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Phytotoxic Effects of Kerosene on Plants of Forest and Bog Phytocenoses of Southern Taiga

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Abstract: One of the most important problems of environmental sciences is to determine limits for the sustainable functioning of affected ecosystems. The effects of volatile hydrocarbons (such as gasoline and kerosene) on plants in natural ecosystems have been poorly studied to date. The present work outlines the data of a field experiment on the effects of kerosene on the plants of forest and bog communities in Central Russia. In this paper, we model the influence of kerosene spillage on plants growing in a coniferous broad-leaved (aspen–spruce) forest and a raised bog with a subshrub–sphagnum pine forest. We used TS-1 kerosene, which is the most commonly used fuel for commercial aviation in Russia. The applied pollutant (loads of 1 to 100 g/kg) had a significant impact on herbaceous plants, leading to the death of individuals even at minimal doses. The shrubs of the bog community as well as the mosses of both communities were more resistant to kerosene. The recovery processes of plant communities were clearly pronounced as early as 2 years after the application of the pollutant. The level of kerosene threshold exposure, which significantly affects the dominant plants of the herb–shrub layer, can be defined as 1–5 g/kg for the forest community and 5–10 g/kg for the bog community.

Keywords: soil pollution; jet fuel; vegetation recovery; field experiments; vegetation dynamics; demutation

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1. Introduction

Environmental pollution by hydrocarbons is a major ecological problems because hydrocarbon fuels (such as kerosene, petrol and diesel) are the main fuels for transportation engines and known to be phytotoxic. Petroleum hydrocarbons cause various reactions in plants, such as enzymatic disfunction, troubles with membrane permeability, disfunction of the electron transport chain in chloroplasts, formation of covalent bonds with proteins and nucleic acids, increase in reactivity, hydrophilicity and electrophilicity [1]. In addition to the direct negative effects on plant roots and leaves, hydrocarbon fuel pollution affects plants indirectly by changing the physico-chemical [2–4] and biological [5–7] properties of soils. However, despite the considerable focus placed on the effects of petroleum and petroleum products on the components of natural environments, the effects of volatile hydrocarbon fuels on soils and plants have predominantly been studied in laboratory experimental settings [8–14], which limits their applicability to natural ecosystems.

Another feature of numerous laboratory experiments on hydrocarbon exposure is the use of seeds of commonly cultivated crops as test subjects, including radish [9], bean [11], barley [8] and flax [10]. Along with them, less common meadow species used, for example, as fodder plants, lawn grasses and cover crops, have been considered in experiments [13]. At the same time, in the case of spills of kerosene, which are typical, for example, of airfields [6,10] or space rocket stage impact areas [15,16], contamination often affects natural rather than cultivated plant communities, for which little is known about species resistance to kerosene. Field studies on the effects of petroleum products on vegetation, which could increase the applicability of these laboratory experiments to natural conditions, are relatively rare. Perhaps, the reason for the rarity of such studies may be a combination of the high labor intensity of setting up field experiments, the legal restrictions on soil contamination with hydrocarbons, and the greater focus on environmental damage caused by crude oil spills than from the less common spills of hydrocarbon fuels. In addition, the existing field studies on the impact of hydrocarbon fuels on vegetation cover were generally conducted over 25–40 years ago and vary considerably regarding the methodology of the experiments [17–23]. Among other factors, the vast majority of these studies consider the less volatile [24] diesel, which also differs from petrol and kerosene in its chemical composition [25]. Thus, the impact of volatile hydrocarbon fuels on natural ecosystems is still poorly understood.

Previously, in a field experiment, we characterized the response of forest, wet meadow and fen species of the southern taiga of the Russian Far East to kerosene applications ranging from 1 to 500 g/kg [16]. This article focuses on the effects of kerosene on plant species typical of communities in the southern taiga sub-zone of European Russia (Central Russia) and their ability to recover from this exposure. We performed the experiments in connection with microbiome studies of the same soils in same location; the results of the microbiome studies are published in [7] and [26]. As a scientific hypothesis, we expected that taxonomically, ecologically and biomorphologically similar plant species from the Far East and European Russia would show a similar response to pollution by the same hydrocarbon fuels. The results of present study reveal the threshold levels of hydrocarbon fuel pollution that cause a significant impact on the vegetation cover, which can be applied in the field of reclamation of sites of anthropogenic accidents associated with hydrocarbon fuel spills, which has been repeatedly observed in Russia in recent years (for example, https://iz.ru/1034485/2020-07-12/10-kubometrov-aviakerosina-vylilos-v-grunt-iz-za-razgermetizatcii-truby-na-taimyre (accessed on 27 March 2023) or https://www.kommersant.ru/doc/4928374 (accessed on 27 March 2023) (in Russian)).

2. Materials and Methods

2.1. Description of the Study Site

The impact of kerosene on plant species of the herb–shrub and moss layer of forest and bog communities in the vicinity of Butovka village (Borovskiy district, Kaluga region; Figure 1) was studied within the framework of a field experiment in 2020–2022. This area, located in the South-East of the Smolensk–Moscow Upland, was chosen as a reference benchmark for the Moscow region and Kaluga Oblast, where several international airports are located: Sheremetyevo, Domodedovo, Vnukovo, Kaluga and Zhukovsky. In this space, contamination with kerosene occurs because it is the largest aviation hub in Russia.

The Kaluga region is characterized by a snowy, fully humid climate with a warm summer, index 'Dfb' [27], with the annual precipitation of about 650 mm. The growing season lasts from May to September. The parent rocks of well-drained interfluves and slopes are Quaternary loess-like loams, at least 2 m thick, underlain by lacustrine sediments. In the local depressions of the interfluves, on clayic or loamic rocks under the sphagnum mosses, Fibric Histosols with a peat thickness of about 1.5 m are formed. Albic Luvisols are the main soils in this region.

The zonal vegetation consists of mixed (coniferous broad-leaved) forests, dominated by the European spruce (*Picea abies* (L.) H. Karst.), and broadleaf forests, dominated by the pedunculate oak (*Quercus robur* L.), small-leaved lime (*Tilia cordata* Mill.) and common ash (*Fraxinus excelsior* L.). The structure of the forest communities include a dense underwood layer (except in the darkest mixed forests), in which the common species are the common hazel (*Corylus avellana* L.), fly honeysuckle (*Lonicera xylosteum* L.), *Euonymus verrucosus* Scop. and other shrubs. The composition of the herbal layer varies considerably, from shrubs of the Ericaceae family (*Vaccinium myrtillus* L. and *V. vitis-idaea* L.), typical for coniferous forests, to nemoral herbs (for example, *Lamium galeobdolon* (L.) Crantz, *Allium ursinum* L., *Carex pilosa* Scop. and *Aegopodium podagraria* L.). The moss layer, composed of various green mosses (or *Sphagnum* mosses in waterlogged areas), is more typical of coniferous and mixed forests.

Figure 1. Location of the study site (red label). Bing map (www.bing.com (accessed on 27 March 2023)) used as background.

The intrazonal vegetation consist of Scots pine forests (*Pinus sylvestris* L.) confined to sand deposits of ancient alluvial plains, small-leaved secondary forests of silver birch (*Betula pendula* Roth) and aspen (*Populus tremula* L.), bogs, fens and meadows.

2.2. Description of the Soil and Vegetation in the Sample Plots

All plant names are provided according to the World Flora Online database (http://www.worldfloraonline.org/ (accessed on 27 March 2023)), only with the exception of *Pteridium pinetorum* C.N. Page and R.R. Mill, which are typical to most parts of Russia [28], as the taxonomy of the genus *Pteridium* differs according to the database.

The plant community of the forest site with Albic Retisols (N 55°11′ E 36°25′) is constituted by a coniferous broad-leaved (aspen-spruce) forest. The dominant trees are the European spruce (*Picea abies* (L.) H. Karst.) and aspen (*Populus tremula* L.). Crown density reaches 60%, with an approximate canopy height of 30 m. The developed understory with a total projective cover (TPC) of 20% is dominated by *Corylus avellana* L. The sparse herb-shrub layer reaches 30% of the TPC, dominated by *Athyrium filix-femina* (L.) Roth, *Ajuga reptans* L. and, to a lesser extent, *Lysimachia nummularia* L. Green mosses predominate in the moss layer with an TPC of up to 20%: *Atrichum undulatum* (Hedw.) P. Beauv., *Rhytidiadelphus triquertus* (Hedw.) Warnst. and *Plagiomnium undulatum* (Hedw.) T.J.Kop. The total species richness of vascular plants during the 3 seasons of the study was 26 species per 100 m^2.

The plant community on the bog site with Fibric Histosols (N 55°11′ E 36°24′) constitutes a raised bog with a developed stand of Scots pine (*Pinus sylvestris* L., crown density 20%). Here, the understory is practically absent (TPC up to 1%); meanwhile, the herb–shrub layer makes up a TPC of up to 60%, dominated by *Ledum palustre* L., *Chamaedaphne calyculata* (L.) Moench, *Vaccinium oxycoccos* L. and *Eriophorum vaginatum* L. The moss layer is composed of species of the genus *Sphagnum* (primarily *S. angustifolium* (C.E.O.Jensen ex Russow) C.E.O.Jensen, *S. squarrosum* Crome and *S. fallax* (H.Klinggr.) H.Klinggr.), and reaches a TPC of at least 95%. The total species richness of vascular plants during the 3 seasons of the study was 8 species per 100 m^2.

2.3. Experimental Design

Before the experiment began on 29 June 2020, in each site, 18 quadrat plots of 50 cm × 50 cm in size were marked out. These were approximately representative of the background communities, relatively homogeneous in terms of vegetation cover and identical in terms of the main dominant herb–shrub layer species (for the forest site, these were *Athyrium filix-femina* and *Ajuga reptans*; and for the bog site, these were *Ledum palustre*, *Chamaedaphne calyculata*, *Vaccinium oxycoccos* and *Eriophorum vaginatum*). For each quadrat, the TPC of the herb–shrub and moss layers (in % relative to the size of the quadrat) were described, together with the approximate coverage of the analyzed species (in % relative to the size of the quadrat). TPC was estimated for values over 10% visually in gradation of 10%; for values less than 10%, visually in gradations of 5%, 3%, 1% and <1%.

After describing the initial condition of the plants, five kerosene loads (1, 5, 10, 25 and 100 g/kg of soil that correspond to 0.13, 0.68., 1.36, 3.44 and 13.76 L/m^2, respectively) were applied to the various quadrats in triplicate. Moreover, three quadrats were unpolluted and used as the control. For treatment, we used TS-1 kerosene, which is the most commonly used fuel for commercial aviation in Russia [15]. Kerosene loads of 1 and 5 g/kg were applied as a spray using a portable sprayer device. The other loads (10, 25 and 100 g/kg) were applied using a watering can. We tried to distribute the kerosene evenly over the soil surface within the quadrats. The loads were selected based on previous results on the response of vegetation [16] and cultivated soil microorganisms [29] to kerosene contamination.

The condition of the vegetation cover for the same parameters in the quadrats was monitored on the following dates (Table 1):

Table 1. Weather conditions in the study area during the period of the experiment (according to the weather station in Maloyaroslavets https://rp5.ru/Weather_in_Maloyaroslavets (accessed on 27 March 2023)).

Criteria	First Growing Season		Second Growing Season (29 March 2020– 5 July 2021)	Third Growing Season 21 March 2022– 23 June 2022)
	Before Experiment Began (4 March 2020– 29 June 2020)	3 Months after Experiment Began (30 June 2020– 21 September 2020)		
Date on which the daily average temperature surpassed 4 °C	4 March 2020		29 March 2021	21 March 2022
Sum of the effective temperatures * for the period, °C	640	1033	888	877
Sum of rainfall for the period, mm	402	210	238	371

* The sum of effective temperatures is a Russian agronomical concept referring to the sum of the average daily temperatures above +5 °C over a selected time period (+5 °C is usually chosen as a baseline for vegetation growth, with higher values for cultivated crops). It is usually used to calculate the total amount of heat a plant receives to complete its growing season (or an animal its life cycle).

- 2 July 2020 (3 days after pollutant application);
- 30 July 2020 (1 month after pollutant application);
- 21 September 2020 (3 months after pollutant application);
- 5 July 2021 (12 months after pollutant application);
- 23 June 2022 (24 months after pollutant application).

2.4. Statistical Analysis

Statistical processing was performed using non-parametric tests: Mann–Whitney U-test for independent variables and the paired samples Wilcoxon W-test. The statistical significance level was set as (p-value) = 0.05.

3. Results

3.1. External Signs of the Phytotoxic Effects of Kerosene

Plants immediately responded to kerosene exposure. After 3 days, the tissue necrosis of leaves and their deformation were noted on all experimental sites where kerosene doses were applied (Figure 2). Mosses were less damaged by kerosene, with deformation of leaves in some individuals—*Atrichum undulatum* and *Rhitidiadelphus triquertus,* and some shoots of *Sphagnum* spp. bleached.

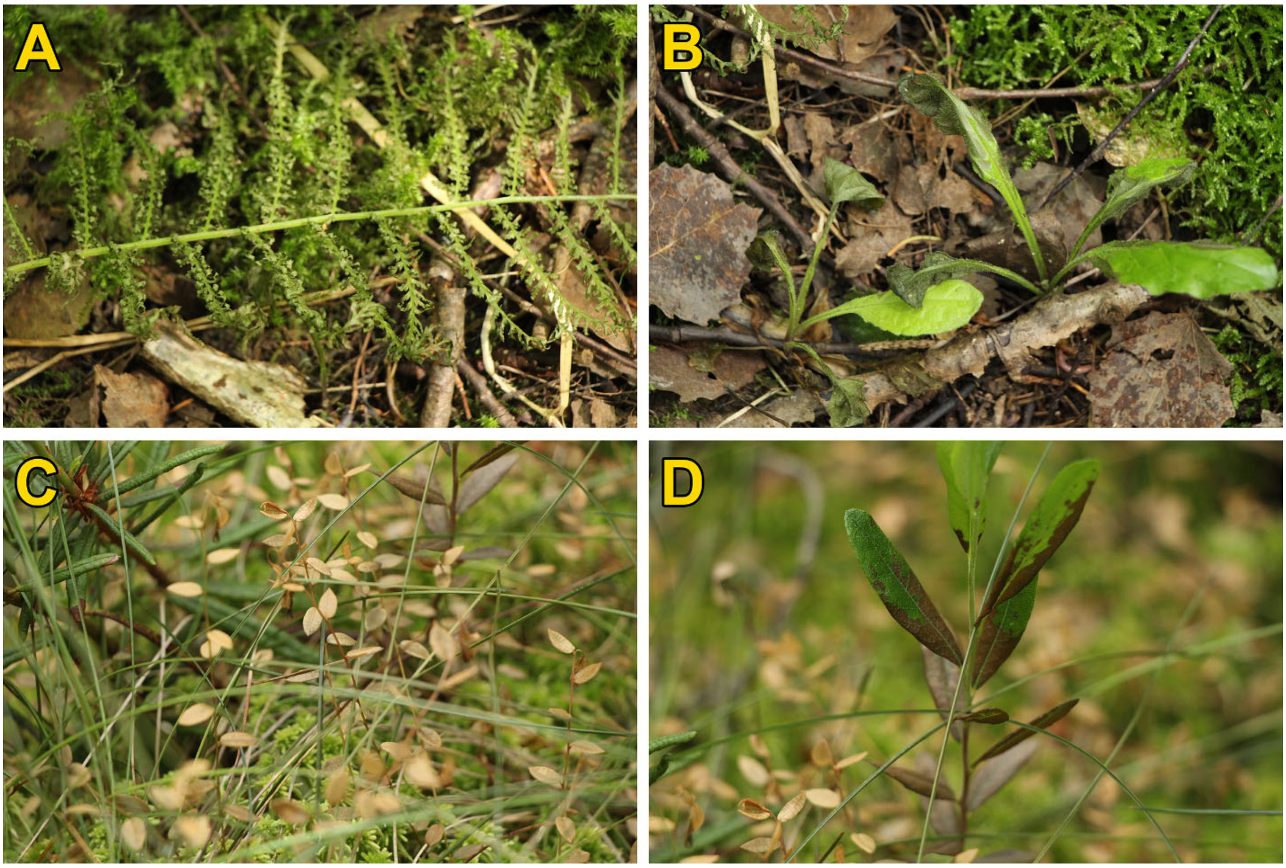

Figure 2. State of the species of the herb–shrub layer of the forest and bog phytocenoses 3 days after kerosene application (doses of 25–100 g/kg). Tissue necrosis and deformation of vegetative organs: (**A**) fronds of *Athyrium filix-femina* and (**B**) leaves of *Ajuga reptans*. Change in the coloration of the leaves and stems: (**C**) *Vaccinium oxycoccos* and (**D**) *Chamaedaphne calyculata*.

3.2. Effects of Kerosene on the Total Projective Cover (TPC) of the Vegetation Layers

The observed difference in the damage of plants of the herb–shrub and moss layers subsequently changed the ratio of their TPC at the experimental sites in the forest community. In all sites contaminated with kerosene in the first growing season (Figure 3), the disappearance of herbaceous plants was noted, while the projective coverage of mosses did not change, owing to which, at all doses, the coverage of the moss layer was significantly higher (p-value < 0.05 (hereafter, it represents the calculation of the p-value by the Mann–Whitney U-test for adjacent dose pairs of 100 + 25 g/kg, 10 + 5 g/kg, 5 + 1 g/kg and 1 + 0 g/kg (N = 6 quadrats in each case), since the sample size for comparisons within a single dose (N = 3) is not sufficient to obtain a p-value < 0.05)). The same trend persisted one year after kerosene application (p-value < 0.05), and in the case of doses of 1 to 10 g/kg, even 2 years later (p-value <0.05). At the same time, for the control site, the TPC of both layers, varying within 10% in different years, did not show similar dynamics.

Table 2. *p*-values for difference between the TPC of the moss and herb–shrub layers at selected kerosene loads. Statistically significant values ($p < 0.05$) are marked in red.

Time after Pollution	100 + 25 g/kg	10 + 5 g/kg	5 + 1 g/kg	1 + 0 g/kg
3 days	0.676923	0.250399	0.054665	1.000000
30 days	0.005075	0.005075	0.006486	0.522817
90 days	0.005075	0.004408	0.004625	0.270032
365 days	0.006118	0.004625	0.004847	0.581294
720 days	0.521840	0.004408	0.045328	1.000000

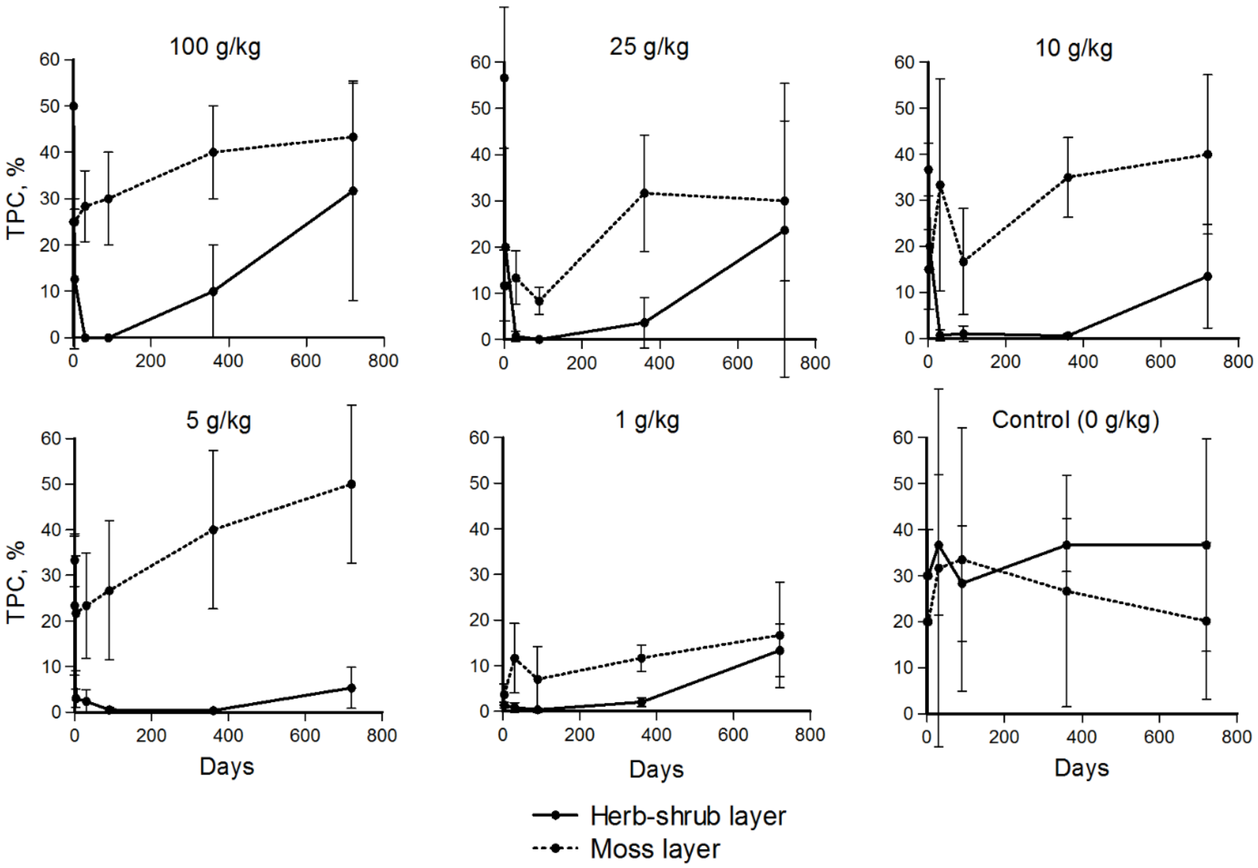

Figure 3. Average values of the TPC of the herb–shrub and moss layers at the experimental quadrats in the forest phytocenosis. The whiskers indicate standard deviation. The connecting lines were added to simplify visual perception and do not carry information about the specific values of TPC in the intermediate stages. Statistical differences are presented in Table 2.

For the raised bog community, there was also no observed negative effect on the TPC of the moss layer. In sphagnum mosses, 3 days after kerosene application, only a bleaching of lateral branches in the upper parts of the shoots was noted, presumably associated with the death of photosynthetic cells in the leaves. Nevertheless, at the same doses, the green coloration of the moss cover was restored after 1 month. There were no visible changes in the TPC of the moss layer, and after one and two years, the moss cover of the quadrats, even at a dose of 100 g/kg, was not visually different from the moss cover of the unaffected areas (see Figure S2). At the same time, the TPC of the herb–shrub layer in the bog community decreased markedly for all doses (Figure 4), which suggests that the moss layer of both communities is significantly more stable compared to the herb–shrub layer.

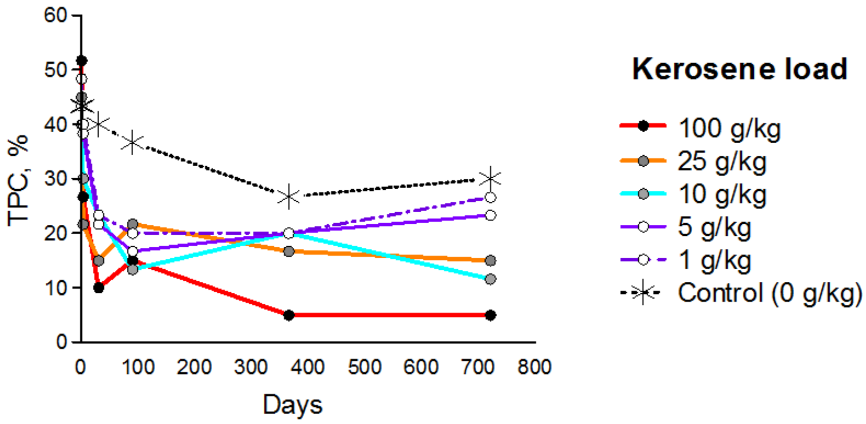

Figure 4. Changes in the TPC of the herb–shrub layer on experimental quadrats in the bog phytocenosis.

3.3. Dynamics of the Dominant Species Cover

The dominant species of the herb–shrub layer of the mixed forest proved to be weakly resistant to any kerosene application. One month after applying kerosene, the vast majority of the individuals at both sites died (Figure 5). The most rigid axial fragments of *Athyrium filix-femina* fronds were preserved only at low (up to 5 g/kg) kerosene doses. No *A. filix-femina* was observed for the second growing season (except for a single new individual in one of the quadrats with a dose of 5 g/kg). *A. filix-femina* only began to recover at doses of up to 25 g/kg only 2 years after kerosene application (Figure S1 and Table S1).

Shoots of *Ajuga reptans* were even more vulnerable to kerosene exposure compared to *Athyrium filix-femina*, because, 1 month after the beginning of the experiment, all individuals in the quadrats with kerosene exposure died. At the same time, during the second growing season, new individuals appeared in some quadrats (100 g/kg and 25 g/kg), and the species coverage recovered up to 100% of the original (Figure S1). It should be noted that all new individuals emerged through vegetative propagation using above-ground stolons from off-site mother plants. In doing so, they retained the connection of their vascular system with the mother plant outside the quadrat, which probably allows them to avoid the phytotoxic effects of kerosene without rooting in the contaminated soil. Meanwhile, 2 years after kerosene exposure, bugle coverage continued to grow (reliably for all doses, $p = 0.027$; Figure 5) in proportion to the increase in kerosene load applied. The success in the colonization of the sites by the above-ground stolons of *A. reptans*, probably, first of all, should be associated with the absence of competition with other vascular plants at high doses of the pollutant.

In the raised bogs, large, erect, woody shrubs of the Ericaceae family (*Ledum palustre* and *Chamaedaphne calyculata*) were more resistant to the effects of kerosene. The phytotoxic effect of kerosene was manifested by the leaves' tissue necrosis (see Figure 2), the partial defoliation of shoots for 1–3 months and the preservation of the viability of individuals, even under maximum exposure doses. Many partially damaged leaves remained on the plants until the end of the growing season. For the second and third vegetation seasons of the experiment, the shrubs remained viable and formed a cover in the range of 40%–100% of their original (Figure S2). At the same time, judging by the dynamics of the TPC of the control quadrats, the observed decrease in TPC can largely be attributed to the difference in weather conditions of the two different growing seasons (Table 1).

Vaccinium oxycoccos, having thinner creeping shoots, unlike the two other considered species of the Ericaceae family, is more vulnerable to the effects of kerosene: any exposure caused chemical burns and defoliation. At the same time, at low doses (from 1 to 10 g/kg) in the first year of the experiment, the individuals did not die; viable buds were preserved and continued to grow one month after kerosene application. At the same time, the projective coverage was in inverse relation to the kerosene doses applied. One year later, a few individuals of *V. oxycoccos* were noted only on sites with a dose of up to 5 g/kg, and 2 years later, on all sites, but with a relatively low projective coverage, which was close to the background (control) levels only at a dose of 1 g/kg.

Eriophorum vaginatum, the only herbaceous plant among the dominant herb–shrub layer in the raised bog, is the least resistant to the effects of kerosene among bog plants. The introduction of any dose of kerosene causes the death of individuals. At the same time, during the vegetation season, new shoots appeared on the sites with doses of 1 to 10 g/kg. At the same exposure doses, the projective cover partially recovered 2 years after kerosene application (Table S1).

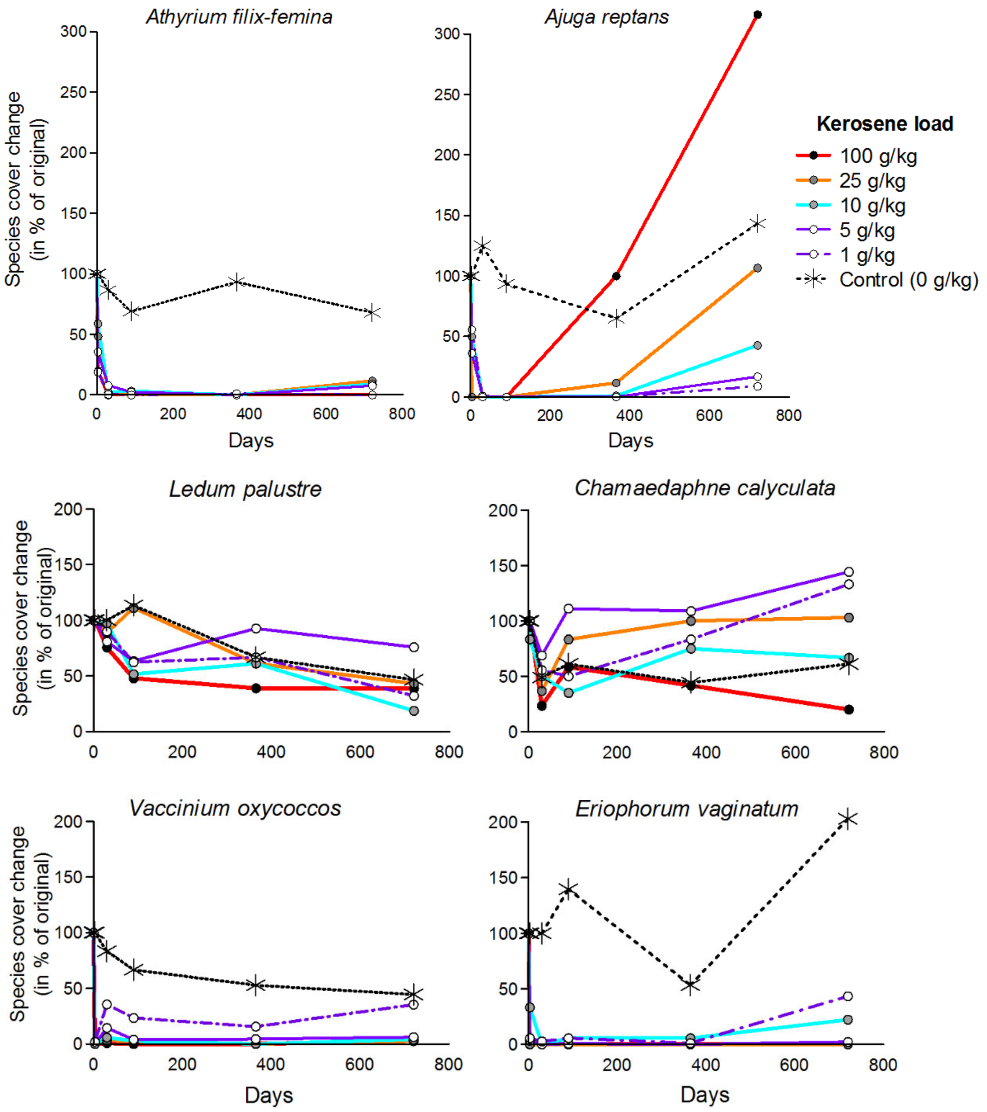

Figure 5. Changes in projective cover for the dominant species of the herb–shrub layer in the mixed forest (**up**) and in the raised bog (**middle** and **down**) during the experiment.

4. Discussion

Our previous study [16] characterized the effect produced by applying different doses of kerosene to plants in the southern taiga of the Russian Far East. In spite of the considerable difference in the flora of the regions considered, it is possible to identify general trends in the response of plants to volatile hydrocarbon fuels. First of all, in both cases, the low resistance of ferns to kerosene (*Pteridium pinetorum* and *Athyrium filix-femina*) was observed in the forest communities. In contrast, the bog communities were characterized by the relatively higher resistance of woody shrubs of the Ericaceae family (*Vaccinium* *uliginosum*, *Ledum palustre* and *Chamaedaphne calyculata)*, some of which even tolerate the maximum dose exposure of kerosene (100 g/kg or more). Both for the Far East and for Eastern European Russia, a high resistance of the moss cover to the effects of kerosene was also shown. Thus, the hypothesis of a similar response of ecologically, taxonomically and biomorphologically similar plant species of the two regions can be considered confirmed. At the same time, the present study allowed us to clarify the threshold levels of exposure causing significant deviations in the coverage of the studied species. If for the southern taiga of the Far East, where mixed forest, deciduous forest, sedge fen and wet meadow sites were studied, the obtained values lay in the range from 5 to 25 g/kg, then according to the data obtained in the present study, we can assume that, for species of the herb–shrub layer of the Southern Taiga of East European Russia, the threshold dose of kerosene is 1–5 g/kg in forest communities and 5–10 g/kg in bog communities. We consider 5 g/kg as an average threshold level of pollution that does not threaten species growth in the short and long term, with possible variation in both directions for more sensitive and resistant species.

In the herb–shrub layer, kerosene mainly affects herbaceous plants. Our experiment showed that fern *A. filix-femina* is very susceptible to kerosene, which is consistent with previous assumptions about the low resistance of ferns to hydrocarbon pollution [16] and the proposal of their possible use as bioindicators for a given pollutant in forest communities. Both studies show that ferns disappear from forest communities even at low levels of kerosene pollution. Moreover, *A. filix-femina* is probably less resistant to kerosene compared to *Pteridium pinetorum*, since *Pteridium* plants recovered at doses of 1 and 5 g/kg one year after the application of pollutant. For the raised bog community, the most pronounced response to kerosene application potentially allowed us to consider *Eriophorum* as a bioindicator in cases of petroleum product pollution. Shrubs in the raised bog are more resistant to kerosene and thus less acceptable as bioindicators; this is consistent with the previously obtained data on the relatively high resistance of shrubs of the Ericaceae family to kerosene exposure [16].

The results obtained are consistent with some literature data on the effects of petroleum products on plants in natural conditions. For example, Walker et al. [17] showed that tundra communities in wet habitats recover faster after exposure to diesel fuel in contrast to communities in drier areas. Walker et al. also noted high shrub viability under hydrocarbon pollution, consistent with the observed resilience of *Ledum palustre* and *Chamaedaphne calyculata* at experimental quadrats in raised bog. The potential to use ferns as bioindicators of hydrocarbon pollution can be indirectly compared with the already known data on the possible use of ferns (including *Athyrium filix-femina*) as bioindicators of soil pollution by heavy metals [30–32].

Microbiome studies conducted in conjunction with the present study suggest that the plant community recovers slower after exposure to kerosene than the soil microbiota. For example, the cellulosolytic activity of Albic Retisols, as measured under laboratory conditions in soil samples from the same sites, was restored to background values within a year after exposure to doses of up to and including 10 g/kg, which is most likely due to the evaporation and biodegradation of kerosene [26]. The composition of the soil microbiome in the forest community at a load of 5 g/kg in one year did not manage to recover to background values, whereas in the bog community, it recovered in 6–12 months even at high kerosene doses [7]. The slower recovery of vegetation relative to the microbial community can be explained not only by the slower cycles of plant development and reproduction, but also by the relationship between plants and soil microbiota. It is generally assumed that there is a two-way positive relationship between plants and bacteria during the phytoremediation of oil pollution: on the one hand, plants stimulate microbiological activity and, on the other hand, plant-associated microorganisms under these conditions reduce environmental harshness for plants and improve their growth [33,34]. The results of this work, on the one hand, support the relationship between microbiome and vegetation recovery after hydrocarbon fuel pollution, but, on the other hand, lead us to think about the priority role of one of the components of ecosystems in this process.

5. Conclusions

Our results show that kerosene cannot be considered as a safe substance for plant communities of the southern taiga. Even two years after treatment, the composition of the plant communities (especially at high loads) differed from the initial one, which we indicate as a 'kerosene label'. Kerosene pollution should be taken into account when conducting soil ecological monitoring.

In the considered forest and bog communities of the southern taiga of the East European Plain, the sensitivity of species to kerosene decreases from herbaceous plants (*Athyrium filix-femina, Ajuga reptans* and *Eriophorum vaginatum*) and shrubs with woody shoots (*Ledum palustre, Chamaedaphne calyculata* and to a lesser extent *Vaccinium oxycoccos*) to the most resistant mosses (*Sphagnum* spp., *Atrichum undulatum* and *Plagiomnium undulatum*). In a forest community, whose herb–shrub layer is composed mainly of herbaceous plants, kerosene application leads to the death of individuals already at minimum application doses, and the recovery of vegetation is actively seen only in the third growing season (2 years after pollution) for all doses. The bog community, dominated by shrubs, is generally more resistant to the effects of kerosene, although the projective cover of plants is slower to recover, which may be due to the edaphic conditions of bogs, not allowing rapid growth even in the absence of pollution as a limiting factor.

The results of the present study allow us to assume that the average threshold level of pollution, which causes significant consequences for forest and bog plant communities, is a kerosene load of 5 g/kg of soil. Our data can be applied in the environmental monitoring of hydrocarbon pollution, in assessing the environmental impact of fuel and energy complex facilities, and in predicting the environmental risks of possible accidents. However, it should be taken into account that, under different climatic and edaphic conditions, the response of plant species to hydrocarbon fuel pollution may differ.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f14050873/s1. Figure S1: Dynamics of plant conditions in the experimental quadrats in the forest community at maximum kerosene doses (100 g/kg), average doses (10 g/kg) and the control: 1—before treatment; 2—first vegetation season (1 month after application); 3—second vegetation season (1 year after application); and 4—third vegetation season (2 years after application). Figure S2: Dynamics of plant conditions in the experimental quadrats in the bog community at maximum kerosene doses (100 g/kg), average doses (10 g/kg) and the control: 1—before treatment; 2—first vegetation season (1 month after application); 3—second vegetation season (1 year after application); and 4—third vegetation season (2 years after application). Table S1: Characteristics of species recovery in the experimental quadrats.

Author Contributions: S.A.L.: Conceptualization; Data curation; Formal analysis; Investigation; Visualization; and Writing—original draft. I.N.S.: Investigation; and Writing—review and editing. T.V.K.: Conceptualization; Funding acquisition; Supervision; Project administration; and Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data are available upon request.

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. Haider, F.U.; Ejaz, M.; Cheema, S.A.; Khan, M.I.; Zhao, B.; Liqun, C.; Salim, M.A.; Naveed, M.; Khan, N.; Núñez-Delgado, A.; et al. Phytotoxicity of petroleum hydrocarbons: Sources, impacts and remediation strategies. *Environ. Res.* **2021**, *197*, 111031. [CrossRef]
2. Zahermand, S.; Vafaeian, M.; Bazyar, M.H. Analysis of the physical and chemical properties of soil contaminated with oily (petroleum) hydrocarbons. *Earth Sci. Res. J.* **2020**, *24*, 163–168. [CrossRef]
3. Fallah, M.; Shabanpor, M.; Zakerinia, M.; Ebrahimi, S. Risk assessment of gas oil and kerosene contamination on some properties of silty clay soil. *Environ. Monit. Assess.* **2015**, *187*, 437. [CrossRef]
4. Yazdi, A.; Sharifi Teshnizi, E. Effects of contamination with gasoline on engineering properties of fine-grained silty soils with an emphasis on the duration of exposure. *SN Appl. Sci.* **2021**, *3*, 704. [CrossRef]
5. Gałązka, A.; Grządziel, J.; Gałązka, R.; Ukalska-Jaruga, A.; Strzelecka, J.; Smreczak, B. Genetic and Functional Diversity of Bacterial Microbiome in Soils with Long Term Impacts of Petroleum Hydrocarbons. *Front. Microbiol.* **2018**, *9*, 1923. [CrossRef] [PubMed]
6. Korotkevych, O.; Josefiova, J.; Praveckova, M.; Cajthaml, T.; Stavelova, M.; Brennerova, M.V. Functional adaptation of microbial communities from jet fuel-contaminated soil under bioremediation treatment: Simulation of pollutant rebound. *FEMS Microbiol. Ecol.* **2011**, *78*, 137–149. [CrossRef] [PubMed]
7. Shelyakin, P.V.; Semenkov, I.N.; Tutukina, M.N.; Nikolaeva, D.D.; Sharapova, A.V.; Sarana, Y.V.; Lednev, S.A.; Smolenkov, A.D.; Gelfand, M.S.; Krechetov, P.P.; et al. The influence of kerosene on microbiomes of diverse soils. *Life* **2022**, *12*, 221. [CrossRef]
8. Ali, M.F.; M-Ridha, M.J.; Taly, A.H. Phytotoxicity test of kerosene-contaminated soil using barley. *Iraqi J. Agric. Sci.* **2020**, *51*, 376–391. [CrossRef]
9. Buluktaev, A.A. Phytotoxicity of Oil-Polluted Soils in Arid Territories: Analyzing Results of Simulation Experiments. *Russ. J. Ecosyst. Ecol.* **2019**, *4*. [CrossRef]
10. Cherniak, L.; Mikhyeyev, O.; Madzhd, S.; Lapan, O.; Korniienko, I.; Dmytrukha, T. The Usage of Plant Test Systems for the Determination of Phytotoxicity of Contaminated with Petroleum Products Soil. *J. Ecol. Eng.* **2021**, *22*, 66–71. [CrossRef]
11. Igboama, W.N.; Ugwu, N.U. Laboratory Evaluation of the Impact of Contaminants on Soil Resistivity and the Consequent Effect on Plant's Growth. *J. Environ. Prot.* **2016**, *7*, 1802–1809. [CrossRef]
12. Kim, K.D. Effects of diesel and kerosene on germination and growth of coastal wetland plant species. *Bull. Environ. Contam. Toxicol.* **2014**, *93*, 596–602. [CrossRef]
13. Potashev, K.; Sharonova, N.; Breus, I. The use of cluster analysis for plant grouping by their tolerance to soil contamination with hydrocarbons at the germination stage. *Sci. Total Environ.* **2014**, *485–486*, 71–82. [CrossRef] [PubMed]
14. Sharonova, N.; Breus, I. Tolerance of cultivated and wild plants of different taxonomy to soil contamination by kerosene. *Sci. Total Environ.* **2012**, *424*, 121–129. [CrossRef]
15. Koroleva, T.V.; Krechetov, P.P.; Semenkov, I.N.; Sharapova, A.V.; Lednev, S.A.; Karpachevskiy, A.M.; Kondratyev, A.D.; Kasimov, N.S. The environmental impact of space transport. *Transp. Res. Part D Transp. Environ.* **2018**, *58*, 54–69. [CrossRef]
16. Lednev, S.A.; Semenkov, I.N.; Klink, G.V.; Krechetov, P.P.; Sharapova, A.V.; Koroleva, T.V. Impact of kerosene pollution on ground vegetation of southern taiga in the Amur Region, Russia. *Sci. Total Environ.* **2021**, *772*, 144965. [CrossRef]
17. Walker, D.A.; Webber, P.J.; Everett, K.R.; Brown, J. Effects of Crude and Diesel Oil Spills on Plant Communities at Prudhoe Bay, Alaska, and the Derivation of Oil Spill Sensitivity Maps. *ARCTIC* **1978**, *31*, 242–259. [CrossRef]
18. Hutchinson, T.C.; Freedman, W. Effects of experimental crude oil spills on subarctic boreal forest vegetation near Norman Wells, N.W.T., Canada. *Can. J. Bot.* **1978**, *56*, 2424–2433. [CrossRef]
19. Webb, J.W.; Alexander, S.K.; Winters, J.K. Effects of autumn application of oil on *Spartina alterniflora* in a Texas salt marsh. *Environ. Pollution. Ser. A Ecol. Biol.* **1985**, *38*, 321–337. [CrossRef]
20. Holt, S. The effects of crude and diesel oil spills on plant communities at Mesters Vig, northeast Greenland. *Arct. Alp. Res.* **1987**, *19*, 490–497. [CrossRef]
21. Clarke, P.J.; Ward, T.J. The response of southern hemisphere saltmarsh plants and gastropods to experimental contamination by petroleum hydrocarbons. *J. Exp. Mar. Bio. Ecol.* **1994**, *175*, 43–57. [CrossRef]
22. Racine, C.H. Long-term recovery of vegetation on two experimental crude oil spills in interior Alaska black spruce taiga. *Can. J. Bot.* **1994**, *72*, 1171–1177. [CrossRef]
23. Bay, C. *Effects of Experimental Spills of Crude and Diesel Oil on Arctic Vegetation. A Long-Term Study on High Arctic Terrestrial Plant Communities in Jameson Land, Central East Greenland*; Ministry of Environment and Energy: Copenhagen, Denmark, 1997.
24. Won, H.W.; Pitsch, H.; Tait, N.; Kalghatgi, G. Some effects of gasoline and diesel mixtures on partially premixed combustion and comparison with the practical fuels gasoline and diesel in a compression ignition engine. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2012**, *226*, 1259–1270. [CrossRef]
25. Azeez, O.M.; Akhigbe, R.E.; Ige, S.F.; Saka, W.A.; Anigbogu, C.N. Variability in cardiovascular functions and baroflex sensitivity following inhalation of petroleum hydrocarbons. *J. Cardiovasc. Dis. Res.* **2012**, *3*, 99–103. [CrossRef] [PubMed]
26. Sharapova, A.V.; Semenkov, I.N.; Krechetov, P.P.; Lednev, S.A.; Koroleva, T.V. The Effect of Kerosene Pollution on the Cellulolytic Activity of Albic Retisols and Arenosols (Aridic): A Laboratory Experiment. *Eurasian Soil Sci.* **2022**, *55*, 235–241. [CrossRef]
27. Peel, M.C.; Finlayson, B.L.; McMahon, T.A. Updated world map of the Köppen-Geiger climate classification. *Hydrol. Earth Syst. Sci.* **2007**, *11*, 1633–1644. [CrossRef]
28. Gureeva, I.I.; Page, C.N. The generum Pteridium (Hypolepidaceae) in Northern Eurasia. *Bot. J.* **2008**, *93*, 915–934.

29. Dorokhova, M.F.; Krechetov, P.P.; Koroleva, T.V.; Sharapova, A.V. Algo-Cyanobacterial Communities as Indicators of Soil Pollution with Jet-Fuel. In Proceedings of the II International Scientific and Practical Conference Dedicated to the 105th Anniversary of the Birth of Professor Emilia Adrianovna Shtina "Algae and Cyanobacteria in Natural and Agricultural Ecosystems", Kirov, Russia, 19–23 October 2015; Vyatskaya GSHA: Kirov, Russia, 2015; pp. 118–122.
30. Samecka-Cymerman, A.; Kolon, K.; Stankiewicz, A.; Kaszewska, J.; Mróz, L.; Kempers, A.J. Rhizomes and fronds of *Athyrium filix-femina* as possible bioindicators of chemical elements from soils over different parent materials in southwest Poland. *Ecol. Indic.* **2011**, *11*, 1105–1111. [CrossRef]
31. Chang, J.-S.; Yoon, I.-H.; Kim, K.-W. Heavy metal and arsenic accumulating fern species as potential ecological indicators in As-contaminated abandoned mines. *Ecol. Indic.* **2009**, *9*, 1275–1279. [CrossRef]
32. Della, A.P.; Falkenberg, D.D.B. Pteridophytes as ecological indicators: An overview. *Hoehnea* **2019**, *46*. [CrossRef]
33. Gkorezis, P.; Daghio, M.; Franzetti, A.; Van Hamme, J.D.; Sillen, W.; Vangronsveld, J. The Interaction between Plants and Bacteria in the Remediation of Petroleum Hydrocarbons: An Environmental Perspective. *Front. Microbiol.* **2016**, *7*, 1836. [CrossRef] [PubMed]
34. Kuzina, E.; Rafikova, G.; Vysotskaya, L.; Arkhipova, T.; Bakaeva, M.; Chetverikova, D.; Kudoyarova, G.; Korshunova, T.; Chetverikov, S. Influence of Hydrocarbon-Oxidizing Bacteria on the Growth, Biochemical Characteristics, and Hormonal Status of Barley Plants and the Content of Petroleum Hydrocarbons in the Soil. *Plants* **2021**, *10*, 1745. [CrossRef] [PubMed]