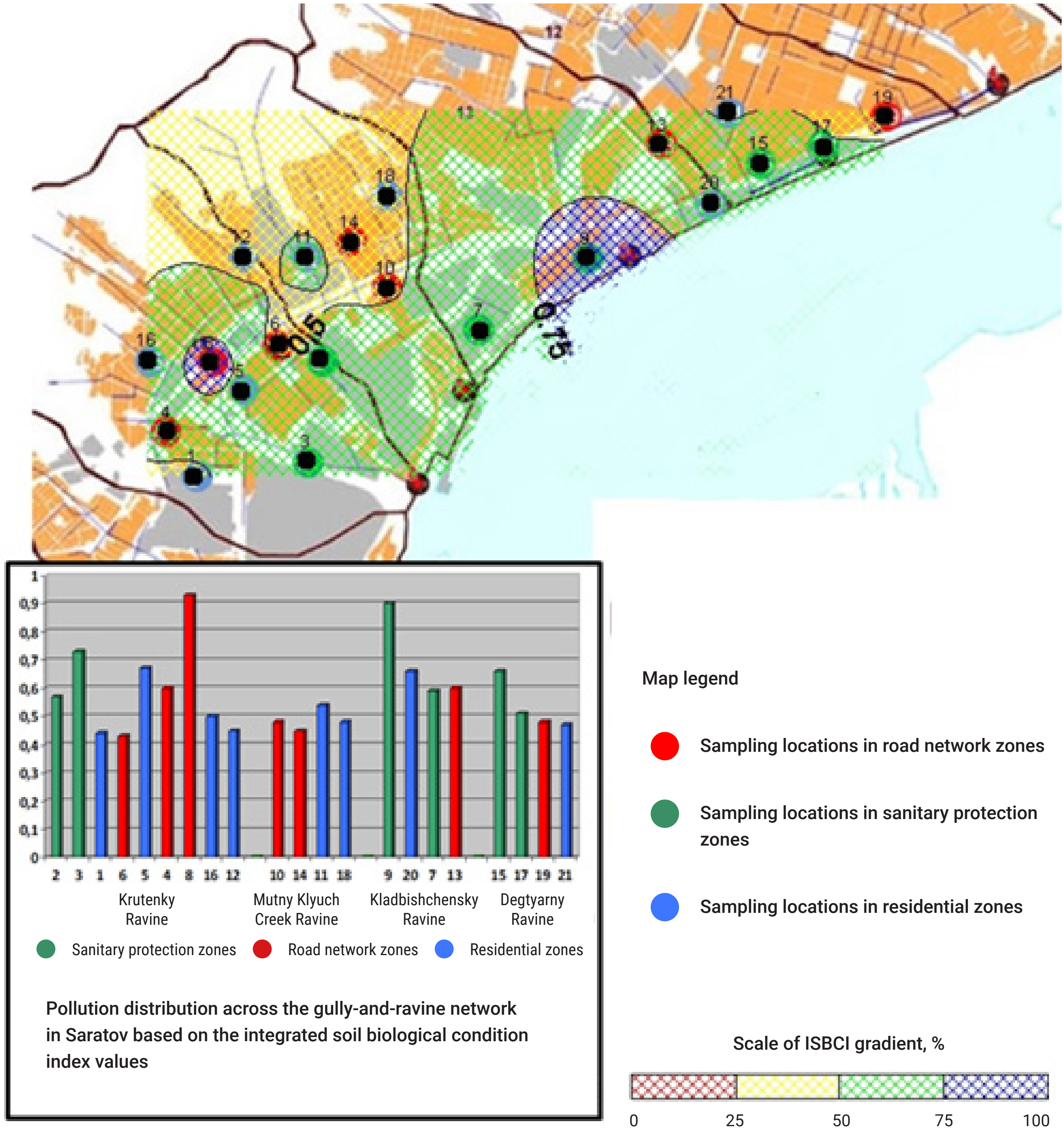


Figure 4. **Map of ecological conditions of soils in various functional zones of Saratov with reference to the features of the gully-and-ravine network**

Conclusion

In order to preserve soils in Saratov Oblast, it is necessary to apply a set of various measures, such as conducting land reclamation, planting protective forest stands, observing the regulations of caring for existing arboreous plantations. Particular attention should be paid to studying available methods of soil decontamination, for example, via natural increase in the numbers of soil microorganisms by supplying various organic components into soil cover.

The main justification for continuing this study is the search for new remediation technologies – specifically, reliable, convenient and, most importantly, affordable methods for soil cover remediation in urban environment. This is a fairly laborious and lengthy work, including the choice of technology, preparation of samples and materials for analysis, and a practical part, at the end of which, it would be possible to determine the effectiveness of the chosen method.

Conducting a soil survey in various functional zones of Saratov and Engels showed that when assessing the state of soils and processes, occurring in them, in conditions of technogenic pollution, it is advisable to use microbiological and biochemical indicators. The latter help determining the degree of anthropogenic impact on urban soil cover, taking into account the peculiarities of ravine system and flat terrain in the city.

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