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Species Diversity of Plant Communities from Territories Anthropogenically Contaminated with Natural Radionuclides[1]

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Abstract—The diversity of the vascular plant species, which developed during 50 years on iteratively unoccupied territories with enhanced levels of natural radionuclides and heavy metals, was studied. No differences were found in the geographical and ecological structure of plant communities from the antropogenically impacted and reference sites. However, species diversity of the most contaminated plots studied was shown to be lower when compared to the reference and less contaminated sites.

Keywords: natural radionuclides, heavy metals, vascular plant species diversity.

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A sufficient level of species diversity is required for successful performance of ecosystems and the biosphere as a whole (Lebedeva et al., 2002). The appearance of terrestrial ecosystems is determined by climate, soil and plants, where the vegetation type is formed by vascular plants. The impact of any environmental stressor on terrestrial plants (Mulder and Breure, 2003) and soil invertebrates (Krivolutsky, 1987) can directly affect the structure and function of an ecosystem (Sienkiewicz, 1986) resulting in decreased primary productivity and degradation of wildlife habitat. Understanding the patterns of self-recovery of the plant communities, which were disturbed because of human activity, becomes especially relevant given the large-scale contamination of ecosystems with toxic heavy metals, artificial and naturally occurring radionuclides (Richards et al., 2008) and other pollutants. Detailed studies exist on the consequences of vegetation destruction as a result of mechanical impact, breakdown in mining operations and aerial anthropogenic contamination (Mironycheva-Tokareva, 1998; Moskalenko, 1999; Ganicheva et al., 2004; Pozolotina et al., 2009, 2013). However, data on formation of vascular plant communities on the radioactively contaminated soils of the north taiga zone in cold climatic conditions are practically lacking (Gruzdev et al., 1971).

The goal of the investigation was to study the diversity of vascular plant species in the anthropogenically contaminated area and to identify its interrelation with the level of disturbance of these areas.

MATERIALS AND METHODS

The diversity of plant species on the territory with enhanced levels of natural radionuclides in soil in the vicinity of Vodny settlement (Komi Republic, Russia) was studied. The commercial extraction of radium, storage of the uranium mill tailings and radium production wastes took place in this area between the 1930s and 1950s (Ievlev, 2011). The study area is situated in the north taiga subzone, and covers the lower course of the Ukhta River. Three experimental sites, which differ in level of anthropogenic impact and spectrum of basic pollutants, were investigated. Reference sites were chosen from outside of the zone influenced by the radiochemical plant zone, but with similar ecological conditions.

Soil samples (0–20 cm depth) were collected from all four corners and the center of a 1 m^2 sample plot (GOST 17.4.4.02-84; GOST R 53123-2008). Physical-chemical analysis of soil samples was performed in the laboratories of the Institute of Biology "Ecoanalyt" (accreditation certificate GOST RU.0001.511257). Radionuclide migration and radiochemistry were analyzed in the same laboratory (accreditation certificate CAPK RU.0001.441623).

Floristic analysis was based on lists of species from 27 geobotanical descriptions, made at natural vegetation sites with background and enhanced levels of

[1] The article was translated by the authors.

Table 1. Concentration of chemical substances and elements in soil (0–20 cm layer) of the study sites

Indexes	Sampling plots								
	s1–s3	s4–s6	s7–s9	z1–z3	z4–z6	k1–k3	k4–k6	k7–k9	k10–k12
Humus, %	11.8 ± 0.1	9.3 ± 3.1	7.2 ± 0.2	2.9 ± 1.3	6.4 ± 2.3	5.7 ± 1.9	7.5 ± 1.0	2.9 ± 0.2	7.1 ± 1.3
NO_3^-	3 ± 2	10 ± 4	1 ± 0.1	11 ± 3	15 ± 7	9 ± 8	3 ± 2	2 ± 1	14 ± 7
PO_4^{3-}	1.7 ± 1.2	3.0 ± 0.7	1.8 ± 1.5	2.2 ± 0.1	1.5 ± 0.8	0.6 ± 0.3	0.9 ± 0.3	1.1 ± 0.2	4.8 ±1.8
K^+	21 ± 7	29 ± 5	290 ± 165	10 ± 6	23 ± 13	7 ± 2	8 ± 2	5 ± 1	31 ± 7
Ba^{2+}	314 ± 138	590 ± 120	4600 ± 2000	77 ± 20	148 ± 77	64 ± 10	55 ± 4	63 ± 5	160 ± 17
Ca^{2+}	90 ± 12	71 ± 8	3900 ± 2200	18 ± 7	582 ± 260	64 ± 12	63 ± 13	21 ± 4	23 ± 4
Cl^-	6 ± 1	6 ± 1	150 ± 84	2 ± 1	5 ± 1	3 ± 16	6 ± 2	4 ± 1	6 ± 1
SO_4^{2-}	21 ± 3	29 ± 15	11000 ± 6000	11 ± 4	30 ± 7	13 ± 1	15 ± 1	20 ± 10	32 ± 7
F^-	0.8 ± 0.5	1.0 ± 0.6	9.1 ± 8.1	0.4 ± 0.1	0.5 ± 0.3	0.9 ± 0.3	0.6 ± 0.3	0.6 ± 0.1	0.6 ± 0.2
Z_c	39 ± 10	59 ± 11	599 ± 286	3 ± 2	45 ± 23	3 ± 2	4 ± 3	3 ± 2	36 ± 9

All data presented are in mean values with error.

chemical pollutants in the soil. All vascular plants present in 100 m^2 meadow plots were recorded and the percentage cover of each plant species within the plot and the whole area was visually estimated. Each species was assigned a life form according to Raunkiær (Bikov, 1978) and a geographical and ecological group according to the regional classification (Martynenko and Gruzdev, 2008). Plant species richness was measured as the sum of all species identified in each plot and by Shannon diversity index calculations (Lebedeva et al., 2002).

Geobotanical plots were chosen on similar relief elements with approximately equal light and thermal conditions. The Ramensky moisture scale was used to assess water availability for plant communities (Ramensky et al., 1965). Total index of landscape contamination (Z_c) was calculated based on heavy metal concentrations in soil samples (Revitch et al., 1982). It was used to characterize the ecological state of the territory by the degree of complex soil contamination with chemical elements of hazard classes I (Hg, Cd, Pb, Zn, As) and II (Cu, Ni, Cr, Co, Mo).

Methods of descriptive statistics and Mann—Whitney U-test was used to process, analyze and interpret data obtained. Routine statistical analysis was performed with the STATISTICA 7.0 software (StatSoft Inc., 2006).

RESULTS AND DISCUSSION

Sampling plots s1–s9, which were chosen for geobotanical description, are located on the unequipped waste storage cell territory. Increased levels of chlorides, sulphates, barium and mineral salts in anthropogenically modified soil (Geraskin et al., 2007) resulted from the spills of radium-containing stratal water on the area and side effects of the technological process. The stratal water also had high levels of manganese, lead, calcium and some other elements. Storage of modified rocks with high activity concentration of ^{238}U and its decay products on the territory studied had resulted in increased levels of fluorides and other heavy metals associated with uranium minerals (Ievlev, 2001). The territory was covered with a mixture of sand and gravel in the beginning of the 1960s in order to deactivate the sites. But even after the deactivation of γ-radiation the air dose rate was reaching 3000 μR/h (30 μSv/h) and higher (Geras'kin et al., 2007) owing to the unequal lateral distribution of natural isotopes and different thickness of the sand and gravel layer.

The intensive recovery of the site with grass started after deactivation. The high relief area is currently covered with cereal-herbaceous and the water-logged first floodplain terrace area—with sedge-herbaceous plant communities. The three sites located on the second floodplain terrace (sampling plots s1–s3), its slope (s4–s6) and the first floodplain terrace (s7–s9) were selected for the investigation due to the features of relief. Anthropogenically modified Albeluvisol soils of the sampling plots are characterized by high concentrations of SO_4^{2-} (Table 1), Ba^{2+}, heavy metals and natural radionuclides of the uranium-238 series (Table 2). The dose rates of γ-radiation in the air range from 0.57 to 1.60 μSv/h (Table 2).

Sampling plots z1–z6 are located on the territory of the former radium production plant and are characterized by a lower level of anthropogenic impact. Soil contamination here is caused by chemical components of the stratal water and its by-products (Gruzdev et al., 1971). Phytocenoses of the z1–z3 sampling plots are formed on shallow Albeluvisol soils and represent a herb meadow. Deactivation with a mixture of

Table 2. Specific activities of the main doseforming radionuclides in soil (0–20 cm layer) of study sites and the γ-radiation air dose rates

Specific activity, Bq/kg	Sampling site								
	s1–s3	s4–s6	s7–s9	z1–z3	z4–z6	k1–k3	k4–k6	k7–k9	k10–k12
^{238}U	22 ± 3	34 ± 4	102 ± 12	5 ± 1	12 ± 3	8 ± 1	8 ± 1	13 ± 2	9 ± 1
^{230}Th	543 ± 35	1300 ± 90	3030 ± 190	43 ± 3	153 ± 13	19 ± 1	18 ± 1	36 ± 3	22 ± 3
^{226}Ra	1690 ± 110	5080 ± 340	6940 ± 480	219 ± 30	870 ± 420	31 ± 6	28 ± 6	16 ± 4	48 ± 6
^{210}Po	1600 ± 140	3180 ± 280	5440 ± 470	184 ± 16	264 ± 134	134 ± 12	151 ± 13	66 ± 6	160 ± 14
^{210}Pb	120 ± 10	309 ± 27	1264 ± 110	37 ± 3	357 ± 167	37 ± 3	78 ± 7	46 ± 4	60 ± 5
^{232}Th	5.1 ± 0.5	7.5 ± 0.8	10.0 ± 0.9	1.5 ± 0.1	6.8 ± 1.5	0.8 ± 0.1	6.0 ± 0.6	10.0 ± 0.9	8.7 ± 0.8
^{228}Th	6.5 ± 0.6	6.1 ± 0.6	5.0 ± 0.4	1.7 ± 0.1	9.4 ± 3.0	5.7 ± 0.5	5.6 ± 0.5	8.5 ± 0.8	7.2 ± 0.6
γ-radiation air dose rate, μSv/h	0.57 ± 0.04	1.2 ± 0.1	1.6 ± 0.1	1.0 ± 0.2	1.5 ± 0.4	0.11 ± 0.01	0.11 ± 0.01	0.11 ± 0.01	0.14 ± 0.01

All data presented are in mean values with error.

sand and gravel was also made here, as on other investigated sites. The current air dose rate of γ-radiation is 0.99 ± 0.02 μSv/h. Levels of mineral salts, heavy metals and natural radionuclides in upper soil layer at the site are lower as compared with the territory of radioactive wastes storage cell (Tables 1 and 2).

Sampling plots z1–z6 are located in the flood of the Ukhta and the Tchut rivers. After the closure of radium production, the γ-radiation air dose rate reached up to 8000 μR/h (80 μSv/h) in several places. The soil and gravel mixture layer allowed to decrease it up to 50–250 μR/h (0.5–2.5 μSv/h) on average (Gruzdev et al., 1971). The current γ-radiation air dose rate is 1.5 ± 0.4 μSv/h (Table 2). Increased concentrations of barium and calcium in the Umbric Fluvisols soils (Table 1) resulted from both spills of stratal water, and features of the ^{226}Ra extraction processes. The plant community of the studied sampling plots is characterized as herbaceous-cereal.

The rationale for choosing reference sites included their similarity with the contaminated sites in edaphotopic and ecological conditions, and floristic composition. The reference sites, as well as radioactively contaminated ones, underwent mechanical anthropogenic transformation, which resulted in the disappearance of natural plant cover. But there were no industrial activities here which could cause radioactive and chemical contamination of soil. The natural restoration of the plant cover resulted from the overgrowth with common grassland species and undesirable plants from adjacent areas. Reference sampling plots are located 300–700 m from the settlement. Soils of k1–k6 sampling plots are Umbric Albeluvisols and of k7–k12—Umbric Fluvisols. Geochemical background of the reference sites is in line with the regional values (Beznosikov et al., 2007; *Atlas*..., 2010), except the insignificant increase in Ba concentration in soil of the k10–k12 plots (Table 1), that is likely caused by its proximity to the radioactive waste storage cell. The average value of γ-irradiation dose rate in the air does not exceed 0.14 μSv/h, which is typical for the region (Table 2).

Deactivation of the radioactively contaminated areas with a mixture of sand and gravel has completely destroyed the pre-existing plant communities. Intensive recovery of plant cover has started in the first years after deactivation. It was a result of natural overgrowing with species typical for physiographic and climatic conditions of the area, which came within a deactivating mixture and expansion of the adjacent meadow communities (Gruzdev et al., 1971). Revegetation studies, which started just after the deactivation (Gruzdev et al., 1971) show that weeds and ruderal species (*Matricaria inodora*, *Cirsium setosum*, *Erysimum cheiranthoides*, *Tussilago farfara* and others) were the first to inhabit the available area. Then the abundance and diversity of the pioneer and weed plants decreased and some of them were replaced by meadow species. So if eight years after the deactivation 50% of species' list consisted of undesirable and adventitious plants (Gruzdev et al., 1971), nowadays their part on the same site has decreased up to 8.4 ± 1.6% and this value does not differ from that of a reference site (8.1 ± 1.4%). The proportion of undesirable plants is still high at the z1–z3 sampling plots (30.9 ± 2.7%) which are characterized by the similar genesis of the contamination. It is supposed that the prevalence of undesirable plants in the community indicates (Ganicheva et al., 2004) an on-going anthropogenic impact and is caused by the proximity to the settlement and roads. The proportion of undesirable plants on the most contaminated territory of the radioactive waste storage cell (16.6 ± 2.0%) is higher than the reference value. The storage cell territory has been isolated from mechanical urban exposure for last decades, which decreases anthropogenic pressure on the area, but limits the introduction of

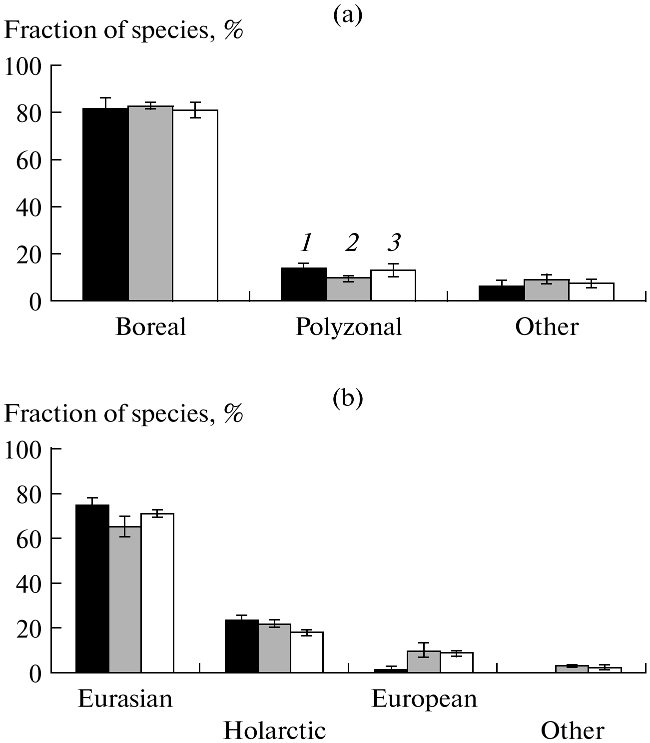

Fig. 1. Geographical structure of species composition of the vascular plants on sites with enhanced and background levels of natural radionuclides in soil. (a) Latitude, (b) longitude groups; here and after: (*1*) sampling plots s1–s9; (*2*) z1–z6; (*3*) k1–k12.

seeds of meadow plants from the neighboring area. In addition, industrial wastes are uncovered in some places due to erosion, and the topsoil layer is poor with nutrients.

The geobotanical mapping identified 95 vascular plant species from 27 families on all sampling sites studied. The greatest species richness was seen for Asteraceae and Rosaceae (14 species from 11 generas both) and Poaceae (12 species from 11 generas) families which is common for the whole investigated region (Martynenko et al., 2006). Permanent grasses are typical for meadows of the north taiga subzone studied due to their ability for vegetative propagation. The Fabaceae and Ranunculaceae families have lower diversity; they unify 5 genera each and include 9 and 6 different species correspondingly. Nevertheless, they both play an important role in meadow plant communities. Representatives of Fabaceae family do not require nitrogen-containing compounds in the soil. They also have a deeply penetrating root system, which allows them to get mineral substances from a greater volume of soil. Other families from the geobotanical species list included 1–5 species.

The list of species of the reference sampling plots has 65 vascular plant species. The list of species from the territories of former radiochemical plants included 56 vascular plant species. Plots located on the meadow part of the radioactive waste storage cell territory have the lowest species diversity: only 39 vascular plant species were identified here. Perennial herbs were the dominant plant type on both sites with enhanced levels of chemical pollutants and radionuclides and on the reference site due to the absence of agricultural activity on the territory and its climate conditions, including frost penetration of the soil up to 60–100 cm depth. The species list only includes three annual species: *Rhinanthus vernalis*, *Berteroa incana* and *Spergularia rubra*. The expansion of arboreal species in vegetation (from Salix, Betula, Picea and Pinus genera) was noted at both the contaminated, and the reference sites.

Geographical analysis of the species shows predominance of boreal species within the latitude group (Fig. 1a) which is typical for the north taiga communities on all the territories studied. On the territory of radioactive waste storage cell, 80.5 ± 4.5% of species referred to that group; 82.5 ± 0.9 and 80.5 ± 3.1%—on the former radiochemical plant and reference sites correspondently. Species of the polyzonal group have a significantly lower part (from 8.9 up to 13.3%) and their projective cover on the sampling plots is minor (1–15%) except for *Cirsium setosum* (17–40%). Such ratio of species with different natural habitats, where boreal species are dominants and edificators in plant communities, is typical for the region (Martynenko et al., 2006). The polyzonal group stands out and is essentially represented by undesirable plants. The part of nemoral and forest-steppe groups in the communities, which have developed in 50 years of succession, is insignificant. Among the longitude groups, 65–75% of species appeared to have a wide eurasian natural habitat (Fig. 1b) and about 20% belonged to the holarctic group which is typical for the flora of the region and is caused by frontier location and close floristic links of northeast European region to the Asia area (Martynenko et al., 2006).

Hereby, the distribution of the vascular plant species in the geographical structure of communities formed up to nowadays, is defined by physiographical conditions of the territory studied and provides evidences of unidirectionality of the succession on both contaminated and reference areas.

The spectra of mesophyte species dominate among the ecological group (Fig. 2a) of the plant communities studied, which reflects the similarity in the ecological conditions and location of sampling plots. Soils of sampling plots are characterized as humid-meadow according to the humidity scale (Ramensky et al., 1965) and the humidity index values vary from 62.9 ± 1.1 up to 74.0 ± 1.0. Those conditions facilitate development of vegetation, which requires sufficient but not excessive amount of water in the soil. Species representing this ecological group are *Dactiylis glomerata*, *Phleum pratense*, *Achillea millefolium*, *Vicia cracca*, *Lathyrus pratensis* and *C. setosum*. They were registered on the sampling plots and are characterized by the maximal projective cover. Some hygrophyte species were also identified (*Geum rivale* and *Filipendula ulmaria*), but their projective cover is low because the permanent excess of humidification of the territory is absent.

Similar species distribution in the ecological group structure was observed on all sampling plots studied. Presence of numerous *Linaria vulgaris* plants on the z1–z3 plots, located in close proximity to the settlement, reflects conditions of the community formed here. Appearance of xeromesophyte ecological group representative in the phytocenose indicates seasonal periods of moisture deficiency, which is likely caused by the mechanical composition of the Albeluvisol soils formed here. A higher portion of the sand fraction in this type of soil as compared with other sampling plots result in its low water-retaining force. This may result in a decrease in the water quantity required for the vital activity of mesophytes in shallow summer time, which is compensated with development of more resistant ecological groups. On the other hand a little higher humidification of the s7–s9 sampling plots resulted in appearance of hygrophytes like *F. ulmaria*, *Carex acuta* and *C. rostrata* in the ecological spectrum of the community; those species are now dominate in the sedge-herbaceous phytocenosis.

Prevalence of some geographical or ecological groups in the plant community structure reflects the particular qualities of vascular plant habitat in relation to some environmental factors, which are important for life activity like light, warmth, humidity and others. Plant life form, according to Raunkiær, is the biological reflection of all the existing ecological factors. Hemicryptophytes united 75–78% of species (Fig. 2b) and dominate in plant communities studied on both radioactively contaminated and reference sites. This group includes the majority of perennial herbs common for the region investigated. The proportions of Hamephytes and Fanerophyres are low, because the meadow communities were studied. Percentage of annual species is also low, which is typical for high latitudes (Martynenko et al., 2006).

Geobotanical studies of plant communities found no differences in geographical and ecological structures of the species inhabiting contaminated and reference sites. Analysis of ecological, biomorphological and geographical structures of species composition of meadow communities formed on deactivated radioactively contaminated territories showed that the majority of species are indicated as boreal (77–82%) vascular plants with Eurasian (64–77%) type of areal, which belong to hemicryptophyte life form (75–78%) with dominating meadow cenosis group. The high portion (43%) of undesirable plants in the community formed on the z1–z3 plots is an exception from the patterns found.

Shannon index calculations indicated a significant ($p < 0.05$) decrease in species diversity on sampling plots s1–s9 of the highly contaminated radioactive

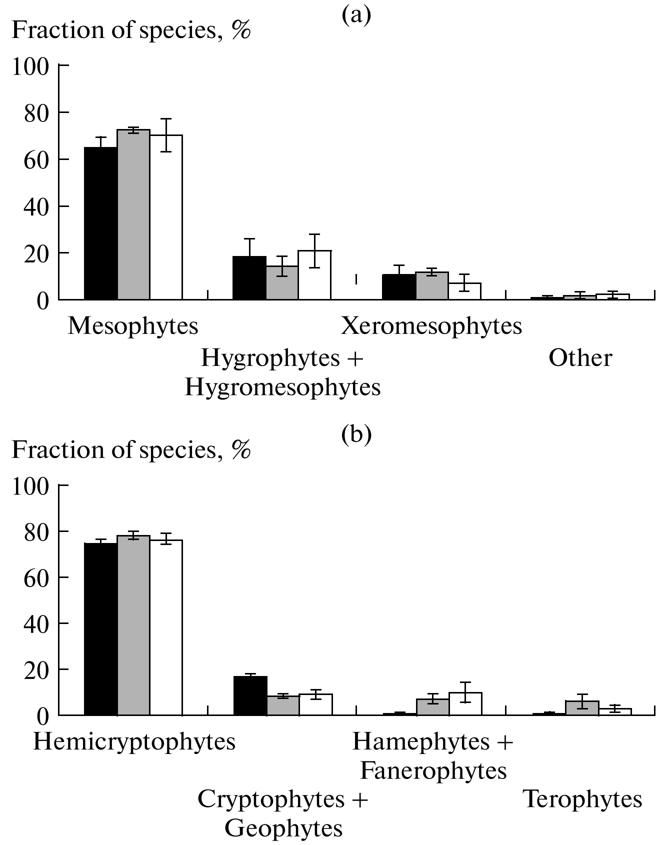

Fig. 2. Ecological structure of species composition of the vascular plants on sites with enhanced and background levels of natural radionuclides in soil. (a) According to the water regime, (b) life forms according to Raunkiær.

waste storage cell. Mean value of the index was 3.06 ± 0.12 as compared to areas of the former radium production plant (z1–z6) and the reference site, which were 3.84 ± 0.17 and 3.82 ± 0.12, respectively. The number of species registered on the sample plots s1–s9 was also decreased (15.4 ± 0.5) whereas the lists from the reference site and the z1–z6 plots contain 22.8 ± 2.2 and 25.3 ± 2.8 species, respectively.

The development of plant communities on the studied territories has not resulted in the formation of a forest ecosystem with pronounced base indicators of climax communities during 50 years of succession. This is due to an initially high anthropogenic impact and the slow biological cycle in the north taiga landscape (Moskalenko, 1999). The distribution of vascular plant species in the structure of phytocenoses, which formed on the impacted territories, provides evidences of succession unidirectionality on both the contaminated landscapes and reference areas (Ganicheva et al., 2004). It appears that the development of plant communities on highly contaminated territories of radioactive waste storage cell is slower as compared to sites with lower levels of contamination. This is despite of a favourable combination of factors like humidity and isolation from mechanical impact. Thus in the absence of additional anthropogenic impact the plant species diversity on the high contaminated sites at Vodny is not likely to differ from adjacent areas in some decades.

The results obtained on species diversity of plant communities from anthropogenically impacted territories are in line with other investigations (Mironycheva-Tokareva, 1998; Moskalenko, 1999; Ganicheva et al., 2004; Pozolotina et al., 2009, 2013). In addition, unique data on 50 years with dynamics of meadow plant cover in the north-east taiga zone of the European part of Russia, and special features of phytocenoses studied, supplement the present knowledge and extend a spectrum of possible oscillating processes in natural development of impacted ecosystems.

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