ISSN 0147-6874, Moscow University Soil Science Bulletin, 2023, Vol. 78, No. 4, pp. 387–395. © Allerton Press, Inc., 2023.
Russian Text © The Author(s), 2023, published in Vestnik Moskovskogo Universiteta, Seriya 17: Pochvovedenie, 2023, No. 4, pp. 83–93.

Studies of Oil-Contaminated Soils and Prospective Approaches for Their Remediation

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Received July 31, 2023; revised August 28, 2023; accepted August 31, 2023

Abstract—The main milestones of the study of oil-contaminated soils at the Faculty of Soil Science of Moscow State University (Russia) in 50 years since its foundation are discussed from the perspective of the development of environmental regulation and new technologies of soil reclamation prospects. The main stages in the development of a procedural framework for the determination of oil and petroleum hydrocarbons in soils and studies of the soil properties and chemistry of oil and its components in soil and adjacent environments are considered. The development of legislation on the rationing of petroleum hydrocarbons in soils is provided. The important role played by the staff of the Faculty of Soil Science in adoption of a number of regional standards for the permissible residual content of petroleum hydrocarbons in soils is noted. The approaches to ecological rationing of oil and petroleum hydrocarbons in soils that take into account natural environments and types of land use are proposed. The importance of improving the regulatory and procedural framework and continuing activities in this direction are emphasized. The necessity of studies aimed at development of reclamation technologies for oil-contaminated lands and special use of oil-contaminated waste is indicated.

Keywords: soils, oil and petroleum hydrocarbons, rationing, reclamation, remediants, technologies

DOI: 10.3103/S0147687423040099

INTRODUCTION

Oil production and refining have made up one of the most important sectors of the national economy of the Russian Federation (or Soviet Union) for many decades. However, the increase in the volume of oil produced was, unfortunately, accompanied by an increase in environmental loading. Over the past decades, environmental conditions in the areas of intensive oil production significantly degraded, due, among other things, to degradation of the soil cover. This largely results from soil pollution, which occurs at almost all stages of the oil-production process, during oil spills due to various unforeseen situations, e.g., well blowing, oil-pipeline ruptures, overflowing of sludge pits, etc., as well as due to contamination with oil-containing products (produced water, wash water, entering liquids), highly mineralized formation waters, chemicals, emissions of combustion products, etc. Oil production negatively affects the soil cover at oil-spill sites and its components have an impact on adjacent environments (vegetation cover, surface and ground water, and fauna). Thus, oil-transformation products can be found in various objects of the biosphere (Hostettler et al., 1992; Ganster et al., 1993). Therefore, this problem became the focus of intense research interest on the part of scientists from various scientific organizations of the Soviet Union. Scientists from many scientific organizations of the Soviet Union played a major role in revealing the patterns of oil behavior in soils and its influence on microbial communities and plant development. An assessment of their contribution to the development of this issue deserves a separate publication. Scientists from Moscow State University were among the pioneers in this area, which was driven by the works of M.A. Glazovskaya, N.P. Solntseva, Yu.I. Pikovskii, A.N. Gennadiev, and other people. These works considered the patterns of migration of petroleum hydrocarbons in soils and landscapes, developed the concept of technogenic halogenesis, etc. This topic also became a subject to heavy scrutiny by the staff of the Faculty of Soil Science of Moscow State University practically from the moment of its creation. The aim of this work is to analyze the contribution of scientists from the Faculty of Soil Science of Moscow State University in solving the theoretical and applied aspects of the soil oil pollution over the 50-year history of the existence of the faculty.

MILESTONES IN THE STUDY OF OIL-POLLUTED SOILS AT THE FACULTY OF SOIL SCIENCE (1973–2023)

Study of the Properties of Oil-Contaminated Soils

Problems of soil chemical contamination have become the main focus of the activities of the head of the Department of Soil Chemistry, Prof. N.G. Zyrina. Although his work was mainly related to soil contamination with heavy metals, it is of great importance also for studying the behavior of oil-contaminated soils, as oil contains a significant set of elements, including heavy metals (mainly V and Ni), which are found mainly in the form of complex compounds in the resin–asphaltene oil fraction. Since the 1980s, Ya.M. Ammosova has been actively working on the problem of oil pollution at the Faculty of Soil Science. Along with her graduate students and colleagues, she studied the influence of oil on the soils of various regions, the Absheron Peninsula, Bashkortostan, and Tyumen and Moscow oblasts. They showed that soil contamination with oil changes many soil properties, e.g., elemental composition, color, pH, and content of nutrients and their availability to plants (Ammosova and Golev, 1998; Ammosova et al., 1999, 2000). Bocharnikova (1990) examined the influence of oil pollution on the properties of gray-brown soils of Absheron and gray forest soils of Bashkortostan. The research of D.S. Orlov on the development of methods for determining the oil content in soils (Orlov and Ammosova, 1994) also greatly contributes to the development of this issue. In subsequent years, the staff of the Department of Soil Chemistry also continued work on the creation of new methods (Trofimov et al., 2004; Zavgorodnyaya et al., 2018).

At the Department of Soil Chemistry of the Faculty of Soil Science, much attention has always been paid to soil organic matter (OM), so it was important to understand how oil will behave when treated with solvents used to study soil OM. Experiments conducted with quartz sand contaminated with oil showed that oil did not interact with chemical solvents used to isolate various groups and fractions of soil organic matter. Oil introduced into quartz sand does not transform into acidic and alkaline extracts and is defined as a nonhydrolyzable residue. Thus, by treating soil contaminated with oil by acid or alkali solutions, it is possible to obtain fractions and groups of soil organic matter, rather than oil ones (Trofimov and Rozanova, 2002).

Studies have shown that oil pollution causes a significant increase in soil organic carbon. In oil-contaminated soils, the composition of soluble fractions of organic matter changes: the content of humic-acid fractions, presumably associated with calcium (HA-2), as well as fractions of free fulvic acids (FA-1), decreases, while the content of nonhydrolyzable residues significantly increases. As a result of oil pollution, the humus status of soils also changes: the content of humate substances in humus increases, while humification of organic matter decreases. This results from an increase in nonhydrolyzable residue and, accordingly, a decrease in the proportion of soluble fractions in the composition of soil organic matter (Trofimov and Rozanova, 2003). The studies of the transformation of soil OM in peat soils of Western Siberia show that long-term interaction of organic oil compounds with soil organic matter leads to a gradual "incorporation" of hydrocarbons (HC) into soil OM, which is expressed in an increase in the content of some humus fractions, in particular, the humic fraction acids and nonhydrolyzable residue, humin (Sukhova et al., 2004). In wetland soils, oil hydrocarbons are actively sorbed by peat OM due to intermolecular interactions with hydrophobic fragments of peat OM molecules. This, in particular, is evidenced by a decrease in the amount of carbon in the preparation of humic acid (HA), isolated from oil-contaminated peat soil, after treatment of HA with hexane: the sorbed oil hydrocarbons pass into a hexane extract (Sukhova, 2004). Oil pollution significantly affects the spectral reflectivity of soils. Spectral factors are greatly reduced, as is mirrored by the slope of the spectral curve as a whole.

These works laid the foundation for the further development of this area of research, the need for which was dictated not only by the logic of the development of science, but also by the request for the practical use of scientific research results.

Development of a Regulatory and Procedural Framework for Regulating the Content of Oil and Petroleum Products

In the mid-1990s, the state of the environment in many oil-producing regions was extremely poor and reached a critical level due to a sharp increase in accident rates on in-field oil pipelines due to their wear and tear, which led to the formation of significant areas of oil-contaminated lands. A significant expansion of the activities on their reclamation was required, which entailed the need to improve reclamation technologies and develop a regulatory framework for the acceptance of reclaimed soils. Both required an in-depth study of the processes in oil-contaminated soils, as well as the formation of new principles of regulation in relation to oil contamination of soils. This need roots from the specific features of oil pollution of soils in comparison with other types of pollution, including:

—a multicomponent composition of oil: oil contains thousands of individual compounds belonging to various classes of hydrocarbons; in addition, there are organic substances of non-hydrocarbon nature, heavy metals, radionuclides, etc.;

—diverse effects of various components of oil: light fractions are toxic to organisms, but are quickly removed; heavy fractions are less toxic, but persist for a long time;

—an impact on various soil properties and processes, vegetation and soil biota: on the water–air regime of soils, soil structure, absorption of water and mineral nutrition of plants, direct toxic effects on organisms, etc.; and

—a burst nature of the impact: in most cases, contamination occurs almost instantly and in quantities many times higher than the level of the normal functioning of soils. Oil cleaning and subsequent reclamation often leave no chance of restoring the original ecosystem, especially in the cases of forest ecosystems pollution. Therefore, traditional ideas about the maximum permissible impact as being one that does not change the state beyond the limits of natural fluctuations are practically not acceptable in relation to oil pollution, and, therefore, there is an urgent need to develop specific conceptual apparatuses and criteria for assessing the soil condition.

The background content of hydrocarbons in soils can serve as a basis for a criterion for soil contamination with oil and oil products. However, its use is also debatable, since, in different soils, the background content is not the same, and often even hydrocarbons of plant-microbial origin can create a false impression of the presence of anthropogenic pollution. In addition, it is obvious that achieving the background content of hydrocarbons at the end of reclamation work in most cases even harms the surrounding natural environment, since the only method of reclamation in such a situation is cutting off the contaminated soil layer and replacing it with a clean substrate. In addition, three sets of problems arise from this solution: (1) it is necessary to solve the problem of transporting a large volume of contaminated soil, which, in addition to high cost, leads to additional pollution of the atmosphere with carbon and nitrogen oxides, as well as products of incomplete combustion of fuel, which, in turn, will lead to soil pollution with hydrocarbons; (2) it is necessary to find clean fertile soil; and (3) it is necessary to find a place for storage of contaminated soil or dispose it. Therefore, a more reasonable solution is the development of environmental standards for the permissible residual oil content in soils (hereinafter, "PROCS standards"), that are based on the doctrine of the functions of soils in the biosphere and terrestrial ecosystems (Dobrovolsky and Nikitin, 1986). Consideration of these functions, as well as the general principles of environmental regulation (Federal Law "On Environmental Protection" dated January 10, 2002) made it possible to conclude that the permissible level of residual oil content in the soil (at least until the development of purification technologies that allow reducing the oil concentration in soils to the initial level without mechanical destruction of the ecosystem) should be considered as one in which there is no significant negative impact on adjacent environments (atmospheric air, surface and ground water, vegetation, etc.) and soil biota and there is no change in soil properties, entailing loss of the soil-system stability and the inability of the soil to fulfill its ecosystem and biosphere functions. In other words, to justify the PROCS environmental standard, it is necessary to establish a maximum level of oil content in soils that enables the soil community to independently return to its natural state through natural self-purification mechanisms. The first publications on the issue and the need to create a regulatory framework on the impact of oil pollution on soils have already appeared in the literature (Trofimov et al., 2000).

The diversity of soils and their properties, which must be taken into account, manifests itself at various levels: the soil-climatic zone, geochemical landscape, and natural or technogenically disturbed biogeocenosis.

Due to all of the above, the development of the PROCS standards should include consideration of the following aspects:

—the zonal and climatic features that determine the composition of the soil cover and the rate of transformation processes of oil components;

—the landscape–lithological–geomorphological conditions that determine the rate of oil migration across the landscape and transition to adjacent environments and modify the characteristics of the physicochemical and biological properties of soils within the zone;

—the structure of the soil profile, which determines the intensity of sorption and migration of oil within the soil profile,

—the economic and environmental status of the territory, which determines the possibility of using the land for its intended purpose;

—capacity for soil reclamation to an acceptable level without causing greater damage to the environment; and

—the combined effect of oil, associated pollutants, and other negative factors.

To solve the above problems, the staff of the faculty participated in the development of a number of issues related to the impact of the oil industry on soil and vegetation cover, taking into account the natural and climatic characteristics of the regions of the Russian Federation, from the Arctic zone to the dry steppe. Scientific research is complex and is carried out in such areas as the structure of the soil cover of oil-production areas, geobotanical indication, the response of the biotic component of soils (bioindication) changed as a result of oil and salt pollution of soils, and their geochemical characteristics. In addition, much attention is paid to the issues of regulating oil pollution of soils, reclamation of disturbed lands of oil fields, and the possibility of using oil-production waste as a substrate for soil formation.

PRACTICAL WORK ON THE STUDY OF OIL-CONTAMINATED SOILS IN CONNECTION WITH THE DEVELOPMENT OF STANDARDS FOR THE PERMISSIBLE RESIDUAL CONTENT OF OIL IN SOILS

One of the first areas in which soil and vegetation cover were studied was the taiga zone of Tyumen oblast (Khanty-Mansi autonomous okrug—Yugra and Yamal-Nenets autonomous okrug), which is the leader in oil and gas production in the Russian Federation. As a part of these studies, in the center of the West Siberian Lowland, the soil cover of the areas of the Salym (Avetov and Trofimov, 2000), Pyakupur (Avetov and Trofimov, 1997), and Kazym (Avetov et al., 2022) river basins was characterized, and the main differentiation factors of the soil cover and the dominant classes of soil combinations were established. These studies support the selection of the main set of types of ecosystems and soils for development of the PROCS standards.

Since the state of vegetation is an important indicator of soil functioning, much attention has been paid to bio-indication issues. Research carried out by employees of the Department of Soil Geography of the Faculty of Soil Science on the geobotanical indication of disturbances in soil and vegetation cover is of great importance for the oil production region, since such properties as trophicity and moisture, first, respond to oil pollution and, at the same time, can be reliably and with minimal costs identified by indicator plants (Avetov and Shishkonakova, 2008, 2010; Avetov, 2009; Shishkonakova et al., 2020; Avetov et al., 2007). The association of geochemical parameters of peat soils with geobotanical indicators was revealed for wetlands located in the zone of influence of oil-sludge pits and areas of emergency oil and salt spills (Vodyanitskii et al., 2013, 2020; Kozlov and Avetov, 2014; Kozlov et al., 2017). Analyses of remediation experience of oil-contaminated soils in the Khanty-Mansi autonomous okrug—yugra and existing trends in restoration successions revealed those most suitable for phytoremediation of oil-contaminated raised bogs plant species of the local flora.

Plant Response to Oil Pollution of Soils

An important indicator for determination of the PROCS standards is the total projective cover of vegetation (TPC). Work (Solov'eva and Trofimov, 2008) revealed relationships between the TPC and oil content for the main types of soils in the taiga zone of Western Siberia. It has been established that the oil concentration in the soils over 100 g/kg leads to a decrease in the natural TPC in self-overgrowth areas of peat upland soils; however, for gley soils, a decrease in TPC occurs already at a concentration of 5 g/kg.

Compared to natural vegetation, agricultural crops are more sensitive to oil pollution. A model experiment with wheat plants (Trofimov et al., 2008) showed that the oil content in the soil up to a level of 3 g/kg does not have a negative effect on the growth of wheat. Apparently, the composition of oil has a significant impact on the resistance of wheat plants, because, in other experiments (Arzamazova et al., 2016, 2017), inhibition of wheat growth was observed at a concentration of 1 g/kg.

The response of higher plants to oil pollution of soils in the aspect of environmental regulation is discussed in detail in the work of Kovaleva et al. (2022). In an experiment on vegetation, the effects of different doses of oil on the bioproductivity of wheat and peas grown on chernozems were assessed. In terms of dry biomass, wheat showed greater sensitivity to oil pollution with predominantly medium and heavy fractions than peas. The value of the quality standard established for wheat biomass for chernozems varies from 0.4 to 1.0 g/kg depending on the particle-size distribution and the degree of humus content. The values of PROCS, taken as 30% of changes in soil functioning (which corresponds to the level of risk of soil degradation, assessed by the soil fertility parameter, dry wheat biomass), were higher and varied from 0.5 to 1.2 g/kg.

Soil-Biological Indicators for Regulating the Content of Petroleum Products in Soils

An equally important area of research in environmental regulation is the study of the response of soil biota, which can be assessed using a large set of indicators. The works of Zvyagintsev et al. (1989) and many others carried out at the Department of Soil Biology of the Faculty of Soil Science of Moscow State University identified the main patterns of the state of soil microbial community depending on the concentration of oil in soils (Stepanov et al., 2012; Kozlova et al., 2014, 2015; Manucharova et al., 2020, 2021; etc.).

An important integral indicator of the state of soil biota is basal respiration (BR) of soils. Work (Trofimov et al., 2022) showed that, in most samples from oil-contaminated soils, the formation of CO_2 under the conditions of a model experiment was lower than in background soils and negatively correlated with the content of oil products ($K = -0.59$), *n*-alkanes ($K = -0.66$), and oil biodegradation coefficient ($K = -0.71$).

Basal respiration, substrate induced respiration (SIR), and microbial biomass carbon (Cmic) were studied for soils of different natural zones. In oligotrophic bog soils of the taiga zone, BR statistically significantly negatively correlated with the content of petroleum products (PP) ($R^2 = -0.97$, $p < 0.0001$) (Kovaleva et al., 2021a, 2021c). The first significant decrease in BR activity was observed at a PP content of 9 g/kg. A PP content of 93 g/kg led to ~50% decrease of the BR values in comparison to the control; PPs in concentrations of more than 265 g/kg almost suppressed the SIR activity, as well as Cmic. For chestnut-series soils of the dry-steppe zone, BR increased with increasing PP content, which indicated an intensification of microbial activity. There is a significant correlation between PP and BR ($R = 0.99$, $p < 0.05$). The first significant changes in BR in the soil were observed at a PP content of 0.4 g/kg; at a PP content of 6.8 g/kg, BR increased 15 times compared to the control sample. Thus, the conducted studies revealed the features of changes in bio-indicative functional and structural–functional indicators under conditions of oil pollution for soils in the taiga and steppe zones, and substantiated the criteria for choosing the best indicators that do not depend on natural factors (Kovaleva et al., 2022, 2023).

Migration of Oil and Oil Products in Soils

The development of PROCS standards includes a very important set of studies on the processes of migration and sorption of oil components in soils. Experiments with peat contaminated with oil with addition of microquantities of benzene, phenol, hexadecane, and dodecane labeled with carbon (Trofimov et al., 2008) showed that, after 18% contamination of the upper 4 cm of a monolith of peat soil and contribution of an annual norm of precipitation (spilled through the monolith for a month), the bulk of the introduced oil turned out to be localized in the upper 10 cm, while, at a depth of more than 25 cm, hydrocarbons were found in background quantities and no more than 12% of oil was removed beyond the zone of oil application (upper 4 cm). In addition, the behaviors of the labeled compounds were different: *n*-alkanes (hexadecane and dodecane) remained completely in the application zone, while aromatic compounds (phenol and benzene) were detected in small quantities to a depth of 12 and 18 cm, respectively. No more than 0.01% of the added amount of benzene was transferred to the filtrate. The results obtained indicate the high sorption capacity of peat even in a wet state, as well as also in relation to the most water-soluble aromatic hydrocarbons. A similar experiment with leached chernozem (Trofimov et al., 2008) showed no significant migration of oil components within the soil column and their removal beyond its boundaries, including the most migratory aromatic compounds, with an initial oil concentration of up to 0.75%.

Work (Motorykina et al., 2008) showed that monoaromatic hydrocarbons (benzene, toluene, and *m*-xylene) dissolved in water are quickly and effectively bound by the hydrophobic regions of peat organic matter: the amount of monoaromatic hydrocarbons sorbed by peat is more than three orders of magnitude greater than their equilibrium concentration in the aqueous phase, while the affinity of aromatic hydrocarbons for peat increases with increasing degree of their hydrophobicity.

Work (Vasilkonov et al., 2008) was dedicated to the sorption of naphthalene and naphthol by soils. The more active sorption of naphthol compared to naphthalene was explained by the binding of naphthol not only by hydrophobic interactions with aromatic fragments, but also due to hydrogen bonds between the phenolic group of naphthol and oxygen-containing functional groups (for example, carboxylic and phenolic) of humic acids.

Studies of oil migration in soils of Sakhalin are presented in the works of Kovaleva et al. (2014, 2021). Using the method of soil lysimeters, these researchers assessed the radial migration of petroleum products in the soil profile and their entry into lysimetric filtrates. The results of this study can be used for environmental regulation of the permissible residual content of petroleum products in soil horizons of the main types of Sakhalin. It was established that the maximum concentrations of petroleum products, especially of medium- and high-boiling fractions of petroleum hydrocarbons, are confined to peat, humus horizons, as well as horizons of heavy granulometric composition, which are radial geochemical barriers to the migration of pollutants. Benzene and its homologues were found in filtrates from lysimeters after passing a volume of water corresponding to three-quarters of the annual norm of atmospheric precipitation; however, the passage of the annual norm of precipitation through the soil led to complete washing out of these compounds. Our special test with soil monoliths of oligotrophic bog soils from the middle taiga determined that the maximum sorption capacity of peat soils with a moisture content of 92%, a degree of decomposition of 38%, and a bulk density of 0.112 g/cm^3 was about 80 g/kg (Kovaleva et al., 2021c). The accumulation of pollutants over the maximum sorption capacity can change the hydrosphere function of peat soil. Excess pollutants can migrate vertically and laterally and, thus, affect the quality of ground- and surface waters.

The conducted studies formed the basis for the development of one of the first documents on the rationing of oil and oil products, the regional norm "Permissible Residual Content of Oil and Oil Products in Soils after Reclamation and Other Remediation Activities on the Territory of the Khanty-Mansi autonomous okrug–Yugra," as well as the corresponding norms for Stavropol krai, Sakhalin oblast, the territory of the Taimyr Dolgano-Nenets municipal district, and the city of Norilsk (Krasnoyarsk krai). Studies on the assessment and environmental rationing of petroleum products in soils in different natural and climatic zones are discussed in works (Trofimov, 2013; Kovaleva and Yakovlev, 2018; Kovaleva et al., 2016, 2017, 2018, 2019, 2021a, 2022, 2023; Trofimov and Kovaleva, 2021).

Thus, at present, there is a scientific and methodological basis for further development and improvement of rationing of petroleum products in soils, as well as development or revision of PROCS standards for the constituent entities of the Russian Federation that take into account the composition of oil and petroleum products.

A separate set of studies are devoted to the influence of drilling waste-disposal sites on adjacent territories (Sokolova et al., 2005), including the aspect of rationing petroleum products and associated pollutants in drilling waste and optimizing their properties by ameliorants. Model experiments were carried out with drill cuttings and model mixtures, which included sand, diatomaceous earth, peat, phosphogypsum, cement, and petroleum products (Kovaleva et al, 2019). Migration indicators were used to assess the properties of mixtures and their possible impact on components of the natural environment. It has been established that the optimal ratio of components in soil-like bodies with an oil-product content of no more than 50 g/kg is drill cuttings (no more than 70%), sand (no less than 20%), and diatomaceous earth (no less than 4%).

DEVELOPMENT OF NEW TECHNOLOGIES

The development and implementation of innovative technologies for bioremediation of oil-contaminated ecosystems, as well as the development of project documentation on their basis with the aim of further involving lands in economic circulation for main economic use, are promising and important. The development/selection of effective sorbents and remediants for specific natural and climatic conditions is significant. For example, the concentration of "free" petroleum products can be significantly reduced by sorption on mineral and organic sorbents. It reduces the toxic effect on the microbial community and promotes rapid biodegradation of oil/petroleum products. Since significant areas of oil-contaminated lands in the Russian Federation are represented by waterlogged lands, one of the promising directions in the development of new technologies may be the use of chemical reagents that can gradually release oxygen, for example, calcium peroxide (Vodyanitskii et al., 2016). Laboratory experiments demonstrated the significant increase in the intensity of mineralization of oil components in tundra soils with the addition of calcium peroxide (Kovaleva and Trofimov, 2022).

Works (Tolpeshta et al., 2015; Erkenova et al., 2016; Tolpeshta and Erkenova, 2018) demonstrate the possibility of significant increase of the rate of oil destruction by native microorganisms in waterlogged soils associated with introducing additional electron acceptors in the form of nitrates, sulfates, and mineral sorbents, while organoclays can be used as effective sorbents of water-soluble oil components (Chechetko et al., 2017).

A traditional area of research for the faculty is the restoration of soil fertility by optimizing and increasing the efficiency of the use of mineral fertilizers during the reclamation of oil-contaminated soils, which is especially important for agricultural lands (Arzamazova et al., 2023).

In work (Vetrova et al., 2022), hydrocarbon degrading microorganisms were isolated and identified from the main soil types in the Middle Ob region. Microorganisms were screened for their ability to produce biosurfactants and degrade various classes of hydrocarbons, as well as the presence of genes that determine the synthesis of enzymes responsible for the degradation of aromatic and aliphatic hydrocarbons. Based on the screening, a microbial consortium was compiled as the basis of a biological product for bioremediation of oil-contaminated soils of the Middle Ob region. This consortium includes strains *Candida fluviatilis* 24p-51, *Rhodococcus erythropolis* 24-44, *Acinetobacter calcoaceticus* 7-43, and *Pseudomonas extremaustralis* 7-31. Specific regimes for biomass cultivation and lyophilization were determined for the selected microorganisms. The efficiency of degradation of petroleum hydrocarbons by the developed microbial consortium was assessed in laboratory model experiments. The degree of oil degradation by this microbial consortium in a liquid mineral medium and a model soil was 56.05 (for 14 days) and 21.66% (for 21 days), respectively.

A promising and practically significant direction of studies is the development of biological products capable of synthesizing substances (ACC deaminase and phytohormones) that accelerate plant growth on oil-contaminated soils, which will help to speed up the decomposition of oil components and restore vegetation cover. The greatest effect can be expected on waterlogged soils, because the stimulating effect of microorganisms on plants with aerenchyma will overcome the main problem of using biological petroleum-degrading products in wetlands—a lack of oxygen (Trofimov et al., 2018).

Since contamination with crude oil (formation fluid), as a rule, leads to soil salinization, the problem of creating soil-desalinization technologies is still acute, as natural desalinization occurs very slowly even in humid climate. The enormous experience of the staff of the Faculty of Soil Science in the study of saline soils may be in demand as concerns this issue (Vodyanitskii et al., 2013; Kozlov et al., 2015; Shishkonakova et al., 2020).

Research aimed at developing technologies for processing drilling waste should be continued. Optimization of the properties of drill cuttings will provide designing of soil-like bodies that can organically integrate and function in the ecosystem. The substantiated results have made it possible to provide recommendations for the design of soil-like bodies (Kovaleva et al., 2021b).

CONCLUSIONS

Over a more than 40-year period of studying oil pollution of soils, employees of the Faculty of Soil Science have studied the mechanisms of the impact of oil on soil processes, established the basic patterns of changes in soil properties under the influence of oil pollution, developed new methods for determining the content of oil and its products in soils, etc. A methodological approach has been proposed and implemented to establish the permissible residual oil content in soils after reclamation activities, which is reflected in a number of legislative acts of the constituent entities of the Russian Federation: decree of the Government of the Khanty-Mansi autonomous okrug–Yugra no. 466-p dated December 10, 2004; order of the Ministry of Natural Resources and Environmental Protection of Stavropol krai no. 13 dated January 16, 2017; decree of the Government of Sakhalin oblast no. 279 dated June 20, 2018; and decree of the Government of Krasnoyarsk krai no. 902-p dated December 17, 2021.

Currently, the faculty staff are continuing to work on the further development of the system for regulating the content of oil and its products in soils, regulating the content of easily soluble salts in the soils of oil-producing regions, and solve problems related to the reclamation of oil-contaminated and saline soils, the safe disposal and processing of drilling waste and the design of soil-like bodies that can be integrated into ecosystems, optimization and increasing the efficiency of the use of mineral fertilizers during the reclamation of oil-contaminated soils, etc.

Thus, the research conducted at the Faculty of Soil Science of Moscow State University is of great importance for the further development of the regulatory framework and technologies for the reclamation of oil-contaminated lands.

FUNDING

This study was carried out within the framework of a state order of the Ministry of Science and Higher Education of the Russian Federation, topic no. 121040800147-0 “Soil Information Systems and Optimization of the Use of Soil Resources.”

COMPLIANCE WITH ETHICAL STANDARDS

This article does not contain any studies involving animals performed by any of the authors.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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Translated by T. Kuznetsova