Трансформация экосистем
Ecosystem Transformation

ISSN 2619-0931 Online
www.ecosysttrans.com

DOI 10.23859/estr-230217
EDN NNMVRYS
UDC 57.042+57.044+57.045

Article

Informative indicators of the ecological state of soil exposed to low stress factors: pollution, drought, acidity

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Abstract. The article is devoted to the problem of choosing informative indicators of the ecological state of soil with a low stress factor. The purpose of this work is to compare toxicological (*ex situ*) and bioindicative indicators (*in situ*) of soil under conditions of pollution, drought, and increased acidity. The number of zymogenic and oligotrophic microflora, the activity of catalase and urease exoenzymes, including the acute toxicity of soil extracts in tests for *Paramecium caudatum* and *Escherichia coli* were determined in soil samples. Most of the reactions observed ex situ and in situ were hormetic or equal to the control. As compared to the control, an increase in the number was noted in oligocarbophiles in moderately acidic soil (by 13 times), in oligotrophs in drought-exposed soil (by 22 times), in amylolytics in contaminated and acidic soil (by 6 times), as well as in arid soil (by 1.6 times). The values of the following parameters significantly decreased in the conditions of the applied factors: the number of ammonifiers under low-level cadmium stress (by 3 times) and moderate soil acidity (by 5 times), cellulolytics in response to soil acidity (by 2.5 times) and under drought (by 1.7 times), urease activity in moderately acidic soil (by 1.7 times). In addition, the toxicity index for moderately acidic soil in the test for *P. caudatum* increased by 1.4 times.

Keywords: soil models, cadmium, lack of moisture, bioassay, eco-trophic groups of microorganisms, soil enzymes

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To cite this article: Olkova, A.S., Tovstik, E.V., 2024. Informative indicators of the ecological state of soil exposed to low stress factors: pollution, drought, acidity. *Ecosystem Transformation* **7** (3), 138–152. https://doi.org/10.23859/estr-230217

Received: 17.02.2023
Accepted: 14.03.2023
Published online: 16.08.2024

DOI 10.23859/estr-230217
EDN NNMVRYS
УДК 57.042+57.044+57.045

Научная статья

Информативность показателей экологического состояния почвы, находящейся в условиях низкоуровневого стресса: загрязнение, засуха, кислотность

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Аннотация. Статья посвящена проблеме выбора информативных показателей экологического состояния почвы с низкоуровневым стресс-фактором. Цель данной работы – сравнение токсикологических (*ex situ*) и биоиндикационных показателей (*in situ*) почвы, находящейся в условиях загрязнения, засухи, повышенной кислотности. В образцах почвы определяли численность зимогенной и олиготрофной микрофлоры, активность экзоферментов каталазы и уреазы, острую токсичность почвенных вытяжек в тестах на *Paramecium caudatum* и *Escherichia coli.* Большинство реакций, проявившихся *ex situ* и *in situ*, были горметическими или равными контролю. Увеличение численности по сравнению с контролем наблюдали у олигокарбофилов в среднекислой почве (в 13 раз), у олиготрофов в почве, испытавшей засуху (в 22 раза), у амилолитиков в загрязненной и кислой почве (в 6 раз), а также в засушливой (в 1.6 раза). Достоверно уменьшались в условиях приложенных факторов значения следующих показателей: численность аммонификаторов при кадмиевом стрессе низкого уровня (в 3 раза) и средней кислотности почвы (в 5 раз), целлюлозолитиков в ответ на кислотность почвы (в 2.5 раза) и при засухе (в 1.7 раза), активность уреазы в среднекислой почве (в 1.7 раза). Кроме того, в 1.4 раза возрастал индекс токсичности для среднекислой почвы в тесте на *P. caudatum.*

Ключевые слова: почвенные модели, кадмий, недостаток увлажнения, биотестирование, эколого-трофические группы микроорганизмов, почвенные ферменты

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Для цитирования: Олькова, А.С., Товстик, Е.В., 2024. Информативность показателей экологического состояния почвы, находящейся в условиях низкоуровневого стресса: загрязнение, засуха, кислотность. *Трансформация экосистем* **7** (3), 138–152. https://doi.org/10.23859/estr-230217

Поступила в редакцию: 17.02.2023
Принята к печати: 14.03.2023
Опубликована онлайн: 16.08.2024

Introduction

A well-grounded ecological assessment of the soil state is an important interdisciplinary natural science area since its results influence on planning the land use, the possibility of agricultural exploitation of soils, and contribute to the overall picture of the ecological well-being of the territory[1].

The methodology for assessing the ecological state of soil is in progress. The scientific community has recognized and then accepted at the national and international levels that the state of soil must be determined through a set of indicators. This approach is known as the "triad" (TRIAD) and means an evaluation based on a combination of chemical, toxicological (*ex situ*) and bioindicative (*in situ*) data[2] (Terekhova, 2022).

When assessing the impact of toxicants on the environment, including soil, most approaches are aimed at determining safe concentrations of pollutants that do not disrupt of the biota functions. In our country, this is implemented through a legislatively approved system of maximum permissible concentrations, as well as other hygienic and environmental standards with due regard for types of land use[3, 4, 5]. At the same time, when using this system, numerous soil properties extremely rarely are taken into account, i.e. its mechanical composition, acidity, temperature conditions, pedocommunity diversity, etc. Options for overcoming the problem have already been proposed. For instance, the method of local environmental standards based on division of permissible and impermissible intensity of environmental factors, is among them (Konovalov and Risnik, 2017).

There are known cases when the standardization of soil pollutants is carried out depending on its purpose, properties or a set of these features[5] (Antoniadis et al., 2019). For example, three types of threshold values are used in China to regulate the content of heavy metals and metalloids in agricultural soils to ensure food safety, maintain crop yields, and protect the soil microbial system (Li et al., 2019).

Thus, the assessment of the ecological state of soils using such integral parameters as the intensity of soil respiration, the activity of soil enzymes, the vital state of bioindicator organisms and well-being of their populations, the structure of soil communities is becoming increasingly relevant (Akimenko et al., 2019; Bünemann et al., 2018).

Some of integral ecological indicators of soil condition used in scientific research are also applied in the state environmental control and monitoring of environmental components. Thus, the determination of soil toxicity is provided in programs for environmental monitoring of hazardous industrial facilities (Chupis et al., 2013) and microbiological indicators – in the sanitary evaluation of soils in the populated areas and agricultural lands[6].

According to the most important environmental laws (Odum, 1983), the indicators of vital activity of soil biota and, consequently, the integral indicators of soil state depend on the environmental factors. For example, soil enzymatic activity is defined both from abundance and species diversity of soil microorganisms, as well as species composition of plants (Farooq et al., 2021) and seasonality (Garcia-Ruiz et al., 2009).

The formation of the soil microbial community depends on its type, temperature and water conditions, pH level, enrichment with macro- and microelements (Islam et al., 2020; Zuccarini et al., 2020).

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[1] GOST R 54003-2010. Environmental management. Assessment of past environmental damage accumulated in the locations of organizations. General provisions.

[2] GOST R ISO 17616-2022. Soil quality. Guidelines for the selection and evaluation of bioassays to determine the ecotoxicological characteristics of soils and soil materials.

[3] Resolution of the Chief State Sanitary Doctor of the Russian Federation No. 1 of January 23, 2006 "On the introduction of Hygienic Standards GN 2.1.7.2041-06".

[4] Regulation on state sanitary and epidemiological standardization, approved by Decree of the Government of the Russian Federation of July 24, 2000 No. 554.

[5] SanPiN 1.2.3685-21. Hygienic standards and requirements for ensuring the safety and (or) harmlessness of environmental factors for humans.

[6] SanPiN 2.1.7.1287-03. Sanitary and epidemiological requirements for the quality of soil and ground.

Ecological and toxicological indicators of soil, determined in bioassays due to various laboratory organisms, also depend on a set of environmental factors despite being isolated from the environment at the time of analysis (Olkova and Tovstik, 2022).

The problem of establishing the relationship between the soil characteristics and the affecting factors is under development; it is relevant for the objective interpretation of the data obtained. In practice, specialists in the field of agronomy, ecology, soil science and other related sciences most often deal with assessing impacts (classified as low-level stress) on soil and its functions. This concept is conditional and characterized, first of all, by deviation of a factor from optimal conditions to values that allow the living system (from the organismic to the ecosystem level) to exist for a long time. Thus, when pH values of salt extract from soils go beyond 6.1–7.8, soil acidity becomes a stress factor that is explained by both a direct action of hydrogen ions and a change in the availability of soil nutrients for biota (Msimbira and Smith, 2020).

The purpose of this work was to compare the information content of integral indicators of soil exposed to a low-level stress (pollution, drought, acidity) for its environmental assessment.

Materials and methods

Scheme of the model experiment

The experiment was carried out under conditions close to field studies (Kirov, Kirov Oblast Russia). Sod-podzolic soil, sampled near Kirov, with different acidity levels (pH 4.8 and 6.5) was placed in vegetation containers with subsequent sowing of barley seeds (*Hordeum vulgare* L.). Soil was characterized as medium-humus (humus content – 1.9–2.5%), with a low content of mobile phosphorus (20–50 mg/kg) and nitrate nitrogen (1.1–1.7 mg/kg). Standard field conditions without exposure (control, pH = 6.5), as well as three types of unfavorable factors were simulated:

1) Soil pollution with cadmium. The toxicant was introduced into soil (pH = 6.5) in the form of a cadmium acetate solution. According to atomic absorption spectroscopy, the level of mobile cadmium compounds in soil reached 6.4 ± 0.5 mg/kg. There are no MPCs for cadmium in soil; the APC value is set only for its mobile forms[7]. For soils with pH close to neutral values, APC was 2.0 mg/kg.

2) Soil acidity. For this variant, we used soil characterized by a moderately acidic pH level of salt soil extract (1N KCl solution) – 4.8 ± 0.1 pH units (that is 1.7 units lower than the control). In terms of other characteristics, soil did not show reliable differences from the control sample.

3) Short-term drought. The modeling was carried out by isolating soil (pH = 6.5) with crops from atmospheric precipitation for 25 days using a poorly ventilated transparent polyethylene tent. The drought modeling began on the 42nd day of the experiment. After the completion of the model drought, these experimental variants were in the same conditions as the control.

The total duration of the experiment, regardless of the variant, was 90 days. Later, soil samples were taken for the analysis.

Weather conditions for the experiment

According to meteorological parameters, the year of the experiment was characterized by relatively higher average daily temperatures compared to the ten-year average annual values of the indicator for the growing season (Fig. 1).

Assessed integrated environmental indicators

All selected indicators of soil state were associated with microorganisms:

A response of the soil microbial complex based on the number of individual representatives of ecological-trophic groups was determined through sowing soil suspensions on agar nutrient media of various compositions with subsequent accounting of the number of grown colonies. Among the representatives of the zymogenic ecological niche, we considered ammonifiers on meat-peptone agar, amylolytic microorganisms on starch-ammonia agar and cellulolytic microorganisms on Hutchinson-Clayton medium, whereas among the oligotrophic representatives – oligotrophic microorganisms on soil agar and oligocarbophilic microorganisms on starvation agar (Praktikum..., 2005).

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7 SanPiN 1.2.3685-21. Hygienic standards and requirements for ensuring the safety and (or) harmlessness of environmental factors for humans.

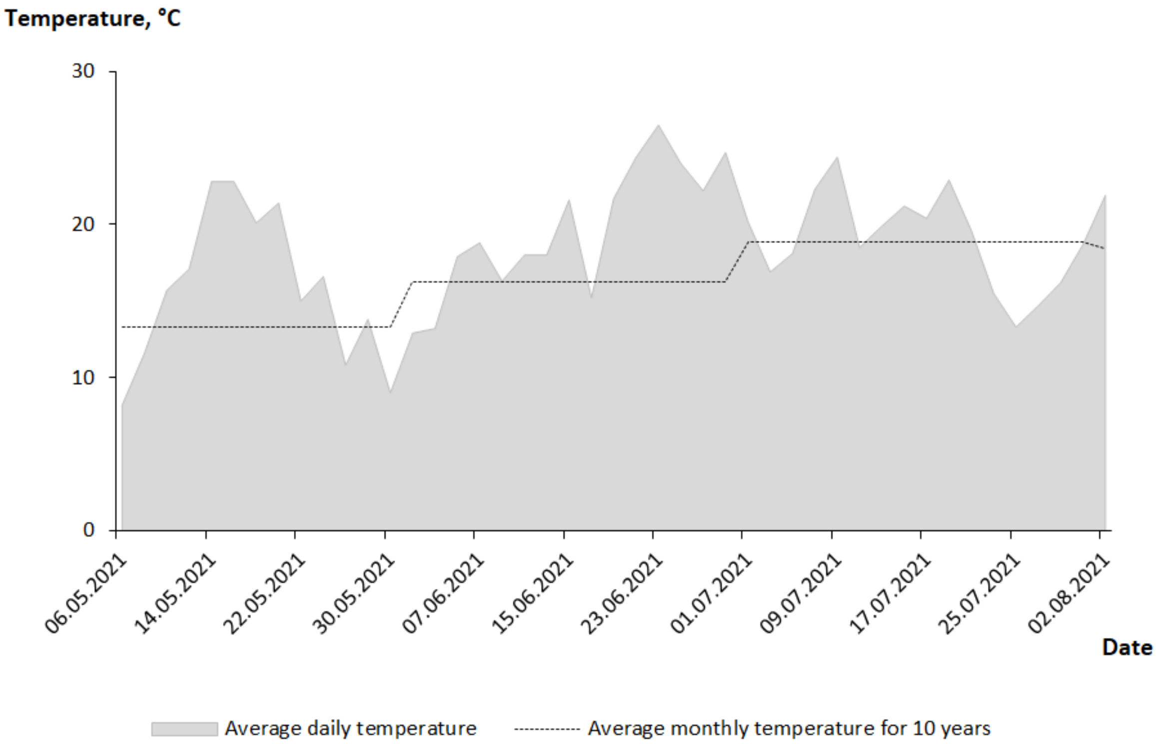


Fig. 1. Air temperature 2 m above the Earth's surface in Kirov, Kirov Oblast, Russia (according to the website https://rp5.ru/).

Acute soil toxicity based on response of laboratory organisms: ciliates *Paramecium caudatum* (Ehrenberg, 1833) and bacteria *Escherichia coli* (Migula, 1895). The assessed test function of *P. caudatum* was chemotaxis[8], *E. coli* – bioluminescence[9]. Aqueous extracts from soil (distilled water) were tested at a phase ratio of 1:4; the contact time of water and soil was 2.5 h, including 2 h on a rotator (100 rpm) and 30 min of settling. The supernatant was filtered through a "white ribbon" paper filter, preventing sediment from becoming disturbed. The extract was then analyzed with the test reaction time of 30 min. To calculate the toxicity index (T), the following formula was used:

$$\mathrm{T} = \frac{\mathrm{T}_c - \mathrm{T}_{test}}{\mathrm{T}_c},$$

where T is the toxicity index, T_{test} is the value for the sample, T_c is the value for the clean environment (control).

For *E. coli*, the obtained toxicity indices (T) were converted into relative values by multiplying the experimental ones by 100% according to the method.

Activity of soil enzymes. Catalase activity was determined using a special device (catalase meter) through a gasometric method based on recording the volume of molecular oxygen released during a soil contact with a 3% hydrogen peroxide solution (Khaziev, 2005). The results were recorded three times after 1, 3, 5 min, followed by averaging the data. Urease activity was determined using a spectrophotometer (PE5300VI, Ekroskhim LLC, Russia) by means of a spectrophotometric method based on recording the amount of ammonia released by urease (Khaziev, 2005). Soil was incubated with 0.1 M Tris buffer and 10% urea solution at 30 °C for 3 hours. Ammonia was estimated after soil incubation by its binding into colored complexes with a Nessler's reagent.

8 FR 1.39.2015.19241. Methodology for determining the toxicity of soil and bottom sediment samples by an express method using a Biotester series device.

9 PNDF T 14.1:2:3:4.11-04. Methodology for determining the integral toxicity of surface water, including sea water, ground water, drinking water, waste water, aqueous extracts of soil, waste, waste water sludge based on changes in bacterial bioluminescence using the Ecolum test system.

Reliability and mathematical processing of results

All analyses were performed in triplicate. The results are presented as mean values and their standard deviations. The reliability of differences of one type of indicator between the data arrays obtained for different soil samples was identified by one-factor analysis using the ANOVA method. To assess the contribution of each factor (cadmium, acidity, drought) to the observed effect, a multifactorial variance analysis of the data was performed with subsequent evaluation of the F-criterion (F-Ratio) and its significance level (P-Value). The critical significance level of all comparisons (p) was 0.05. Correlation analysis between the data arrays was made using the Fisher criterion.

Results

The number of indigenous soil microorganisms in response to the influence of unfavorable factors

The ability of microorganisms to respond the environmental factors can be used to monitor soil quality. It is important to distinguish between changes in the soil microbial complex under anthropogenic loads and those caused by natural factors.

According to the results of microbiological analysis of soil samples, the reaction of microorganisms of the zymogenic ecological niche of was asynchronous (Fig. 2). In the absence of exposure (control), ammonifiers dominated among the representatives of the zymogenic ecological niche ($7.5 \cdot 10^6$ CFU/g) in contrast to amylolytic and cellulolytic microorganisms ($5 \cdot 10^6$ CFU/g and $5 \cdot 10^5$ CFU/g, respectively).

The number of ammonifiers in soil dropped in response to all types of adverse effects. The maximum decrease in their number was marked in soil samples with increased acidity. In terms of impact, cadmium took the second place: 5.4 and 3 times compared to the control, respectively. Short-term drought reduced the development of ammonifiers by 2.3 times.

The number of amylolytics increased under the influence of unfavorable factors, indicating the intensification of mineralization processes in soils. A high degree of development of the amylolytic part of the soil microbial complex (compared to the control) was noted in soils contaminated with cadmium – 6.4 times, and also under the influence of increased acidity – 6.2 times. The rise in number of amylolytic microorganisms in exposed-to-drought soils was the least (1.6 times).

Compared to the control, cellulolytic microorganisms decreased in number only in response to increased acidity (2.5 times) and drought (1.7 times). In contrast to non-affected soils, their number increased 1.7 times due to cadmium influence.

Microorganisms of the oligotrophic ecological niche, characterized by low requirements for nutrients and responsible for completion of organic matter mineralization in soil, responded to unfavorable factors according to the type of hormesis (Fig.3).

The highest number of oligotrophs (22 times higher than in the control) was recorded in the soil that experienced the impact of short-term drought. Cadmium and acidity had a smaller effect on oligotrophs. In these experiments, their number in soil increased by 4.0 and 2.7 times, respectively.

Oligocarbophiles were of particular interest among oligotrophic microorganisms. This group of microorganisms plays an important role in the transformation of soil organic matter due to its high oxidation-reduction enzymatic activity. Under conditions of suppression of most representatives of the zymogenic microflora, number of oligocarbophiles increased and the maximum positive effect was observed in soil contaminated with cadmium (13 times). Acidity and short-term drought also stimulated the development of oligocarbophiles in soil, but to a smaller extent than cadmium (2.8 and 1.7 times, respectively).

Thus, the response of representatives of the native microflora to drought, average soil acidity and cadmium pollution varied from stimulation to significant inhibition thereby indicating a restructuring of the soil community. At the same time, similar reactions to environmental factors were also recorded. Changes in the number of amylolytic microorganisms and oligocarbophiles closely correlated with each other (r = 0.69), the correlation between cellulolytic microorganisms and oligocarbophiles was even higher (r = 0.75).

Among the studied eco-trophic groups of microorganisms, the greatest sensitivity to cadmium pollution was demonstrated by amylolytic (F = 1453; P = 0.0000) and oligocarbophiles (F = 44443; P = 0.0000) microorganisms; to acidity – by ammonifiers (F = 3189; P = 0.0000) and cellulolytics (F = 13.5; P = 0.0063); to short-term drought – by oligotrophs (F = 1361; P = 0.0000).

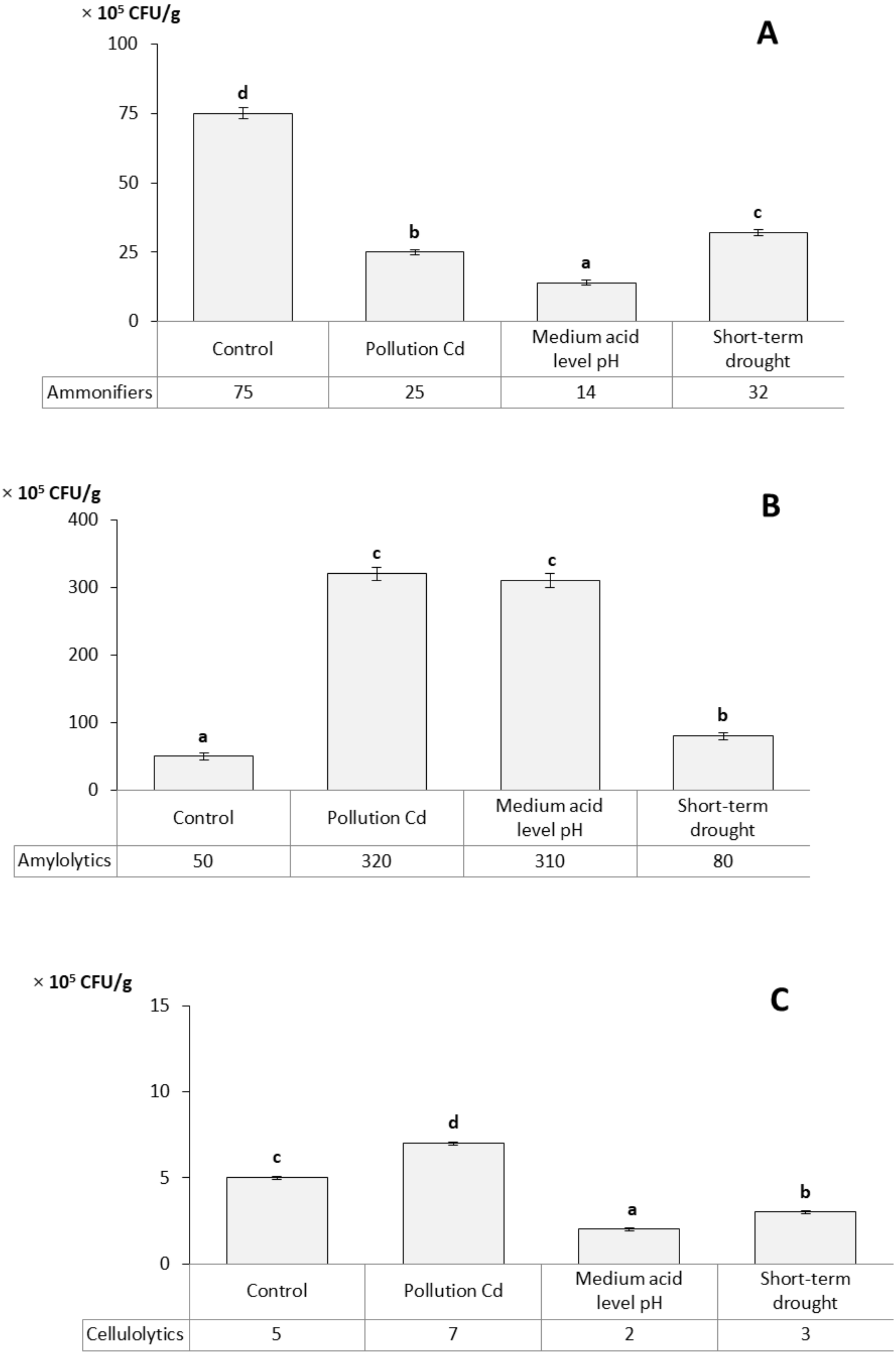
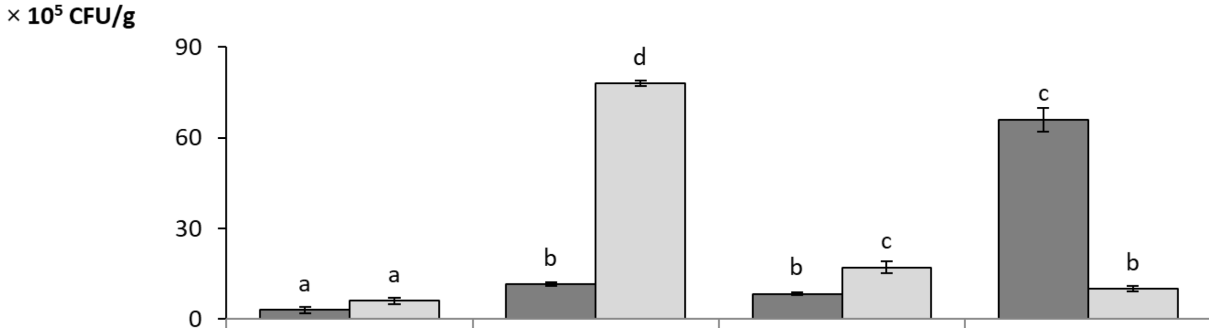


Fig. 2. The number of representatives of the zymogenic ecological niche of microorganisms. **A** – ammonifiers; **B** – amylolytic; **C** – cellulolytic microorganisms. Hereinafter reliable differences between values are indicated by letters.



	Control	Pollution Cd	Medium acid level pH	Short-term drought
Oligotrophs	3	12	8	66
Oligocarbophiles	6	78	17	10

Fig. 3. The number of representatives of the oligotrophic ecological niche of microorganisms.

Reactions of laboratory test organisms to soil exposed to adverse factors

Unlike synecological indicators applied to characterize the state of indigenous microorganisms in soil, the results of bioassays allow us to draw a conclusion about the toxicity of their habitat. For this purpose, test organisms of various systematic groups are used, including lower plants and microorganisms. However, it is known that the reactions of laboratory organisms are determined not only by the presence of toxicants in soil (Olkova and Ashikhmina, 2021).

The lowest toxicity values for the *P. caudatum* reaction were obtained when testing soil samples not exposed to adverse factors (Fig. 4). Toxicity of soils after short-term drought and cadmium pollution did not differ significantly from the control. At the same time, the extract from moderately acidic soil was more toxic than the control, the cadmium and drought variant – by 1.45, 1.20 and 1.21 times, respectively.

In the bacterial test for the *E. coli* reaction, all toxicity index values were negative. Soil extracts of all the studied variants had a stimulating effect on bioluminescence of bacteria compared to distilled water which served as an analytical control when measuring the values of the indices (Fig. 5). As in the previous bioassay, when analyzing soil extracts using *E. coli*, close toxicity index values were obtained for the control variant and soil samples contaminated with cadmium and exposed to short-term drought. The extract from the moderately acidic soil also caused stimulation of the test function, but to much lesser extent than other studied samples. Compared with the control soil, toxicity of the moderately acidic soil increased by 1.8 times.

The results suggest that two performed bioassays are insensitive to soil contamination with cadmium at the level 3.2 times exceeding the approximately permissible concentration for this element. Short-term drought did not cause soil toxicity. The maximum inhibition of the test functions of two laboratory microorganisms occurred as a result of their contact with the extract from moderately acidic soil. Correlation analysis of the data shows that there is a strong positive correlation between the toxicity index values obtained in the bioassays for *P. caudatum* and *E. coli* (r = 0.79). Therefore, the results cannot be considered random. The studied test organisms were most sensitive to acidity, in the case of *P. caudatum* – at a statistically significant level (F = 19.4; P = 0.0023). In general, the results of bioassays and assessment of the number of native soil microflora are consistent with each other in terms of a fairly strong effect of soil acidity on vital functions of organisms. A close relationship was noted between the number of some soil microorganisms and the data on *P. caudatum*: positive with amylolytics (r = 0.71); negative with ammonifiers and cellulolytics (r = −0.85 and r = −0.61, respectively). The reactions of *E. coli* negatively correlated with the number of cellulolytic microorganisms (r = −0.82).

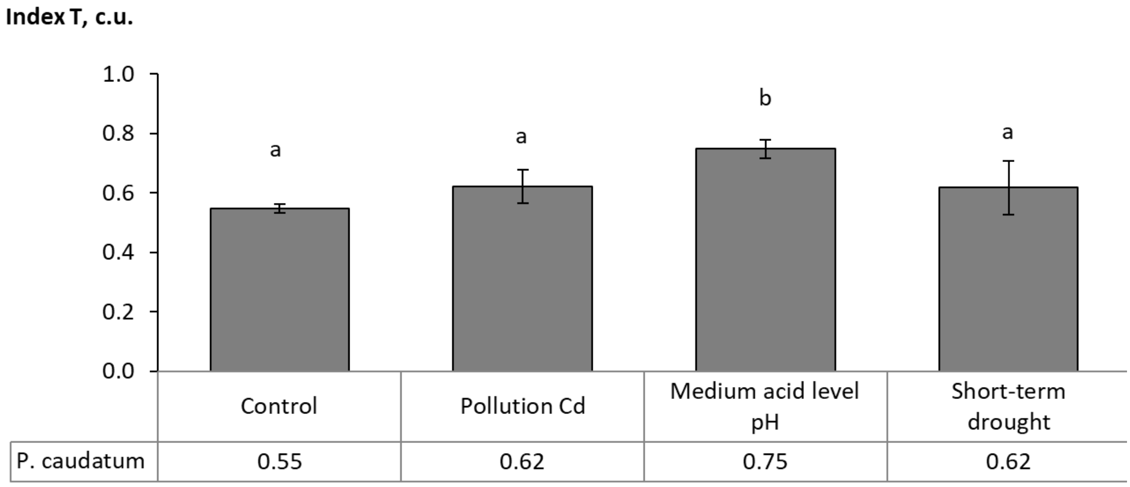


Fig. 4. Toxicity of the studied soil samples for *P. caudatum*.

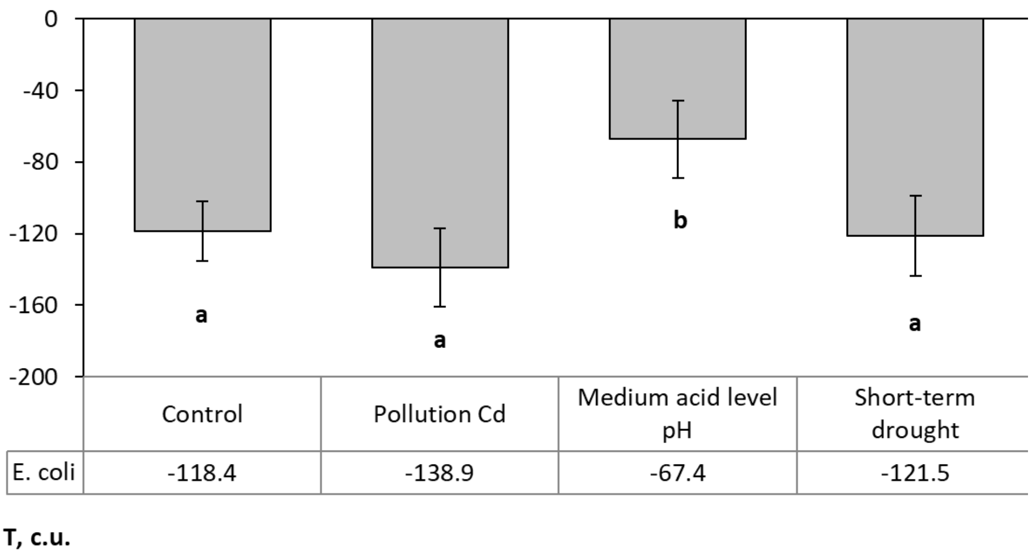


Fig. 5. Toxicity of the studied soil samples for *E. coli*.

Enzymatic activity of soil influenced by unfavorable environmental factors

Soil enzymatic activity reflects the functional state of soil biota. Among the enzymes found in soil, catalase was given special attention due to its significant role in regulating the rate of oxidation-reduction reactions. According to the degree of enrichment with catalase, the studied samples belonged to the category of poor soils (< 1 cm^3 O_2/g·min). Under the influence of the studied factors, the catalase activity of the soil varied insignificantly and did not differ greatly from the control (Fig. 6**A**). At the trend level, a higher sensitivity of catalase to acidity was noted ($F = 3.36$; $P = 0.1042$).

Urease, like catalase, is one of the most studied soil enzymes. Its role in the soil is reduced to participation in the nitrogen transformation cycle. According to the data obtained, the urease activity of soil, unlike catalase, varied in a wider range (Fig. 6**B**). Soil contamination with cadmium and short-term drought did not cause significant changes in the level of soil urease activity, while acidity reduced it. The highest sensitivity of urease was noted in relation to acidity ($F = 35.4$; $P = 0.0003$). Correlation analysis of the data showed that the activities of catalase and urease were closely interrelated with the responses of laboratory organisms *P. caudatum* ($r = -0.98$ and $r = -0.77$, respectively) and *E. coli* ($r = -0.73$; $r = -0.97$), and strongly correlated with the number of ammonifiers ($r = 0.89$).

Discussion

The experiment simulated the impact of unfavorable factors on soil that cannot be called extreme, but they were considered pessimal for plants and pedobionts: cadmium pollution to the level of detection of its mobile forms (Cd^{2+}) was 6.4 ± 0.5 mg/kg of soil, short-term drought lasted for 25 days, the pH level of soil was reduced to 4.8 compared to 6.5 in the control sample. We have studied the indicators of the ecological state of soil able to affect microorganisms.

A set of independent analyzes has confirmed that soil acidity has a greater effect on the indicators of ecological soil state than drought and cadmium pollution (within the compared load levels). The increase in toxicity indices of extracts from moderately acidic soil compared to the control option made up 1.37 and 1.8 times in tests for *P. caudatum* and *E. coli*, respectively. It is known that the environment response significantly affects vital functions of organisms (Kutsenko, 2004; Olkova and Ashikhmina, 2021). In soil, this can be enhanced by the fact that a low pH level of soil solution increases solubility of humic substances, especially fulvic acids, and also leads to increased lability of many microelements (Orlov, 1990; Varshal et al., 1999).

High sensitivity of test organisms (*ex situ*) and bioindicators (*in situ*) to soil pH is a problem because acidic soils are widespread in nature. As one of possible solutions, P.A. Chapman et al. (2013) identified the organisms that are sensitive to heavy metals and insensitive to soil acidity: *Dendrobaena octaedra* (Savigny, 1826), *Folsomia candida* (Willem, 1902), *Caenorhabditis elegans* (Maupas, 1900), *Oppia nitens* (Koch, 1836), *Brassica rapa* L., *Trifolium pretense* L., *Allium cepa* L., *Quercus rubra* L. and *Acer rubrum* L.

In our study, all ecotrophic groups of microorganisms, except for ammonifiers, demonstrated a hormesis-type response to cadmium stress (in some cases, reliable). The greatest stimulation was shown by amylolytics and oligocarbophiles – an increase in their number relative to the control was 6.4 and 13 times, respectively. Urease activity also tended to increase under the influence of cadmium. Stimulation of ciliate chemotaxis was 1.13 times, and bioluminescence of the bacterial preparation – 1.17 times compared to the control data. Meanwhile, it did not reach reliable differences. Thus, most microbiological characteristics of soil show good agreement in terms of response to soil pollution with cadmium that is confirmed by the performed correlation analysis. The explanation for most of the observed hormesis-type reactions is a relatively low level of created pollution (exceeding the APC by 3.2 times). There are many examples demonstrating that when soil is polluted above the established standards, no significant reaction of pedobionts is noted, or the assessed parameters increase. For example, the toxic load closest to our experiment was described in (Fan et al., 2021) reporting that soil treatment with cadmium at a level of 2 mg Cd/kg and with binary mixtures of 4.0 mg Cd/kg + 200 mg Pb/kg caused stimulation of bacterial and fungal populations.

Low levels of toxic stress were suggested to be used for controlled stimulation of growth and overall productivity of crop plants, as shown in the medicinal plant *Polygonatum sibiricum* Tourn. ex Mill., where Cd accumulation remained at a safe level at cadmium concentrations in soil of 1 mg/kg (Mengdi et al., 2021).

The contribution of short-term drought to changes in the soil state indicators was considerably less as compared to other modeled factors. The activity of catalase and urease did not differ from the indicators of the control soil. Toxicity indices for two bioassays were also the closest to the control values in contrast to other factors. Although the reaction of indigenous microflora ranged from stimulation to inhibition in different groups of organisms, in most cases it was similar to those for the control soil. Only oligotrophs responded positively and most vividly to drought, as compared to the effect of other factors. Unlike the control, their number increased by 22 times. Probably, they received the maximum opportunity to realize their ecological potential in arid soil against the background of inhibition of ammonifiers and cellulolytics. According to literary data, drought can cause a transformation of the soil microbial complex (Ushakov and Ruchkina, 2020). Under drought conditions, microorganisms using mineral nitrogen (amylolytics) develop more intensively (Loskutov et al., 2019). Our experiment can hardly confirm this fact. Among indirect factors able to influence the drought-induced modification of the soil microcommunity is the change in synthesis of plant root exudates (Suzdaleva et al., 2022).

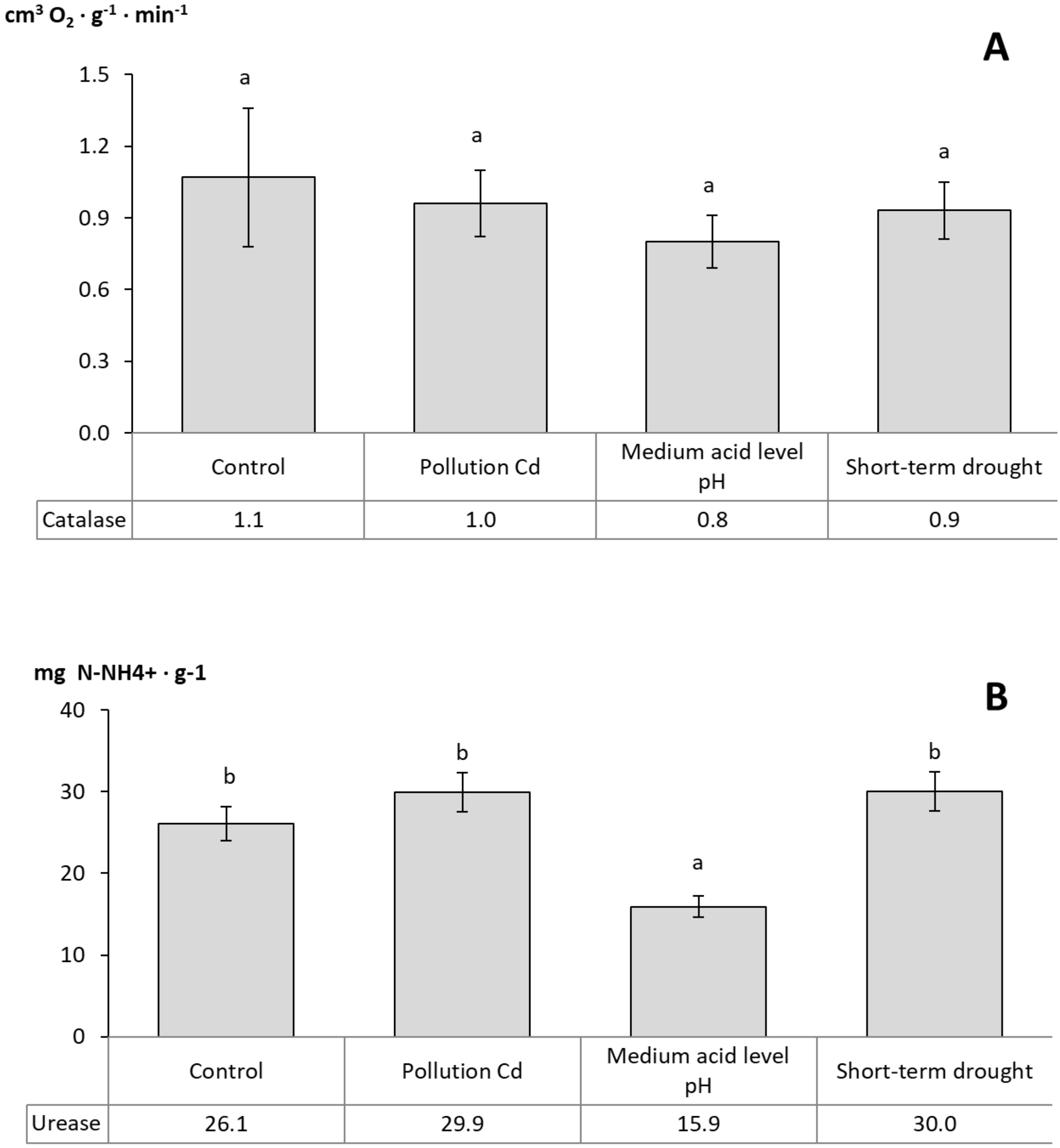


Fig. 6. Enzymatic activity of soil. **A** – catalase activity; **B** – urease activity.

Conclusion

Thus, 6 out of 9 studied soil state parameters positively responded to one of the unfavorable factors. According to the concept of ecological hormesis, stimulation can be caused by any low-dose stressors (abiotic, biotic, anthropogenic) (Erofeeva, 2022). As shown in this work, some types of loads, may significantly affect microbiological parameters of soil (shifting the responses to the inhibition zone) even at low-level stress. For instance, amylolytic microorganisms were sensitive to cadmium pollution and soil acidity, cellulolytics – to acidity and drought, laboratory ciliates *P. caudatum* – to acidity, the exoenzyme urease – to acidity. This is the basis for considering such parameters as most informative in terms of changes in the studied factors. The combination of suppression of native microflora, which requires high-energy resources, and oligotrophs development can serve as an indicator of an adverse impact on soils.

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