Features of the self-restoration of the oil-contaminated peat-bog soil – a field study

Marina Chugunova*, *Lyudmila* Bakina, and *Alexander* Gerasimov

Saint-Petersburg Scientific Research Centre for Ecological Safety – a separate structural subdivision of the Federal State Budgetary Institution of Science “Saint Petersburg Federal Research Center of the Russian Academy of Sciences”, 197110 Saint Petersburg, Russia

Abstract. The features of self-restoration processes of the oligotrophic peat-bog soil disturbed by crude oil pollution were studied. Soil contamination was carried out in field long-term experience. The key soil self-recovery indicators were: (1) the rate of carbon dioxide emission by the soil, which quantitatively characterizes the mineralization of petroleum hydrocarbons by microorganisms; (2) content of petroleum products. The microorganisms of the studied soil were characterized by low resistance to the toxic effects of oil: during the first three years of the experiment, the respiration of oil-contaminated soils was significantly lower than in pure soil. Restoration of microbial respiration to the control level and its further intensive growth occurred after 4-5 years of the experiment only in soils with low oil doses: 0.3 and 0.6 l m-2. In time, this coincided with the maximum rate of oil decomposition, which indicates the microbial nature of its utilization. The respiration of soil with oil high doses (1.8 and 3.0 l m-2) remained significantly lower than in pure soil throughout the entire experiment. At the same time, the amount of oil products in these samples markedly decreased. Oil degradation in these variants could occur due to the activity of anaerobic bacteria or abiotic processes.

1 Introduction

Peat-bog soils, as the largest natural carbon storages, perform the key biospheric function, despite the fact that they occupy only 3% of the earth's land area [1-3]. Peat-bog soils are formed under conditions of excessive moisture by atmospheric, stagnant or slow-flowing groundwater. This type of soil is common in the north of Eurasia and the USA, as well as in Canada. In Russia, large areas with peat-bog soils are located in a cold humid climate in the North-West of the country, including the Saint Petersburg region.

Peat-bog soils are characterized by high sensitivity to anthropogenic impact. Increased anthropogenic pressures cause negative changes in the physical, chemical and biological properties of peat soils, which ultimately leads to the degradation of the soil ecosystem as a whole [2].

Currently, oil pollution of land ecosystems, including soils, is common and one of the most dangerous effect of human activities. There is a lot of information in the scientific

* Corresponding author: chugunova54@gmail.com

literature about the negative impact of oil pollution on the functioning of peat-bog soils [4-8].

Most studies of oil-contaminated peat-bog soils were carried out either in the laboratory or in short-term field experiments. Meanwhile, under natural conditions, the mineralization of petroleum products can take years and even decades [9, 10]. In addition, only in the field experiment it is possible to obtain results that fully correspond to the bioclimatic conditions of the region under study [11].

In this regard, the purpose of our research was to study in long-term field experiment the dynamics and features of natural restoration of the oil-contaminated oligotrophic peat-bog soil, common in the cold humid climate of the North-West of Russia. It should be emphasized that such studies in these bioclimatic conditions were carried out for the first time.

2 Materials and methods

In order to study the features of natural oil degradation in oligotrophic peat-bog soil, a long-term plot field experiment was set. Soil contamination with crude oil was carried out at the site near Saint Petersburg, Russia. The crude oil was applied to the soil surface in amounts of 0.3, 0.6, 1.8 and 3.0 l m-2. Throughout the text, the first two doses will be referred to as low, the third and fourth doses – as high. Peat-bog soil not contaminated with oil served as control.

Duration of the field experiment – 6 years. Sampling depth – 0-10 cm. Samples were taken: for the first time – 10 days after soil contamination with oil and later on – at the end of each growing season.

Soil self-restoration indicators were:

(1) intensity of carbon dioxide emission by the soil (soil respiration), which quantitatively characterizes the mineralization of petroleum hydrocarbons by microorganisms, was determined in laboratory by the adsorption method [12];

(2) total oil content in soils was determined by the method of infrared spectrometry [13].

The number of replications was four-fold. The results obtained were processed by applying the non-parametric Mann-Whitney test.

3 Results

In the first 10 days of the experiment, the biological activity of soils at all levels of pollution was significantly suppressed (Figure 1). Thus, the minimum doses of crude oil reduced microbial respiration by 1.7 times compared to pure soil, and the maximum doses – by almost 2.5 times.

During the next year and a half, the microbiological state of contaminated soils did not change. The only exception was the soil with a minimum pollution level. By the end of the second growing season the intensity of it respiration increased markedly. However, the amount of carbon dioxide emitted by this soil was still less than in the control.

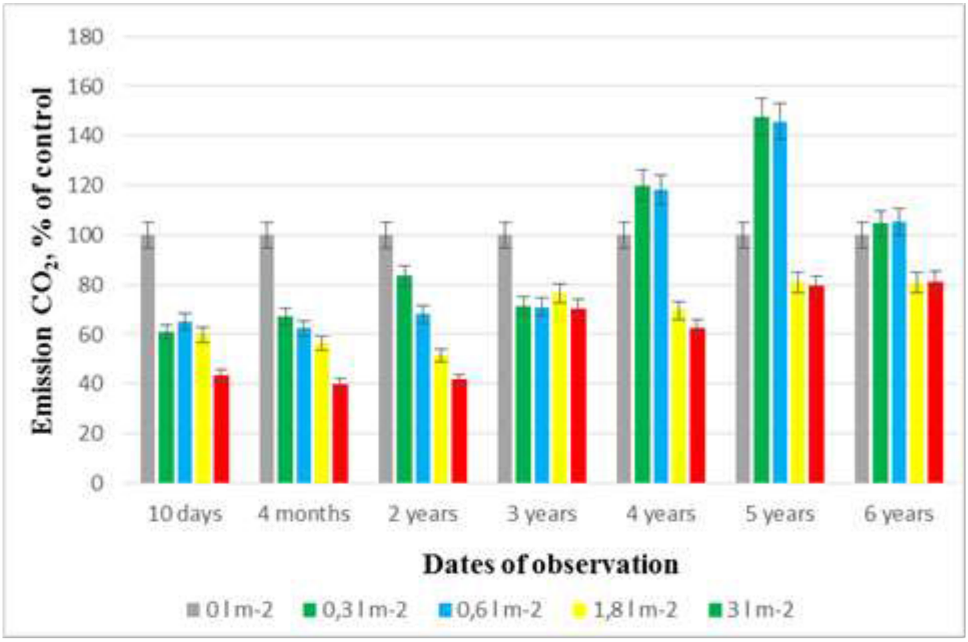

Fig. 1. Carbon Dioxide Emissions from Oil Contaminated and Control Soils, %

Later, starting from the third year of observations, there was an increase of the microbes' functional activity in the all contaminated soils. Soils with the low oil doses were characterized by the most intensive growth of CO_2 emission. The amount of carbon dioxide produced by these soils not only reached the control level, but also exceeded it by 1.6 times at the end of the fifth growing season. At the end of the experiment, the biological activity of slightly contaminated soils decreased and was practically the same as in the pure control soil.

The biological activity of the soils with high oil doses by the end of the fifth growing season almost doubled compared to its values obtained in the first year of the experiment. Meanwhile, the growth of microbial activity in these soils stopped at this point. And until the end of the experiment, it remained almost 1.3 times lower than the control level.

The rate of decrease of the hydrocarbons' concentration in the studied soils changed with the oil dose (Figure 2). Over the first two years of observations, the concentration of oil products in slightly contaminated soils decreased by an average of 1.3 times. In the later years the intensity of degradation of petroleum products in soils with low oil doses markedly speeded up. At the end of the experiment, the total content of oil products in these soils decreased by an average of 5 times compared to the initial observation period. We remind, that in the same period in these soils, a peak of microbial activity was recorded. Its value was much higher than the control level.

In contrast to the variants with low doses of oil, in heavily polluted soils, hydrocarbons degraded most intensively at the beginning of the experiment. So, for all six years of research, against the background of low microbiological activity, the amount of oil in these soils decreased on average by 73%. Besides, more than half of this volume of oil was mineralized during the first two years of the experiment.

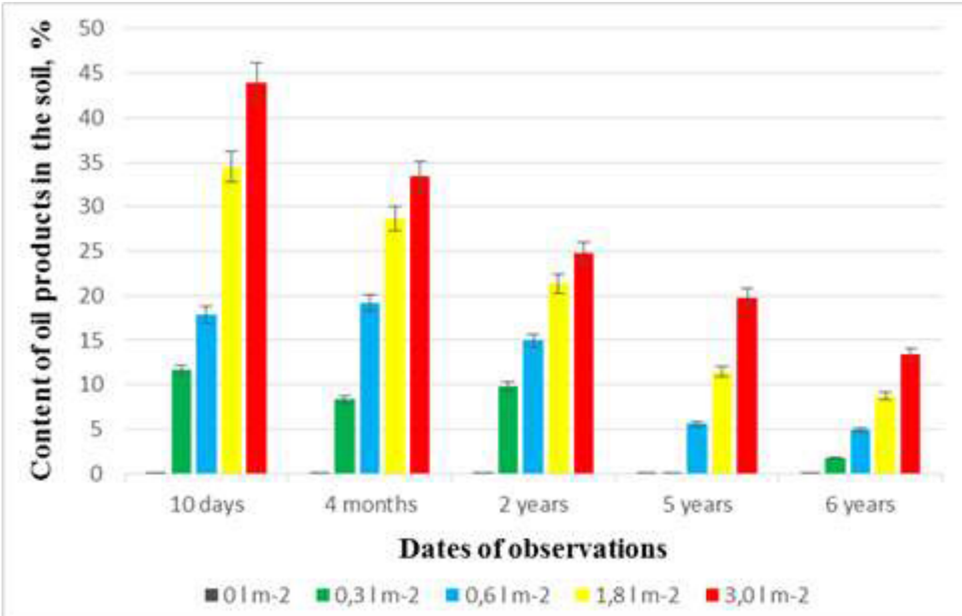

Fig. 2. Total content of oil products in oil contaminated and control soils, %

4 Discussion

Oil had a strong inhibitory effect on the microbiota of the peat-bog soil: the respiratory activity of the soil in the first two years of the experiment was suppressed at all levels of pollution. Other authors also report on the high sensitivity of microbial communities of peat-bog soils to the toxic effects of oil pollution [6]. Our data also indicate a significantly lower resistance of microbiota of the high bog peat soil to the negative impact of crude oil compared to the microbiota of the cultivated soddy-podzolic soil we studied earlier [14]. At a comparable level of pollution, the microbial activity of soddy-podzolic soil at all doses of oil not only fully recovered to the control level, but also significantly exceeded it already four months after the start of the experiment.

Starting from the third year of observations, there was an increase of the microbes' functional activity in the all contaminated soils. Soils with the low oil doses were characterized by the most intensive growth of CO_2 emission. The amount of carbon dioxide produced by these soils reached the pure soil level and at the end of the fifth growing season exceeded it by 1.6 times. The maximum rate of hydrocarbon decomposition was recorded in the same period in this soils.

In soils after oil pollution, a sharp increase in the number and activity of oil-degrading microbiota is observed. As a result, CO_2 emission from polluted soil increase significantly [15-16]. The rate of oil decomposition correlates with the soil integral microbial activity, which is estimated by the amount of carbon dioxide released. Therefore, the intensity of microbial respiration is used as a sensitive quantitative indicator of the process of complete mineralization of oil in the soil [18-20]. In this regard, the data obtained unambiguously point to the intensive processes of complete mineralization of petroleum products to carbon dioxide and water, carried out by aerobic microorganisms in lightly polluted soils.

The respiratory activity of soils with high doses of oil remained significantly lower throughout the experiment than in pure soil. Apparently, the high sensitivity of the microorganisms of the studied soil to high doses of oil is explained by the formation of a bituminous crust on its surface. On the surface of upland bog soils, after oil pollution, the oil slick usually transforms into a bituminous crust over time [21]. Hard bituminous crust covered almost the entire surface of the studied soils and prevented free air exchange between soil and ground air. Thus, in the upper layers of the most oil polluted soils anaerobic or facultative aerobic conditions were formed. And as is known, the most complete destruction of organic pollutants, including petroleum hydrocarbons, with the formation of carbon dioxide and water is possible only under aerobic conditions [22]. Probably, it was this circumstance that reduced the efficiency of aerobic biological degradation of petroleum hydrocarbons. At the same time, despite the low activity of aerobic biochemical processes, the total amount of oil products in highly contaminated samples decreased by an average of 73%.

However, this phenomenon can be explained if we assume that the destruction of oil products in highly contaminated samples occurred due to anaerobic microbial transformation of oil, as evidenced in the scientific literature [23, 24]. In the peat-bog soils the mineralization of organic with the generation of CO_2 proceeds mainly under aerobic conditions. However, in the peat layer with a limit or absence of oxygen, deep biotransformation (not utilisation) of organic matter also proceed [25-29].

In addition, abiotic processes of oil degradation cannot be excluded. Physical and chemical decomposition of oil can continue for quite a long time and in some cases account for 50 to 80% of the total set of chemical changes in oil structures. Besides, almost all homological and isological series of oil hydrocarbons are subject to abiotic degradation processes [30, 31].

5 Conclusion

The microbiota of the peat-bog soil turned out to be unstable to the inhibitory effect of crude oil: in the first 3 years of the field experiment, the respiration of all contaminated soils was significantly below the control level.

Complete restoration of the respiratory activity of microorganisms and its further significant excess of the control level occurred on the 4th and 5th years of the experiment only in soil with low doses of oil (0.3, 0.6 $l\ m^{-2}$). That was also when the highest rate of decrease in the oil products content was established in these soils. It proves the aerobic microbial nature of oil utilization in the soils with its low doses.

The microbiota respiration in the heavily polluted soils (1.8, 3.0 $l\ m^{-2}$) within the experiment was considerably lower than in the control. Nonetheless, the total content of oil products in the heavily polluted soils decreased on average by 72.6% during the experiment. It is likely that in these soils a complex transformation of petroleum hydrocarbons occurred as a result of abiotic processes, as well as the activity of anaerobic microbiota, and not their complete aerobic bio-oxidation to carbon dioxide and water.

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