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A MULTIFACETED APPROACH TO ASSESSING THE EFFECTIVENESS OF REMEDIATING OIL-CONTAMINATED SOILS

O. Z. Eremchenko[1], N. V. Moskvina[2], N. V. Mitrakova[3], E. G. Efimik[4], I. E. Shestakov[5]

[1, 2, 3, 4, 5] *Perm State University, 15 Bukireva street, Perm, 614990, Russia*

[1] *eremch@psu.ru,* [2] *nvmoskvina@mail.ru,* [3] *mitrakovanatalya@mail.ru,* [4] *efimik.elena@mail.ru,* [5] *galendil@yandex.ru*

Abstract. Soil quality is its ability to perform the most important ecological functions, determining the conditions for the existence of biota and the quality of adjacent spheres – water and air. This article is devoted to the study of the remediated area after oil pollution, subject to overgrowing. A comprehensive assessment of the ability of the remediated soil to provide ecosystem services has been conducted. The properties of the remediated soil were assessed with traditional physicochemical methods. The ability of the established Technosol to create ecosystem services was assessed by microbiological activity, the composition of vegetation on the site, as well as by phytotesting to determine the redox activity of the test culture. Technosol properties (pH, organic carbon content, catalase activity, CO_2 efflux) varied greatly within the remediated area, which was also reflected in the phytotesting results. In certain areas of the investigated territory Technosol had a good ecological state, but in other areas it had a satisfactory and unsatisfactory state with moderate to severe toxicity. The residual content of oil products in the layer of 20–50 cm under the brought soil had a negative effect on the height of the test culture. A close correlation was established between the indicators of microbiological activity and the state of the test culture (height, weight, redox activity), together they reflected the ability of Technosol to provide ecosystem services or perform the ecological functions of the soil. Residual oil products and the associated certain toxicity did not interfere with the self-overgrowth process of Technosol.

Keywords: biochemical activity, ecosystem services, meadow vegetation, oil pollution, phytotesting, remediation, Technosol, self-overgrowth, toxicity

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КОМПЛЕКСНЫЙ ПОДХОД К ОЦЕНКЕ ЭФФЕКТИВНОСТИ РЕКУЛЬТИВАЦИИ НЕФТЕЗАГРЯЗНЕННЫХ ПОЧВ

О. З. Еремченко[1], Н. В. Москвина[2], Н. В. Митракова[3], Е. Г. Ефимик[4], И. Е. Шестаков[5]

[1, 2, 3, 4, 5] *Пермский государственный национальный исследовательский университет, Россия, 614990, Пермь, ул. Букирева, 15*

[1] *eremch@psu.ru,* [2] *nvmoskvina@mail.ru,* [3] *mitrakovanatalya@mail.ru,* [4] *efimik.elena@mail.ru,* [5] *galendil@yandex.ru*

Аннотация. Качество почвы – это ее способность осуществлять важнейшие экологические функции, определяя условия существования биоты и качество сопредельных сред – воды и воздуха. Работа посвящена изучению рекультивированного после нефтезагрязнения участка, подвергнутого самозарастанию. Проведена комплексная оценка способности рекультивированной почвы оказывать экосистемные услуги. Способность Technosol к созданию экосистемных услуг оценили по микробиологической активности, составу растительности на участке, а также методом фитотестирования с определением редокс-активности тест-культуры. Свойства Technosol (pH, содержание органического углерода, активность каталазы, отток CO_2) в пределах рекультивированного участка сильно варьировали, что отразилось и в результатах фитотестирования. В отдельных частях исследованной территории Technosol имеет хорошее экологическое состояние, но местами – удовлетворительное и неудовлетворительное состояние при умеренной и сильной токсичности. Остаточное содержание нефтепродуктов в слое 20–50 см под привезенным грунтом оказало отрицательное влияние на высоту тест-культуры. Между показателями микробиологической активности и состоянием тест-культуры (высота, масса, редокс-активность) установлена тесная корреляционная зависимость, совместно они отражали способность Technosol предоставлять экосистемные услуги или выполнять экологические функции почвы. Остаточные нефтепродукты и связанная с ними определенная токсичность не препятствуют процессу самозарастания Technosol.

Ключевые слова: биохимическая активность, экосистемные услуги, луговая растительность, нефтезагрязнение, фитотестирование, рекультивация, Technosol, самозарастание, токсичность

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Introduction

Soils are the most complex systems on Earth, providing crucial ecosystem functions and closely relating to environmental safety of humankind. An economy developing without environmental constraints causes soil change and degradation. Currently, there are concerns that anthropogenically modified soils will not be able to fulfil the functions of reproduction and maintenance of life on Earth [1–3].

Soil health, or soil quality, is broadly defined as the ability of soil to perform ecological functions within the natural or managed boundaries of an ecosystem, to maintain plant and animal productivity, and to maintain or improve water and air quality. Soil health and control of its changes over time should be considered the main indicator of sustainable land management [4–7].

Since the end of the 20th century researchers have associated soil quality with its ability to fulfil ecological functions [8] or ecosystem services [9]. At the same time, the soil natural capital (its purpose in nature), in general, is not well studied [10–12]. Soil scientists require the involvement of specialists from other fields of biological science to evaluate the ability of soils to provide ecosystem services [9]. It is necessary not only to study the physicochemical and biological properties of specific soils, but also to provide a comprehensive assessment of the functional diversity of soil biota [9].

In the Russian Federation, the intensive development of oil and gas sector is associated with various industries – energy, fuel, petrochemical, and others. Spatial separation between production and consumption sites leads to the necessity to transport oil and its products, which bears the risks of accidental spills [13]. This leads to the increased risks of contamination of soil, surface water sources and other environmental objects.

It is known that oil components disturb the physical, chemical, and biological properties of the soil. Oil-contaminated soils retire from the use in national economy for long time, and require significant investment in remediation works [14–17].

An oil spill occurred in the area of ca. 1 hectare in taiga-forest zone in the Cis-Urals due to depressurisation of an oil pipeline in winter. Immediately after the accident, oil mixed with snow, shrub-herbaceous vegetation and top soil had been removed for subsequent remediation. On the disturbed site, the terrain was leveled with loamy soil remaining after road construction works. Then the site was left for self-overgrowth. It is believed that phytocenoses formed during natural overgrowing are stronger than regrassed crops; while landscape's attractiveness and productivity restore faster this way as well [18].

The aim of our research is to conduct a multifaceted assessment of Technosol's ability to provide ecosystem services in the remediation area. The work was carried out within the first two years after the elimination of oil pollution.

Materials and methods

In the neighboring area of the synanthropic meadow and in the remediated area, the soils were identified according to the World Reference Base (WRB) for soil resources [19].

Within the uncontaminated area, we took soil samples from 3 soil profile walls at depths of 0–20 and 20–50 cm. When sampling the soil, we used a system of 3 concentric circles, located at distances of 15, 35 and 55 m from the oil spill site, covering the remediated area (Fig. 1). The circles were divided into sectors I, II, III, IV. Within the sectors of each circle (aI, aII, aIII, aIV, bI, bII, bIII, bIV, cIV) we took 9 mixed soil samples at depths of 0–20 and 20–50 cm. Mixed (pooled) samples of each sector were prepared from 3–5 separate (point) samples by thorough mixing.

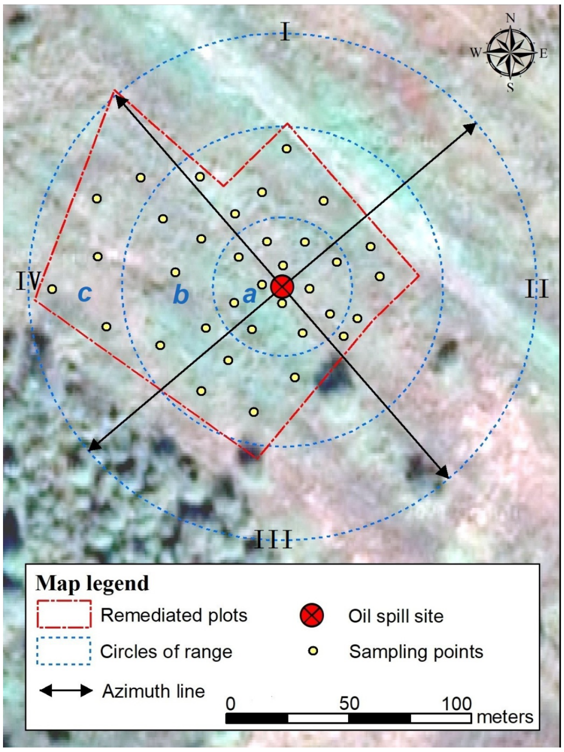


Fig. 1. Map chart of sampling at the remediated site (based on satellite image)

The properties of mixed soil samples were studied in triplicate. The content of residual oil and oil products was determined by the gravimetric method [20]; pH of water suspension – by potentiometric method, organic carbon content was determined by the wet-combustion Tyurin method [21].

The catalase activity was determined by the gasometric method by the amount of oxygen released after adding hydrogen peroxide to the sample. Basal respiration was assessed by the amount of carbon dioxide emitted by the soil during 24 hours at a temperature of 28 °C and 60 % humidity of the total moisture capacity; carbon dioxide was adsorbed by alkali solution. Substrate-induced respiration was established under the same conditions after adding glucose to the soil [21].

The ecological state and the degree of soil toxicity were studied by testing *Lepidium sativum* L. based on the author's method [22]. According to the approved criteria, the state of soil is considered satisfactory with a decrease in the development indicators of *Lepidium sativum* L. by 10–30 % relative to the test-control; unsatisfactory – with a decrease by 30–50 %; if the level of decrease in the indicators is more than 50 %, it should be considered environmentally hazardous. With an increase in the redox activity of the plant extract from the leaves of cress by 10–30 % relative to the test-control, the soil is considered moderately toxic; with an increase by 30–50 % – highly toxic; and if the level of increase in the indicator is more than 50 %, it should be considered environmentally hazardous.

The height and weight of *Lepidium sativum* L. plants grown on soil samples were measured in every 25 plants. The significance of differences with the test-control was assessed using the Student's T-test with a confidence probability of 95 % and higher ($P < 0.05$).

The biological replication of the determination of the redox activity of the extract from the leaves of *Lepidium sativum* L. was fourfold. Comparison of the redox activity of plant extracts grown on soil samples with the redox activity of plants during the test-control was carried out by the analysis of variance (ANOVA) using the Kruskal-Wallis test; differences between the compared mean values were considered significant with a confidence probability of 95 % and higher ($P < 0.05$).

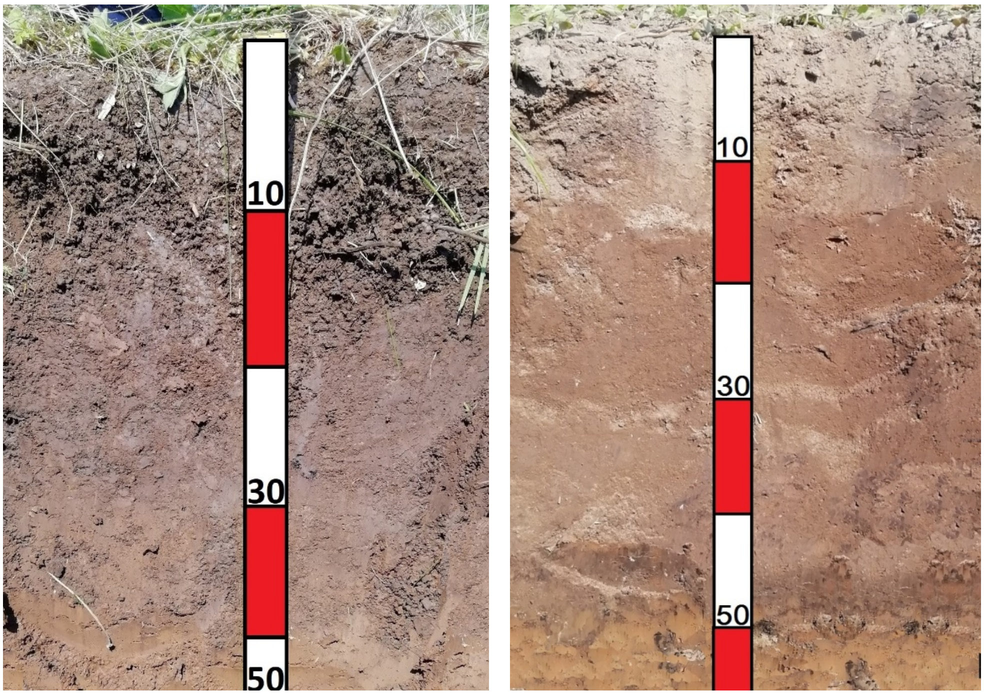
The dependence between the properties of the soil and the results of phytotesting was established by the method of correlation analysis with a confidence probability of 95 % and higher ($P < 0.05$).

We characterized vegetation on sample plots according to established methods. The nomenclature and number of species are adopted according to regional data [23].

Results

Soil diagnostics. The soil of the uncontaminated area is identified as Umbrisols. The morpho-structural profile of this soil contains gray-humus horizon with lumpy structure, which gradually transforms into a yellowish-brown parent rock (Fig. 2A).

The surface of the remediated area was covered with ca. 50 cm layer of soil. Newly formed Technosol had loamy granulometric texture, light brown or brown colour (Fig. 2B); in some areas, traces of hydrochloric acid boiling occurred; single inclusions were found (plastic, pebbles). In Technosol, low traces of oil pollution were visually observed at the depth of 40–50 cm.



a) *b)*

Fig. 2. *A* – Umbrisols; *B* – Technosol (photo by O. Z. Eremchenko)

Content of oil products. After the removal of contaminated snow, vegetation and soil, the residues of oil products redistributed throughout the entire site, so their concentration at a distance (bI, bII, bIII, bIV, cIV) was even higher than at the oil spill site. The amount of oil products in Technosol varied significantly (Fig. 3) and reduced in the surface layer – 134±48 mg/kg (means ± standard errors, n = 9), in comparison to the concentration in the 20–50 cm layer – 521±175 mg/kg of soil.

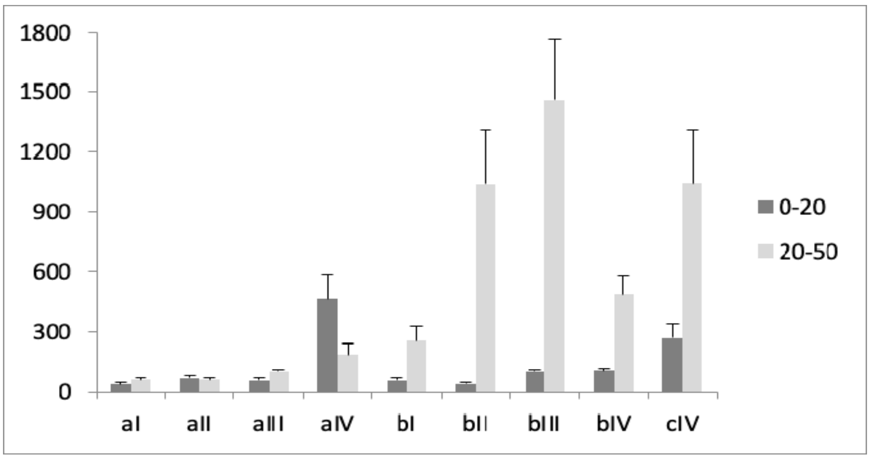


Fig. 3. Content of oil products in Technosol samples, mg/kg of dry soil

Organic carbon content and pH level. Soil properties affect the rate of natural overgrowing of disturbed lands. One of the main indicators of fertility is pH level. In Technosol, the pH value fluctuated within 7.4–8.1 (Fig. 4); no significant differences were found between pH values in the studied 0–20 cm and 20–50 cm layers. Umbrisols of the intact area is neutral in the upper part of the humus horizon and slightly alkaline in the transitional humus horizon.

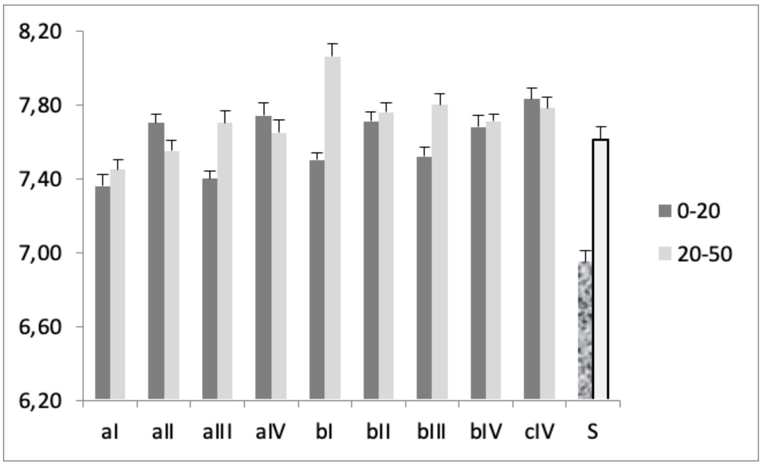


Fig. 4. pH value in Technosol samples; S – content in Umbrisols

The organic carbon content of Technosol fluctuated moderately (Fig. 5); the amount of organic carbon in the 0–20 cm layer was 2.12±0.20 % (means ± standard errors, n = 9), in the 20–50 cm layer – 2.35±0.33 %. The average concentration of organic carbon in the 0–20 cm soil layer did not differ significantly from the amount of organic carbon in the upper part of the Umbrisols humus horizon. However, in the 20–50 cm layer of Technosol, the amount of organic carbon is several times higher than in Umbrisols.

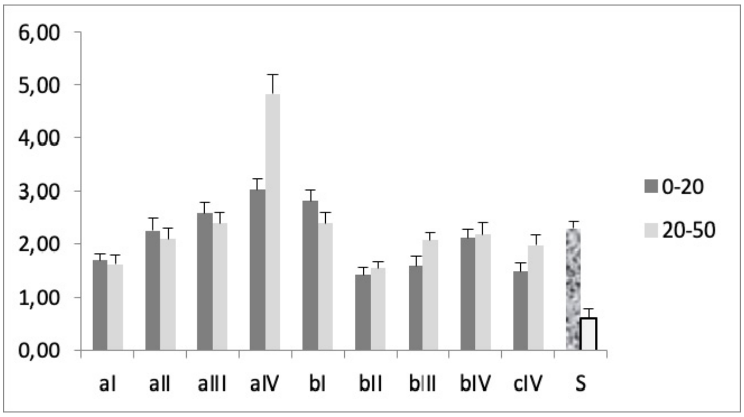


Fig. 5. Organic carbon content in Technosol samples, %; S – content in Umbrisols

Catalase activity. Catalase activity in Technosol within remediated territory varied within 4–7 O_2 cm^3/1 g per 1 min (Fig. 6) and averaged 4.8±0.3 O_2 cm^3/1 g per 1 min (means ± standard errors, n = 9). The catalase activity in most Technosol samples was slightly lower than the catalase activity of Umbrisols.

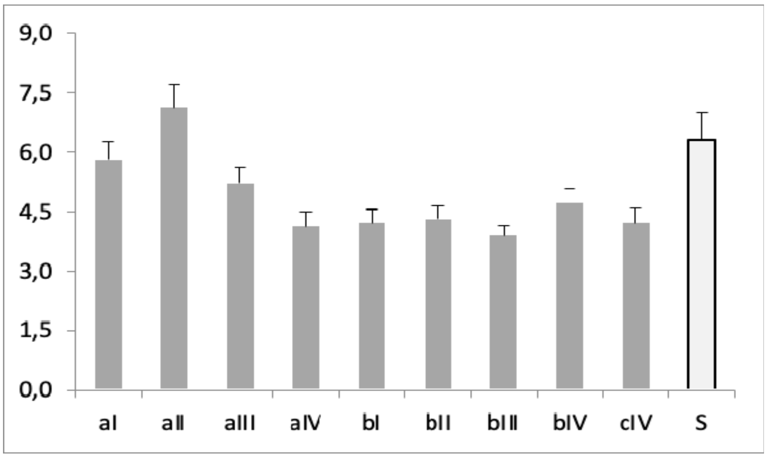


Fig. 6. Catalase activity in Technosol samples, O_2 cm^3/1 g of dry soil per 1 min: S – catalase activity in Umbrisols

Soil respiration. Basal respiration (intensity of carbon dioxide emission of soil) in the upper layer of Technosol fluctuated noticeably (Fig. 7) and averaged 97±7 CO_2 mg/100 g of soil per 24 h (means ± standard errors, n = 9). Most of Technosol samples had higher carbon dioxide efflux than Umbrisols samples. The introduction of glucose as a top dressing on average doubled the release of carbon dioxide (substrate-induced respiration) from the soil (up to 206±4 CO_2 mg/100 g of soil per 24 hours. The intensity of CO_2 release from Technosol samples was 1.5–2 times higher than the release of this gas from Umbrisols (see Fig. 7).

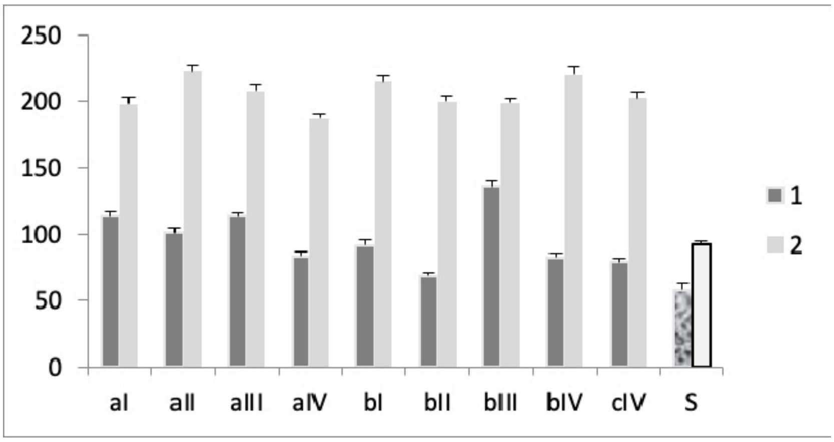


Fig. 7. Intensity of carbon dioxide release from Technosol samples, CO_2 mg/100 g of soil per 24 hours: 1 – basal respiration; 2 – substrate-induced respiration; S – respiration of Umbrisols

Phytotesting. The results of phytotesting showed that only in one Technosol sample (bI) the watercress *Lepidium sativum* L. matched the control test's height and weight values. In 7 soil samples, plant height decreased by 10–30 %, which characterizes the satisfactory ecological state of Technosol. However, in one sample (bII), the height and weight of plants were lower by 36 % and 48 % respectively, which indicates the unsatisfactory state of this Technosol sample (Fig. 8).

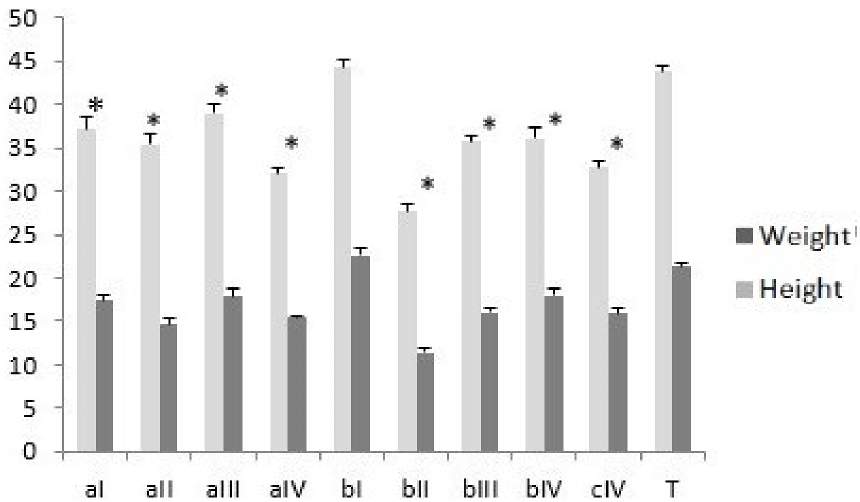


Fig. 8. Height (mm), weight (mg) of the Lepidium sativum test culture: T – control test, * – variants with significant differences from the control test (Values are means and standard errors shown by vertical bars (n = 25))

Redox activity of plant extracts of *Lepidium sativum* L. in the experimental variants varied noticeably (Fig. 9). The redox activity of *Lepidium sativum* L. in two Technosol samples did not differ from control test value; in three variants, the redox activity was even lower than the control values, which indicates nontoxicity of the soil. When grown, the plants showed increased redox activity in four samples; in two of them this indicator increased by 19 % and 27 %, which showed moderate toxicity of Technosol. However, in two soil samples, the redox activity of plants increased by 32 % and 42 %, which showed high toxicity of Technosol. We observed the highest redox activity in plants with the lowest height and weight in bII.

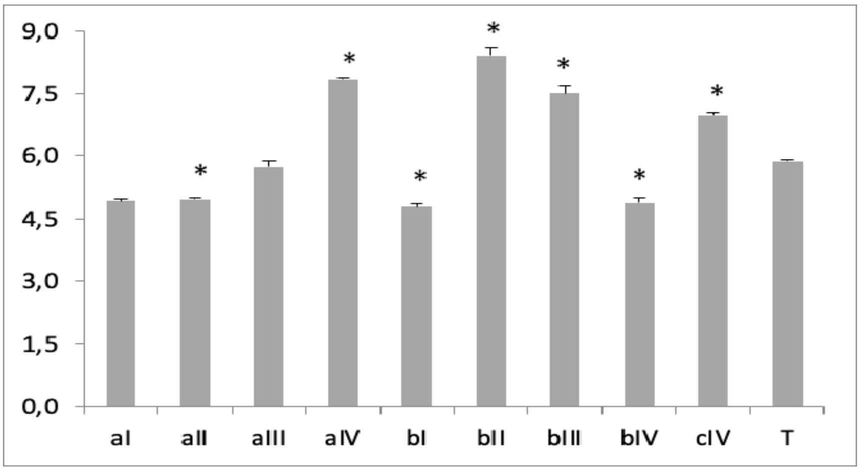


Fig. 9. Redox activity of Lepidium sativum L. leaves extracts, ml of KJO_3 per 1 g of wet weight:
T – control test, * – variants with significant differences from the control test

Vegetation condition. The projective cover of herbage stays within 80–85 % gap in the remediated (Technosol) and control (Umbrisols) areas of the synanthropic meadow. The herbage is high; the average height of plants in the remediated area is 85 cm, in the synanthropic meadow – 65 cm. On the remediated site, we noted 53 species of vascular plants; on the control site we noted 59 species (Table 1). Thus, the species diversity is slightly higher on the control site (synanthropic meadow).

Table 1

List of vascular plant species at Site 1 (remediated) and Site 2 (control)

Plant species	Technosol	Umbrisols
1	2	3
1. *Achillea millefolium* L.	+	+
2. *Aegopodium podagraria* L.		+
3. *Agropyron repens* (L.) Beauv.	+	
4. *Agrostis gigantea* Roth	+	+
5. *Agrostis stolonifera* L.	+	
6. *Alchemilla vulgaris* L.		+
7. *Alisma plantago-aquatica* L.	+	
8. *Angelica sylvestris* L.		+
9. *Arctium tomentosum* Mill.	+	+
10. *Artemisia vulgaris* L.	+	+
11. *Calamagrostis canescens* (Web.) Roth		+
12. *Calamagrostis epigeios* (L.) Roth.		+
13. *Campanula patula* L.		+
14. *Carduus crispus* L.	+	+
15. *Carex acuta* L.		+
16. *Carex pseudocyperus* L.		+
17. *Centaurea scabiosa* L.		+
18. *Chenopodium album* L.	+	
19. *Cirsium arvense* (L.) Scop.	+	+
20. *Cirsium setosum* (Willd.) Bess.	+	+
21. *Cirsium oleraceum* (L.) Scop.		+
22. *Dactylis glomerata* L.	+	+
23. *Deschampsia cespitosa* (L.) Beauv.	+	+
24. *Digraphis arundinacea* (L.) Trin.	+	+
25. *Epilobium hirsutum* L.		+
26. *Epilobium montanum* L.	+	+
27. *Equisetum palustre* L.	+	+
28. *Festuca pratensis* Huds.		+
29. *Filipendula ulmaria* (L.) Maxim.		+
30. *Galega orientalis* Lam.	+	
31. *Galeopsis tetrachit* L.		+

End of the Table 1

1	2	3
32. *Galium mollugo* L.		+
33. *Galium uliginosum* L.	+	+
34. *Geum rivale* L.		+
35. *Heracleum sosnowskyi* Manden.	+	+
36. *Hypericum perforatum* L.		+
37. *Juncus atriculatus* L.	+	
38. *Juncus compressus* Jacq.	+	
39. *Lathyrus pratensis* L.	+	+
40. *Lepidotheca suaveolens* (Pursh) Nutt.	+	
41. *Leucanthemum vulgare* Lam.	+	
42. *Linaria vulgaris* Mill.	+	+
43. *Medicago lupulina* L.	+	
44. *Melilotus albus* Medik	+	
45. *Melilotus officinalis* (L.) Pall.	+	+
46. *Myosotis palustris* (L.) L.	+	+
47. *Odontites vulgaris* Moench	+	+
48. *Pastinaca sylvestris* Mill.	+	+
49. *Phleum pratense* L.	+	+
50. *Phragmites australis* (Cav.) Trim. Ex Steud.	+	+
51. *Picris hieracioides* L.	+	+
52. *Plantago major* L.	+	
53. *Poa palustris* L.	+	+
54. *Poa pratensis* L.	+	+
55. *Polemonium coeruleum* L.		+
56. *Potentilla anserina* L.		+
57. *Potentilla norvegica* L.	+	
58. *Ranunculus acris* L.		+
59. *Ranunculus repens* L.	+	
60. *Rorippa palustris* (L.) Bess.	+	
61. *Rumex crispus* L.	+	+
62. *Scirpus sylvaticus* L.	+	+
63. *Scrophularia nodosa* L.		+
64. *Silene vulgaris* (Moench) Garcke	+	
65. *Sonchus arvensis* L.	+	
66. *Stachys palustris* L.		+
67. *Stellaria graminea* L.		+
68. *Succisa pratensis* Moench		+
69. *Tanacetum vulgare* L.	+	
70. *Taraxacum officinale* Wigg.	+	
71. *Trifolium hybridum* L.	+	+
72. *Trifolium medium* L.	+	+
73. *Tripleurospermum inodorum* (L.) Sch. Bip.	+	+
74. *Tussilago farfara* L.	+	
75. *Typha latifolia* L.	+	+
76. *Urtica dioica* L.		+
77. *Veronica scutellata* L.	+	+
78. *Veronica longifolia* L.		+
79. *Vicia cracca* L.	+	+
80. *Vicia sepium* L.		+
TOTAL	53	59

Discussion

Content of oil products. The effect of oil on plants can be divided into a direct toxic (or stimulating) effect of hydrocarbons (and other substances), and an indirect effect through a change in physicochemical properties of soil and transformation of the soil microbial community. In the remediated area, the level of Technosol pollution with oil products was estimated in accordance with the gradation proposed in GOST R 51858-2002. Crude petroleum. General specifications, 2015 (Russia) [24].

In 0–20 cm layer, the content of oil products fell within background values (100–500 mg/kg of soil). However, in 30 % of Technosol samples from 20–50 cm layer, the content of oil products exceeded 1000 mg/kg of soil, which indicated moderate soil contamination.

pH values and organic carbon content. Technosol, unlike Umbrisols, was characterized by relatively elevated pH values while falling in the range of neutral and slightly alkaline values. Alkalinity of Technosol samples was caused by the presence of lithogenic carbonates in the brought soil, which contained regional rocks of carbonate composition. In general, Technosol's soil acidity can be characterized as favourable for meadow grass. Perceptible variation of organic carbon content in Technosol is, on the one hand, due to different proportions of organic and mineral materials in the brought soil. On the other hand, residual oil products, especially in 20–50 cm layer, contributed to the organic carbon content.

Catalase activity. The primary issues of ecosystems functioning cannot be resolved without the use of data concerning microbial communities inhabiting the soil [25]. Methods of soil enzymology make it possible to determine the activity of adsorbed enzymes on the surface of soil colloids and in soil solution. The catalase activity is one of the criteria for ecological and biological state of soils used for assessment of not only contaminated soils, but also any anthropogenically transformed soils [26–28].

Reduced catalase activity of Technosol in the remediated area, as compared to Umbrisols, is consistent with the data coming from several authors, who state that the decomposition rate of hydrogen peroxide in the soil decreases in the early stages of pollution and at low concentrations of oil products [29, 30]. In our case, the reduced activity of the enzyme can also be caused by prolonged storage of soil without a source of fresh plant residues.

Soil respiration. The carbon dioxide efflux from soils is generated through microorganisms using organic compounds as structural and energetic material, and as a result of extracellular oxidation of organic matter by enzymes of microbial origin [31].

Levels of basal and substrate-induced respiration are illustrative of the reserves and availability of nutrients, the activity of the soil microbial community, and its resistance to the present pollutants [32]. In our studies, increased activity of microorganisms in Technosol, accompanied by the release of carbon dioxide, is caused by decomposition of residual oil products, to a certain extent. The substrate-induced respiration of Technosol is on average 2 times higher than that of Umbrisols (see Fig. 7). The manyfold increase of carbon dioxide release upon addition of readily available organic matter indicates a significant pool of microorganisms in Technosol.

Phytotesting. Currently, phytotesting methods are widely used in soil quality control. Sensitivity of plants to soil-chemical effects is manifested in growth, morphological and biochemical characteristics [33–37]. It is noted that in a situation of oil pollution, plants are sensitive indicators of soil toxicity level [14, 15]. When choosing a test-culture, we proceeded from the fact that many authors considered the effectiveness of *Lepidium sativum* L., which proved its informative value in the analysis of contamination caused by both individual pollutants and their integrated affect [38–41].

In our research, we used *Lepidium sativum* L. grown on vermiculite with Knop's solution as control test for assessment of ecological state of Technosol; the ability of this root environment to create conditions for growth is on par with the most fertile soils of the region [22]. The use of control test made it possible to bypass the method of difference, which needs to be used during phytotesting experimental (contaminated) and control soils [41, 42]. In our experiment, we noted a slowdown in plant growth and development in some samples from the upper layer of Technosol, which may be caused by residual oil products. Phytotesting results show the heterogeneity of the remediated area. In accordance with the criteria used, certain areas of Technosol are considered to be in good ecological state, others – in satisfactory and even unsatisfactory ecological states.

Soil with the oil content of 370 mg/kg provided negative reaction of wheat (in terms of seed germination and seedling height), however *Lepidium sativum* L. showed resistance up to the level of oil products content of 1350 mg/kg of soil [43].

In our experiment, the test-culture grown in Technosol showed high sensitivity, manifested in plants height and weight change with residual oil content of less than 500 mg/kg of soil. These results prove the relative vulnerability of different soils to oil pollution associated with their properties.

It is known that unfavourable soil conditions cause oxidative stress in plants [44]. Earlier, we conducted experiments to prove the increase in the redox activity of *Lepidium sativum* L. in response to acidification, salinization, alkalization, and heavy metal pollution of the root environment [22].

Redox activity of plant leaves extracts was 30 % higher than control values when grown in two Technosol samples, which is likely associated with oil pollution. This result is consistent with the physiological studies on the accumulation of substances characterized by reductive activity (anthocyanins, riboflavin, ascorbic acid) in plant seedlings under oil pollution stress [45]. The level of ascorbic acid that builds up cellular immunity that determines the resistance of a plant cell to stress factors, is recommended to be used for assessment of the physiological state of plants [46].

Results of correlation analysis characterize the response of *Lepidium sativum* L. to the properties of Technosol (Table 2). The height of *Lepidium sativum* L. is closely related to the oil products content, which is probably associated with direct exposure to pollutants. The plants weight and the redox activity of plant extracts showed dependence on catalase activity and substrate-induced respiration, which seemingly shows the indirect effect of oil pollution through changes in physicochemical properties and microbiological activity of Technosol. At the same time, there is a negative correlation between height and weight of plants, on the one hand, and redox activity, on the other hand. Apparently, general suppression of plants occurs with the development of oxidative stress and the accumulation of reduced compounds.

Table 2

Coefficients of correlation between indicators of the state of the test-culture and properties of Technosol in 0–20 cm layer

Parameters	Oil products content	pH	Organic carbon content	Catalase activity	Basal respiration	Substrate-induced respiration	Height	Weight	Redox activity
Oil products content		0,57	0,34	–0,39	–0,32	0,57	–0,73*	–0,63	0,61
pH	0,57		–0,13	–0,19	–0,71	–0,01	–0,20	–0,01	0,36
Organic carbon content	0,34	–0,13		0,05	0,04	0,10	–0,03	–0,19	–0,13
Catalase activity	–0,39	–0,19	0,05		0,21	0,50	0,77*	0,72	–0,82*
Basal respiration	–0,32	–0,71*	–0,04	0,21		–0,04	0,06	0,05	–0,17
Substrate–induced respiration	–0,57	–0,01	0,10	0,50	–0,04		0,82*	0,83*	–0,79*
Height	–0,73*	–0,20	–0,03	0,77*	0,06	0,82*		0,94*	–0,84*
Weight	–0,63	–0,01	–0,19	0,72*	0,05	0,83*	0,94*		–0,77*
Redox activity	0,61	0,36	–0,13	–0,82*	–0,17	–0,79*	–0,84*	–0,77*	

N o t e. * – significant correlation coefficients.

Vegetation condition. It is established that in a situation of oil pollution of the soil many plants are displaced by one or two rapidly growing species [47]. Our observations showed that in the second year of self-overgrowing of Technosol, the vegetation has projective cover; it contains more than 50 species of vascular plants.

The processes of overgrowing of disturbed areas are described in scientific works devoted to plant successions. These works pointed out the fact that meadow phytocenoses recover faster than forest ecosystems. In the southern regions of Belarus or northern regions of Russia, the remediation of meadow ecosystems after technogenic disturbances takes less than 10 years [48–50].

Tight vegetation cover over the examined remediated area with projective cover of 80–85 % almost completely excludes splash erosion. All plant species are typical of the area, mainly meadow grass and ruderal weeds. Comparison of the species composition showed that 32 plant species are common to both remediated and control sites. In general, both sites have high percentage of synanthropic plant species, which is associated with their proximity to the oil pipeline, country roads and agricultural lands.

Most of the species settled in Technosol as a result of seed germination from the brought soil, while colonization of the remediated area by plant diaspores from the nearest meadow phytocenoses is still in its early stage.

In general, it was discovered that a year after the reclamation work, a multi-species mixed herbaceous-grass plant association was formed in Technosol, consisting of local plant species that slightly differ from neighboring phytocenoses in both the qualitative and quantitative composition of vascular plants.

Conclusions

Our research showed that in the upper layer of Technosol, the residual amount of oil products did not exceed background values after the reclamation work, while in the lower layer (20–50 cm), their content indicated moderate pollution. It was decided that mere definition of the physicochemical properties of oil-contaminated soils after reclamation works was not enough to decide on their ability to perform ecosystem functions and provide the conditions for the existence of biota.

The main indicators of fertility (pH and organic carbon) of Technosol are relatively favourable for the growth and development of meadow grasses. Catalase activity in the upper layer of Technosol is slightly reduced, but the intensity of respiration exceeded the CO_2 efflux from Umbrisol: the latter is conditioned, to an extent, by microbial decomposition of residual oil products.

Technosol phytotesting method appeared to be highly indicative in our experiment. These results demonstrate the heterogeneity of the remediated area in terms of plant habitat conditions. The decrease in the height of the test-culture *Lepidium sativum* L. is associated with the direct impact of residual oil products.

The indirect effect of oil pollution on plants manifested itself, seemingly, through a change in microbiological activity, as evidenced by the level of catalase activity and respiration. Along with the general suppression of *Lepidium sativum* L., the redox activity of plant extracts increased, which is associated with the activation of plants defense reactions in response to toxicity of some Technosol sites.

We also found that Technosol, despite some residual oil content, successfully provides the ecosystem services with herbaceous vegetation regeneration process. Already in the second growing season from the beginning of overgrowing, mixed herbaceous-grass plant association of meadow grass and ruderal weeds with high projective cover were formed on the remediated area, slightly differing in species from the neighboring synanthropic meadow.

Our results have demonstrated that the process of self-overgrowing in smaller technogenic areas is promising; the emerging multi-species herbaceous plant community makes it possible to restore attractiveness of the natural landscape relatively quickly. At the same time, there needs to be a source for grass seeds nearby.

In general, it should be noted that the concept of soil ecosystem services has been successfully applied for evaluation of the ecological state of Technosol. However, in order to study the state of the fauna in the area remediated after oil pollution, it is necessary to engage specialists from the field of soil zoology.

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