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The Triad Approach to Ecological Assessment of Urban Soils

V. A. Terekhova[a, b], M. A. Pukalchik[a], and A. S. Yakovlev[a]

[a] *Faculty of Soil Science, Moscow State University, Leninskie gory, Moscow, 119991 Russia*
[b] *Severtsov Institute of Ecology and Evolution, Russian Academy of Sciences, Leninskii pr. 33, Moscow, 119071 Russia*
E-mail: pukalchik.maria@gmail.com, vterekhova@gmail.com

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Abstract—The "triad" approach was suggested by Chapman [22] for assessing the risk of contamination of bottom deposits. We applied this approach for the analysis of urban soils under different loads from motor transport. On its basis, the results of chemical analysis (heavy metals, biogenic elements, and pH), bioindication parameters of the communities of microorganisms, and the results of toxicological investigations with the use of test-organisms were generalized to obtain an integral index of the soil status (IS). A comparison of IS values for test plots at different distances from a highway in the city of Kirov (58.3729–58.624722 N, 49.3743–49.628611 E) showed that the ecological status of the soils could be qualified as disturbed on the plots adjacent to the highway and as slightly disturbed at distances of 30–200 m from the highway. The IS calculated on the basis of data of three disciplines (chemistry, ecology, and toxicology) seems to be a more comprehensive characteristic for assessing the ecological status of urbanozems as compared to *Zc* indices of the chemical contamination of soils (suggested by Saet) or indices of the integral biological characteristics of soil quality.

Keywords: urban soils, heavy metals, biotesting, bioinication, integral index of the soil status

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INTRODUCTION

Deterioration of environmental conditions in the cities is one of the pressing problems of ecology. Negative changes in urban ecosystems are related to the high rates of pollution, diverse physical impacts, and disturbance of the soil cover integrity in the cities. These factors negatively affect the capacity of urban soils to perform their ecological functions [5, 12, 15, 18]. Diverse kinds of economic activity are the sources of ecological problems in large cities, and the role of transport systems is especially important.

The development of approaches for assessing ecological status of soils on the basis of data on changes in their biogenic and abiogenic components has received considerable attention in Russia in the recent decades [3, 8, 9, 28, 29]. It is also important to find optimum ways for integration of ecological monitoring data [1, 4, 14, 16, 28]. Many schemes for calculation of the indices of soil status for their comparison with data on technogenic impact and/or on quality classes of the environment are proposed [4, 7, 11, 19]. A triad approach has been suggested in foreign papers as a reliable tool for characterization of ecological risks upon nature contamination. This approach is based on interdisciplinary methodological principles with the use of data of chemical, bioindication, and toxicological investigations [21–27]. The experience in using this approach for assessing the ecological status of soils, including urban soils, in Russia is insufficient. The aim of our work was to assess the ecological status of urban soils using the triad approach.

OBJECTS AND METHODS

Field studies were performed in Oktyabr'skii district of Kirov. According to the Russian Environmental Control Agency, this is the area with unfavorable ecological conditions [10]. Chemical and metallurgical industries and highways are the major sources of pollution. The studied area is subjected to heavy loads from motor transport on the highway of the Oktyabr'sk prospect.

The samples of urban soils (urbanozems) subjected to the aerial pollution were sampled in May 2010 and 2011 from test plots at different distances from the highway. Overall, five test plots of 10 m^2 under similar grass–dwarf-shrub vegetation were examined. Soil samples from the upper (U1/A1) horizons (0–20 cm) were taken at distances of 5, 30, 50, 150, and 200 m from the highway (test plots 1, 2, 3, 4, and 5, respectively). The studied urbanozems were formed from the natural soddy-podzolic soils. The sixth plot was set in a forest park in the southwestern part of the city. It was used as a control.

The chemical, bioindicational, and toxicological approaches were used in our study.

The chemical analyses included the determination of pH in the water extract by potentiometric approach;

Table 1. Equations used to calculate the indices of soil status on the basis of chemical, toxicological, and bioindication characteristics (according to [21])

Comparison of data on contaminated and background samples	Calculation of the indices of soil state by *i*th component	Integration of data on *i*th into the index of soil state
Index of soil state as based on the chemical indicators (IC)		
$C_i \le C\text{ backgr.}_i$	$\text{IC}_i = \frac{C_i}{C\text{ backgr.}_i} \times 0.50$	$\text{IC} = \frac{\sum_{i=1}^{n} \text{IC}_i}{n}$
$C\text{ backgr.}_i < C_i \le 10\text{ MPC}_i$	$\text{IC}_i = 0.5 + \left(\frac{C_i - C\text{ backgr.}_i}{10\text{ MPC}_i - C\text{ backgr.}_i}\right) \times 0.5$	
$10\text{ MPC}_i < C_i$	$\text{IC}x_i = 1$	
Index of soil state as based on the toxicological indicators (IT)		
$\frac{\lvert T_i - T\text{ backgr.}_i \rvert}{T\text{ backgr.}_i} \le 0.20$	$\text{IT}_i = 0$	$\text{IT} = \frac{\sum_{i=1}^{n} \text{IT}_i}{n}$
$0.20 < \frac{\lvert T_i - T\text{ backgr.}_i \rvert}{T\text{ backgr.}_i} \le 0.80$	$\text{IT}_i = \frac{\frac{\lvert T_i - T\text{ backgr.}_i \rvert}{T\text{ backgr.}_i} - 0.20}{0.80 - 0.20}$	
$0.80 < \frac{\lvert T_i - T\text{ backgr.}_i \rvert}{T\text{ backgr.}_i}$	$\text{IT}_i = 1$	
Index of soil state as based on bioindication (IB)		
$\frac{\lvert \text{B}_i - \text{B backgr.}_i \rvert}{\text{B backgr.}_i} = 0$	$\text{IB}_i = 0$	$\text{IB} = \frac{\sum_{i=1}^{n} \text{IB}_i}{n}$
$0 < \frac{\lvert \text{B}_i - \text{B backgr.}_i \rvert}{\text{B backgr.}_i} \le 0.80$	$\text{IT}_i = \frac{\frac{\lvert \text{B}_i - \text{B backgr.}_i \rvert}{\text{B backgr.}_i}}{0.80}$	
$0.80 < \frac{\lvert \text{B}_i - \text{B backgr.}_i \rvert}{\text{B backgr.}_i}$	$\text{IB}_i = 1$	

C_i is the concentration of the *i*th chemical substance in the sample; C backg$_i$ is the concentration of the *i*th chemical substance in the background soil; T_i is the value of test function of the *i*th biotest in thesample; T backgr$_i$ is the value of test function of the *i*th biotest in the background sample; B_i is the value of test function of the *i*th bioindicator in the sample; B backgr.$_i$ is the value of test function of the *i*th biotest in the background sample; and *n* is the number of studied characteristics.

bulk forms of heavy metals (Pb^{2+}, Ni^{2+}, Cr^{3+}, and Cd^{2+}) were determined by the atomic absorption spectroscopy according to standard methods (PND F16.1:2:2.2.63-09, and PND F 16.1:2.2:2.3:3.36-02); and the main agrochemical characteristics (NPK and C_{org}) were determined by conventional methods.

Biotesting was performed in short-term experiments with the use of test systems and organisms of different trophic levels. Test parameters of organisms-producers included changes in the root length of mustard *Sinapis alba* germs within 96 hrs(as recommended by Russian and international methods FR 1.31.2012.11560 and ISO 11269-1) and changes in the growth rate of microalgae (*Scenedesmus quadricauda*) cells 72 hrs (FR 1.39.2007.03223 and ISO 8692-1). In the biotests with the use of consumers (organisms of another trophic group), we determined the survival rate of crustacean (*Daphnia magna*) within 96 hrs (FR 1.39.2007.0322 and ISO 7346-1) and protozoa (*Paramecium caudatum*) within 24 hrs (FR 1.39.2006.02506). The influence of water extracts from the soils on reducers was determined by differences in the intensity of bioluminescence of genetically modified culture of *Escherichia coli* bacteria in the Ecolum preparation upon their exposure for 30 min in the control and experimental samples (PND FT 14.1:2:3:4.11-04 and PND FT 16.1:2.3:3.8-04 analogous to ISO-11348-2).

Bioindication analysis of urbanozems included the study of ecological parameters of two major groups of soil microorganisms: micromycetes and bacteria.

The micromycete soil complex was studied by the routine method of inoculation of soil suspension into Czapek's medium. Synecological analysis was performed using the total number of colony-forming units (CFU), the portion of dark-pigmented fungi tolerant to adverse factors, and the Shannon indices of biodiversity.

The bacterial complex of soils was studied by the methods of gas chromatography and mass-spectrome-

Table 2. Soil contamination with heavy metals at different distances from the highway (2010–2011)

Test plot no.	Distance from the highway, m	Bulk forms of HM, mg/kg			
		Pb	Ni	Cr	Cd
1	5	422 ± 39 *a*	118 ± 23 *a*	278 ± 31 *a*	3 ± 0.3 *a*
2	30	94 ± 10 *b*	16 ± 6 *b*	60 ± 2 *b*	1.8 ± 0.2 *b*
3	50	130 ± 29 *b*	101 ± 6 *ac*	240 ± 28 *ac*	4 ± 0.1 *c*
4	150	269 ± 28 *d*	67 ± 10 *d*	226 ± 25 *c*	2.0 ± 0.4 *b*
5	200	297 ± 48 *d*	86 ± 9 *cd*	326 ± 40 *d*	0.5 ± 0.2 *d*
6	2000	75 ± 14 *b*	29 ± 5 *b*	59 ± 4 *b*	0.5 ± 0.4 *d*

Values with different letters differ reliably (LSD test, $P < 0.05$) for each characteristic.

Table 3. The impact of water extracts from the soil samples on test functions of biotests (2010–2011)

Test plot no.	Values of test functions of different species in the sample, % of the bacground values				
	S. alba, root length of seedlings	*S. quadricauda*, increase in the number of cells	*D. magna*, number of survived crustaceans	*P. caudatum*, the amount of survived infusoria	*E. coli*, intensity of bioluminescence of bacteria
1	**33.3 ± 14.4** *a*	**42.0 ± 7.6** *a*	**30.2 ± 9.6** *ac*	**46.2 ± 3.3** *a*	**51.6 ± 9.8** *a*
2	78.0 ± 17.7 *b*	78.0 ± 12.8 *b*	**48.0 ± 9.9** *bc*	**20.0 ± 3.1** *b*	79.8 ± 3.8 *b*
3	60.4 ± 17.5 *abc*	54.3 ± 7.6 *a*	**33.8 ± 11.1** *cab*	**26.6 ± 2.4** *c*	67.9 ± 11.5 *b*
4	87.8 ± 19.6 *b*	53.2 ± 9.4 *a*	**33.4 ± 10.0** *abc*	**29.8 ± 2.9** *c*	71.1 ± 7.9 *b*
5	86.5 ± 11.6 *b*	**42.8 ± 6.5** *a*	**30.0 ± 9.8** *acf*	**15.8 ± 3.6** *b*	67.2 ± 4.0 *b*
6	100 ± 14.1 *bd*	100 ± 4.4 *c*	100 ± 2.2 *d*	100 ± 3.3 *d*	100 ± 7.1 *c*

Values with different letters differ reliably (LSD test, $P < 0.05$) for each characteristic. Variants qualified as toxic variants (the values of test functions are less than 50% of the control) are given in bold type.

try (GC–MS) with respect to fatty-acid components of cell walls [2, 20]. We determined the number of bacteria, actinomycetes, and actinobacteria; the ratios between phylogenetic types of prokaryotic organisms in the population; biodiversity indices (according to Shannon); and the portions of anaerobic and facultatively anaerobic bacteria in the population.

The triad approach for assessing the ecological status of the soils implied the use of experimental data on the concentrations of pollutants, toxicity for test organisms, and bioindication parameters of microbial communities. These data were grouped for separate test plots and processed using the triad approach [21]. The indices of the soil ecological status were calculated from the chemical, toxicological, and biological indicators (IC, IT, and IB) in three stages. First, we compared our data on the studied soil samples from the five test plots near the highway with data on the background samples (the sixth test plot afar from the highway). Second, we chose conversion functions to convert these data into the indicators of the ecological state of the soils in dependence on the difference between their values. Finally, we calculated the summary IC, IT, and IB values. The triad approach includes the analysis of "desirability" function (according to [4]), which makes it possible to convert natural values of the chemical, biological, and toxicological characteristics into dimensionless scale with fixed boundaries. The used equations are given in Table 1.

The integral index (InI) was calculated from the triad of chemical, toxicological, and bioindication characteristics with the use of weighted coefficients equal to 1.0, 1.5, and 2.0, respectively:

$$\mathrm{InI} = \frac{1.0 \times \mathrm{IC} + 1.5 \times \mathrm{IT} + 2.0 \times \mathrm{IB}}{1.0 + 1.5 + 2.0}. \quad (1)$$

Table 4. Some characteristics of the communities of soil microorganisms (2010–2011)

Test plot no.	Fungi			Bacteria	
	total number, thousand CFU/g soil	portion of dark-colored colonies	portion of quickly-growing colonies	portion of actinomycetes and actinobacteria in microbiota community, %	anaerobic and facultatively anaerobic bacteria, million cells/g soil
		% in community			
1	176.7 ± 29.1 *a*	93.3 ± 6.2 *a*	4.2 ± 1.3 *a*	8 ± 0.4 *a*	55 ± 2.7 *a*
2	25.1 ± 4.6 *b*	19.2 ± 1.1 *bfg*	2.5 ± 0.8 *a*	1.8 ± 0.1 *b*	67 ± 3.3 *b*
3	14.7 ± 1.5 *b*	5.1 ± 1.6 *cd*	3.6 ± 0.5 *a*	2.7 ± 0.1 *c*	51 ± 2.5 *af*
4	25.7 ± 7.7 *b*	13.0 ± 6.5 *cf*	6.7 ± 1.2 *b*	1.9 ± 0.1 *b*	54 ± 2.7 *af*
5	24.3 ± 7.7 *b*	14.9 ± 5.6 *cfg*	9.1 ± 0.7 *c*	0.2 ± 0.1 *d*	88 ± 4.4 *c*
6	22.0 ± 3.2 *b*	5.8 ± 1.2 *df*	6.1 ± 1.1 *b*	13.3 ± 0.6 *f*	77 ± 3.8 *d*

Values with different letters differ reliably (LSD test, $P < 0.05$) for each characteristic.

The coefficients for the toxicological and bioindication characteristics (1.5 and 2.0, respectively) were taken higher than the coefficient for the chemical characteristics (1.0) as suggested by Dagnino with coauthors [21], because biotic (toxicological and bioindication) characteristics are most informative for assessing ecosystem sustainability and characterizing ecological functions of soil as a habitat of living organisms [21, 28]. Limit values (0 and 1) correspond to good and bad conditions. Intermediate values are interpreted as follows: the higher the index, the greater the difference from the background (control) values, i.e., the worse the ecological status of the soil.

The significance of differences between average values was estimated with the use of one-way ANOVA and the LSD test; the values designated by different letters reliably differ, The plots were constructed with the use of the SigmaPlot program software package.

RESULTS AND DISCUSSION

Assessment of the ecological status of soils by their chemical characteristics. Strong anthropogenic impacts affect physicochemical soil properties. As shown earlier [13], the studied soils are characterized by a slightly alkaline reaction (pH of water extract is 7.40–8.06), disturbed genetic horizons, medium loamy texture, and a somewhat increased bulk density (compaction) of the A1 horizon.

The content of organic substances (C_{org}) in the soil samples increases from 3.50 to 4.69% in the direction toward the highway. In the soil of the background (control) plot, the C_{org} content is 3.42%. The soils are rich in available phosphorus compounds (P_2O_5, from 268 to 345 mg/kg) and exchangeable potassium (K_2O, 167–250 mg/kg), which may favor the accumulation of heavy metals.

Soil contamination by heavy metals—traditional pollutants—is an important factor affecting the ecological status of urban soils. Their contents varied in dependence on the distance from the highway and the particular form of ecotoxicants (Table 2).

Thus, the cadmium content in the soils of test plots 1–4 exceeded the background value (0.66–1.11 mg/kg) by more than two times (background contents of heavy metals in Kirov region are given according to [17]). The samples from the control plot and plot 5 had the lowest cadmium contents. The nickel content in the studied soils averaged 69.5 mg/kg, whereas its regional background content is 40 mg/kg. Four test plots out of

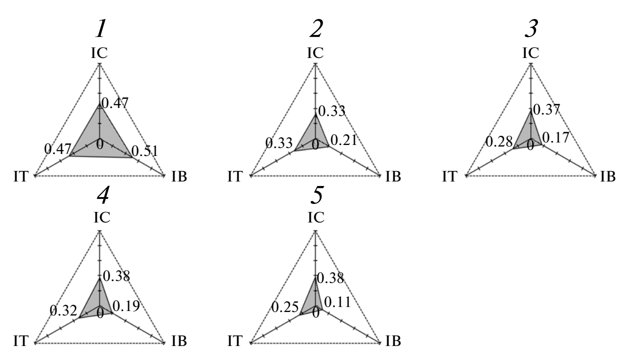

Fig. 1. Assessment of the ecological state urbanozems with the use of the triad approach (the values along the IC, IB, and IT axes correspond to the indices of the ecological state of urbanozems calculated from chemical, bioindication, and toxicological data, respectively); *1–5* are the numbers of test plots. The area of dark-colored triangles reflects the degree of soil disturbance; 0 corresponds to the background state.

Table 5. A comparison of the integral index of the ecological state of soils determined by the triad approach with the indices of soil quality (according to [4]), load value, and soil ecological status (according to [19])

IS value	Soil quality group	Load	Ecological state of the soil
IS = 0	I	Permissible	Background
0 ≤ IS ≤ 0.30	II	Low	Slightly disturbed
0.30 < IS ≤ 0.50	III	Medium	Disturbed
0.50 < IS ≤ 0.79	IV	High	Strongly disturbed
0.79 < IS ≤ 1	V	Very high	Irreversibly disturbed

six plots had a significantly higher nickel content in comparison with the background value. The lead content in the samples taken near the highway was 9.8 times higher in comparison with the regional background (43 mg/kg) and 5.6 times higher in comparison with the control plot. For test plots 2–5, the lead content was also higher significantly higher than the regional background and local background (control) values. The chromium content in the studied soils averaged 226 mg/kg, while its content in the control soil was 59 mg/kg. The chromium content was higher than the regional background in the soils of four test plots.

Thus, the content of analyzed heavy metals in the studied urbanozems exceeded the regional background content of heavy metals established for the agricultural and forest soils [17].

Evaluation of the ecological status of soils by their toxicological characteristics. Biotesting of contaminated soils with the use of test cultures and soil water extracts showed increased toxicity of the soil samples. In many cases, the differences in the growth rates of test cultures were up to 50% of the control values (Table 3). A drop in the soil toxicity with an increase in the distance from the highway was only shown for seedlings of higher plants. The soil from test plot 1 had definite inhibiting action on the growth of all the five test culture. The samples from other plots demonstrated inhibiting action on at least two of the five test cultures, which makes it possible to qualify these plots as ecologically unfavorable.

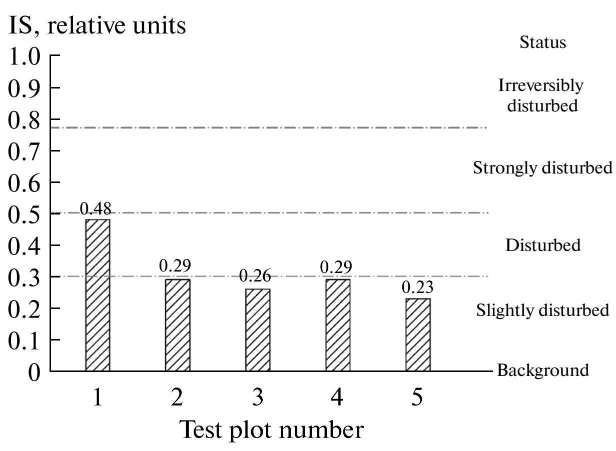

Fig. 2. Integral index calculated by the triad approach and the soil status on test plots according to [19].

Assessment of the ecological status of soils by their bioindication characteristics. The biological diversity of microorganisms in the samples of urbanozems was assessed using parameters of the micromycetal, bacterial, actinomycetal, and actinobacterial communities.

Some characteristics of micromycetal and bacterial communities are given in Table 4. We identified 21 species of cultivated micromycetes capable of growing on the Czapek medium with agar. From 4 to 7 fungal species were present in the samples. Sterile forms predominated among them (100% occurrence). Dark-colored micromycetes were numerous with the occurrence of 80% for *Clonostachys rosea*.

Against the background of relatively low numbers of CFUs of micromycetes, plots 2–6 were characterized by considerable changes in the micromycetal community in comparison with plot 1: the number of melanized (dark-colored) forms in the samples from plots 2–6 was significantly higher. This confirms the bioindicative role of dark-colored micromycetes for the diagnosis of soil contamination with heavy metals [16, 28].

The taxonomic diversity of bacteria in the soil of the control plot was considerably lower than that in the soils of test plots at different distances from the highway. Thus, 23 bacterial species from 17 genera were identified in the soil of the control plot (plot 6), and 37 bacterial species from 28 genera were identified in the soils of test plots 1–5. Taking into account increased concentrations of Pb, Ni, and Cr in the soils of test plots 1–5, we may suppose that these microorganisms are rather tolerant (with respect to their total number) to the impact of excessive amounts of these heavy metals.

Actinomycetes and actinobacteria in the investigated soils were represented by five genera: *Rhodococcus, Pseudonocardia, Streptomyces, Nocardia*, and *Actinomadura*. In the soil of the control plot, the total content of actinobacteria and actinomycetes was higher than that in the soils of contaminated plots (13.3% versus 2.5–8%, respectively). Thus, the contamination of the samples with heavy metals was a factor affecting the total numbers of actinomycetes and

Table 6. Variants of ranged scales for assessing the ecological state of soils and corresponding technogenic impacts (according to data from different sources)

Criterion for impact assessment; ing impact rate and predicted ecological status		Values of characteristics					Information source
Evaluation scales	Limits of critical impact with respect to chemical data, parts of unity	0–0.21	0.21–0.50	0.50–0.79	0.79–1	1	[4]
	Soil quality loss, %	0–5	6–20	21–40	41–70	71–100	[19]
	Decrease in the IB, %	0–5		6–10	11–25	26–100	[7]
	IS value as determined by the triad approach	0	0–0.30	0.30–0.50	0.50–0.79	0.79–1	
Predicted ecological state	Soil state as determined from the IS value	Background	Slightly disturbed	Disturbed	Strongly disturbed	Irreversibly disturbed	[19]
	Technogenic loads	Conventional zero	Low	Medium	High	Catastrophic	[19]
	Characteristics of the state of the environment	Satisfactory ecological situation			Extreme ecological situation	Ecological disaster	[19]

actinobacteria. It is known that actinomycetes grow better in neutral soils enriched in organic matter [6]. These characteristics are more typical of the soil of the control plot.

Multiple ecological assessment of the soil status with the use of the triad approach. We used the triad approach to generalize the obtained data [21]. The results of represented in Fig. 1.

The range of the values of the integral index calculated on the basis of the triad approach was separated into five categories according to [4]. These categories were then compared with the degree of anthropogenic loads on the soils and with the characteristics of the soil ecological status given according to [19] (Table 5). Integral indices of the ecological state of the soils calculated according to Eq. (1) are shown in Fig. 2.

The soil from the test plot 1 (near the highway) is characterized by *the disturbed state* and can be attributed to the third quality group. The soils of other test plots at greater distances from the highway are *slightly disturbed* and can be attributed to the second quality group.

CONCLUSIONS

Modern approaches to the ecological assessment of soils are mainly based on analytical data on the concentrations of pollutants. This is explained by certain difficulties of the analysis of the state of biota and formalization of data obtained by different methods. In contrast to soils subjected to strong anthropogenic impacts from point-size contamination sources, urbanozems of small cities are not subjected to catastrophic levels of contamination. To assess the stage of these soils, the results of biological investigations are of particular importance. The response of separate living organisms and the state of biological communities provide information on the ecological quality of biocenoses and sustainability of the soil functioning.

The triad approach provides the basis for a comprehensive assessment of the ecological status of soils. This approach suggests the use of Formalized data on the response of living organisms in biotests, on changes in the studied communities of microorganisms, and on the chemical contamination of the soils for calculating an integral index of the ecological status of soils.

We tried to compare this index with traditional estimates of soil quality in different biotopes under different anthropogenic loads using available estimates from Russian sources [4, 7, 19]. The results are shown in Table 6.

The integral index calculated using the triad approach (with integration of data on chemistry, ecology, and toxicology) seems to be more adequate for the assessment of the ecological status of urbanozems in comparison with the indices of total chemical contamination Zc (suggested by Saet) or the indices of the integral biological soil quality (according to [7]).

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