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Evaluation of Environmental Transformation in Areas of Hydrocarbon Deposits in the North of Western Siberia

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Abstract—The status of the environment in the development area of oil and gas condensate fields (OGCFs) in the north of Western Siberia (the Yamalo-Nenets autonomous okrug (YNAO)) has been evaluated on the basis of long-term investigations (1993–2016). The content of oil hydrocarbons, polycyclic aromatic hydrocarbons, and heavy metals (Cu, Zn, Fe, Pb, Cd, Ni, Co, Cr, Ba, Cd, and Mn) is determined in soils, natural waters, bottom sediments, and indicator plants (*Larix sibirica*, *Betula nana*, *Salix lanata*, *Ledum decumbens*, *Vaccinium vitis-idaea*, *Vaccinium uliginosum*, and *Cladonia alpestris*). Species pleiads, corresponding to the ecological conditions of habitats and the intensity of technogenic impact, are specified with the use of the coefficients of interspecies conjugation of plants. A complex of indicators of the transformation of natural complexes under the effect of oil and gas extraction is proposed.

Keywords: Transformation of the environment, north of Western Siberia, contamination, heavy metals, petroleum products, bioindication

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INTRODUCTION

Tundra geosystems are the most sensitive to technogenic impact. This is determined by severe climatic conditions, high percentage of swamps, low regeneration capability of plant communities, and other factors, resulting in a smaller metabolic rate and activity of biogeochemical processes (Syso et al., 2001; Kapelkina, 2014; Opekunova et al., 2015; *Bioremediation*...., 2008; Barnes and Chuvilin, 2009).

The development of oil and gas condensate fields (OGCFs) in the Yamalo-Nenets autonomous okrug (YNAO) in recent decades is accompanied by various kinds of impact on natural territorial complexes (NTCs) of the north of Western Siberia, including environmental contamination and a direct mechanical impact (Solntseva, 1998; Moskovchenko, 2010; Vodyanitskii et al., 2013; Laverov et al., 2016). Periodic fires, resulting in a significant transformation of tundra and taiga landscapes, become inevitable.

Drilling wells, wellhead equipment, industrial sites, landing areas, motor transport, and various linear objects (access roads, prefabricated pipelines, duct lines, and inhibitor lines) are the main sources of chemical contamination in the areas of OGCFs. Oil products and heavy metals (HMs) are the main pollutants. They penetrate the environment during all kinds of industrial activity, emergency spills and discharges, and motor transportation exploitation (Solntseva, 1998; Syso et al., 2001; Khaustov and Redina, 2006; Moskovchenko, 2010; Opekunov et al., 2012; Vodyanitskii et al., 2013; Essoka et. al., 2006; Banat et. al., 2006; Pinedo et al., 2014).

Chemical contamination as a result of the arrangement of OGCFs is combined with environmental disturbances of different durations (mainly after fires). Various kinds of multifactor impacts result in the development of complicated processes of regeneration successions. Their intensity and direction depend on a combination of external factors, the initial disturbance of the NTCs, and the resistance of landscapes to negative impact.

It is difficult to obtain representative data on the contamination level of the geographical components in difficultly accessible regions of Western Siberia because of the absence of ecological monitoring stations there. In connection with this, elaborating and applying reliable indicators of the environmental status become urgent. Hence, the aim of this work is to reveal the most informative geo- and bioindicators for evaluating the technogenic transformation of NTCs in the affected area of objects of the oil and gas industry.

MATERIALS AND METHODS

The object of investigation is tundra, forest-tundra, and north-taiga geographical components in the area of 30 OGCFs in the Purovskii, Tazovsk, Krasnosel’kup, and Nadym districts of Tumen oblast of the

YNAO (the Nadym–Pur–Taz interfluve). The works were based on a comparative analysis of geographical components located at various distances from contamination sources along the gradient of technogenic stress: undisturbed natural complexes of tundra, forest-tundra, and peat bogs of the Nadym–Pur–Taz interfluve → slightly disturbed NTCs under the effect of local contamination sources of the oil and gas industry (single passages of heavy machines and flare devices) → technogenic-disturbed NTCs in areas of the oil and gas industry (sites of geological exploration works, settling tanks, passages of heavy machines, emergency spills, pipelines) → technogenic-transformed NTCs of infrastructure objects of the oil and gas industry (industrial and shaft drilling sites, oil plants, shift camps, winter roads, filling roads, and sandpits).

The investigation method is described in detail in some works (Opekunov et al., 2012, 2015). Over the period of 1993–2016, we studied more than 1000 test plots and made comprehensive landscape–ecological descriptions, including a detailed characterization of all geographical components. We examined more than 300 water bodies (composition of water and bottom sediments), 56 key soil profiles, and comprehensively characterized the plant cover (layering, synusium composition, species composition, degree of coverage, species abundance (according to the Drude scale), phenological stage, vitality, and other parameters) (*Polevaya geobotanika*, 1976). Special attention was paid to potential sources of technogenic contamination, their disposition, the possible spread of contaminants in the catenary structure of the NTCs, evaluation of environment disturbance, effects of fires, and other aspects. We took samples of natural water, bottom sediments, soils, and plants for chemical analysis. We paid particular attention to widespread and predominating plant species: *Larix sibirica* Ledeb., *Betula nana* L., *Salix lanata* L., *Ledum decumbens (*Ait.) Lodd.ex Steud., *Vaccinium vitis-idaea* L., *Vaccinium uliginosum* L., and *Cladonia alpestris* (L.) Rubh.

The content of HM (Cu, Zn, Fe, Pb, Cd, Ni, Co, Cr, Ba, Cd, and Mn) in soils, bottom sediments, and plants was determined at the Central Laboratory of the Karpinskii All-Russian Research Geological Institute by inductively coupled plasma mass spectrometry (ICP-MS). The content of mobile forms of HMs in soils and bottom sediments was analyzed with the use of ammonium acetate buffer by atomic absorption spectroscopy (AAS) at the Laboratory of Geoecological Monitoring of St. Petersburg State University and the Botanical Institute of the Russian Academy of Sciences. The content of oil hydrocarbons (HCs) and polycyclic aromatic hydrocarbons (PAHs) (16 polyarenes) in water, soils, and bottom sediments was determined at Laboratory I.K.M. Engineering by the fluorimetric method and high performance liquid chromatography, respectively. We also determined HMs, anion–cation composition, nitrogen (in nitrite, nitrate, and ammonium forms), and mineral phosphorus in natural waters.

The species diversity and floristic features of NTCs were evaluated by the nonlinear graphical method of dendrites with the specification of pleiads of closely interrelated species (Terent'ev, 1959; Neshataev, 1987). The interspecies conjugation of 169 plant species was calculated by the Bravais correlation coefficient.

RESULTS

Chemical composition of natural waters. The surface waters of the YNAO are mainly characterized by a hydrocarbonate calcium and hydrocarbonate sodium composition. It is mainly determined by the atmospheric precipitations, which enrich waters with hydrocarbonates; snowmelt waters, containing a large spectrum of substances; and mineralized groundwater. The increased content of sulfates and chlorides is seen in the area where the Upper Pleistocene marine and alluvial–marine deposits are spread.

No changes in the chemical composition of the water of large rivers are revealed at the regional level. At the local level of small rivers, streams, cutoff meanders, and lakes, oil and gas extraction transforms the hydrocarbonate composition of water into a chloride type with the predomination of calcium and magnesium cations. This is mainly seen in small lakes and cutoff meanders near pollution sources. Nevertheless, the concentration of chlorides does not exceed the maximum allowable concentration (MAC) for fishery water and is relatively low when compared to more developed regions of Western Siberia, where the concentration of chlorides averages up to 260 mg/L (Moskovchenko et al., 2017). Within the developed oil and gas fields, the highest concentrations of chlorides and sulfates and water mineralization are allocated to shaft drilling sites, pipelines, and other objects (Fig. 1).

As concerns biogenic substances, the surface waters of license areas are characterized by the predomination of nitrate nitrogen, which is related to oxidation conditions formed in rivers and lakes of these areas. The increased concentration of ammonium nitrogen (to 0.27 mg/L against a background content equal to several hundredths of 1 mg/L) revealed in certain cases is related to the large percentage of bogs and slowed-down organic-matter decomposition.

The trophic status of water bodies, determined as the phosphorus-to-nitrogen ratio (Dmitriev and Frumin, 2004), varies from oligotrophic to eutrophic in the north–south direction. Within the OGCF, the mean N/P ratio varies widely from 3 to 187. In addition to natural regularities, an increase in trophicity is also related to the higher development rate of the OGCF.

The concentration of Ba, Cu, and V in natural water of the OGCF rises near technogenic objects (Fig. 1). High HC concentrations are seen at the sites of stationary facilities, including oil plants, living

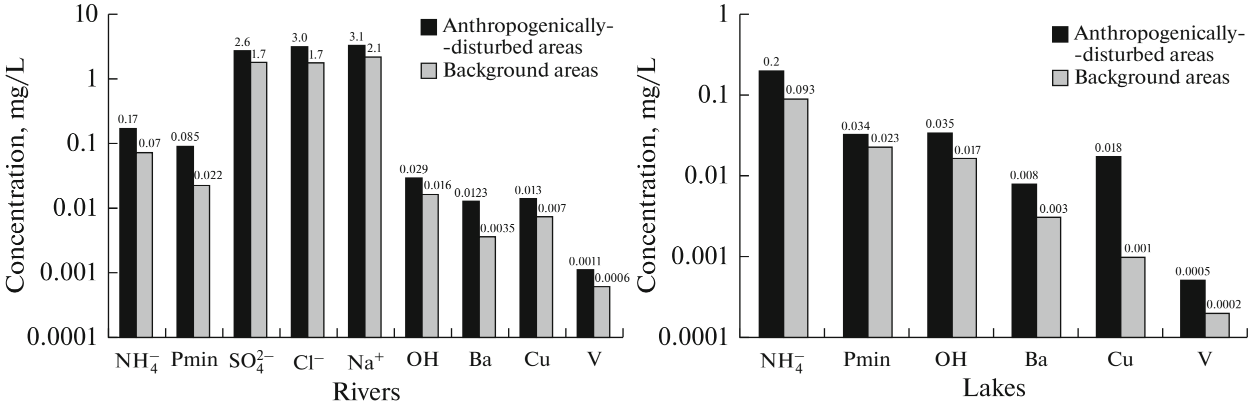


Fig. 1. Content of chemical substances in the surface water of background and disturbed areas.

quarters, and well clusters. Nevertheless, the pollution level is mainly determined by the type of water bodies and the conditions and direction of the runoff in the area. Concentrations of Fe and Mn are not related to technogenic impact and increase in cutoff meanders and zones of rivers with stagnant water characterized by low oxidation potential.

Content of HC and HM in bottom sediments. An investigation of bottom sediments has shown that their chemical composition is mainly determined by ***lithogenic*** and ***facial*** natural factors. The lithogenic factor includes the *sedimentation component*, which reflects the correlation between HM content and granulometric composition of sediments, and the *substance component*, which shows the dependence of HM composition on the underlying Quaternary mountain rocks. The facial factor is related to various accumulation conditions of bottom sediments (alluvial, of cutoff meanders, and lacustrine), the participation of bogs in the landscapes, and latitudinal zonality.

The content of HM in bottom sediments of water bodies in the license areas of the YNAO is mainly determined by their granulometric composition. With respect to the rise in HM content, the specified types of bottom sediments may be arranged in the following series: fine-grained sand < sandy–sludge bottom sediments < mud. For example, the mean content of HMs in mud is 8 (for Fe), 6 (for Mn), 6.5 (for Ni), and 5.5 (for Co) times higher than in fine-grained sands. These data prove the need for an individual analysis of pollution of water bodies for each type of granulometric composition (Table 1).

The analyses of the Upper Pleistocene deposits in the investigated area have revealed the following regularities. The low content of microelements in lacustrine–alluvial, alluvial, and glacial deposits is accompanied by a high content of siderophile (V, Cr, Co, and Ni) and chalcophile (Zn, Cu, and Pb) elements in alluvial–marine clays of the third and fourth sea terraces.

The assessment of the role of the facial factor in the formation of the geochemical structure of bottom sediments has shown the absence of statistically significant differences in HM content in them in rivers, lakes, and cutoff meanders. Nevertheless, the active migration of Fe and Mn is seen in swamped and peaty landscapes of lowlands of the Nadym–Pur–Taz interfluve. These metals are precipitated at the oxidation barrier in the rivers as oxyhydroxides, which results in their very high content in bottom sediments (to 17% for Fe and more than 0.2% for Mn). Therefore, the facial factor mainly exerts an effect on Fe and Mn accumulation, while the distribution pattern of other elements stronger depends on the lithogenic factor.

We evaluated the technogenic factor using a comparison of the chemical composition of bottom sediments of disturbed and background areas. No increase in the mean content of metals under the effect of technogenesis was revealed in any of the three granulometric types of sediments (Table 1). Since the modern contamination level of the area is low, the composition of sediments mainly depends on the substance factor, which reflects the diversity of the Quaternary rocks in the Nadym–Pur–Taz interfluve. Therefore, it may be concluded that the development of hydrocarbon deposits in this region did not exert an effect on the HM content in bottom sediments.

Oil hydrocarbons may be used as a regional indicator of contamination (Table 1). Despite the great dispersion, their content in disturbed landscapes exceeds the background at the level of statistical significance. Polycyclic aromatic hydrocarbons may be use as another reliable indicator. The evaluation of the content of individual PAHs in the bottom sediments of water bodies has shown that they are predominated by naphthalene in contaminated areas (Fig. 2). Its portion averages up to 50% and rises to 90–95% in some samples. Upon heterogenic pollution, the percentage of naphthalene among 16 polyarenes usually does not exceed 7% (Opekunov et al., 2015). Its predomination

Table 1. Content of HM and HC in bottom sediments of water bodies of technogenically disturbed and background areas, mg/kg

	V	Cr	Mn	Co	Ni	Cu	Zn	Cd	Ba	Pb	Fe, %	HC
Mud, peaty silts												
Disturbed areas, *n* = 34	38.2 ± 6.01	34.9 ± 6.19	555 ± 303	7.4 ± 2.03	13.1 ± 2.79	7.3 ± 1.13	27.0 ± 4.42	0.14 ± 0.03	396 ± 48	8.0 ± 0.87	3.2 ± 1.49	449 ± 262
Background areas, *n* = 48	42.7 ± 8.0	40.0 ± 6.9	420 ± 146	9.6 ± 2.21	15.4 ± 2.86	9.3 ± 1.54	32.5 ± 5.35	0.20 ± 0.04	411 ± 59.5	9.2 ± 1.1	2.1 ± 0.47	65 ± 26
Sludge sands												
Disturbed areas, *n* = 32	17.1 ± 3.2	16.6 ± 3.8	137 ± 41	3.1 ± 1.17	4.9 ± 1.52	3.2 ± 0.50	13.1 ± 2.72	0.08 ± 0.02	305 ± 41.9	5.8 ± 0.68	0.74 ± 0.18	203 ± 218
Background areas, *n* = 57	25.7 ± 4.6	22.7 ± 4.2	190 ± 50	4.9 ± 1.6	5.1 ± 1.0	3.8 ± 0.6	17.0 ± 3.2	0.09 ± 0.02	359 ± 47	6.2 ± 1.0	0.94 ± 0.19	26.2 ± 13.2
Fine-grained sands												
Disturbed areas, *n* = 16	7.34 ± 1.57	16.3 ± 11.8	34 ± 9.0	1.09 ± 0.34	1.72 ± 0.47	1.82 ± 0.36	5.5 ± 0.71	0.13 ± 0.08	135 ± 25	2.49 ± 0.32	0.19 ± 0.04	24.8 ± 12.5
Background areas, *n* = 28	7.94 ± 1.11	8.7 ± 2.1	57 ± 17	1.87 ± 0.46	1.90 ± 0.48	2.05 ± 0.50	6.52 ± 0.91	0.07 ± 0.02	171 ± 31	3.40 ± 0.56	0.28 ± 0.04	14.5 ± 7.1

is related to environmental contamination by highly mineralized formation water (Patin, 2001).

Content of HC and HM in soils. The diversity of facial–genetic types of Quaternary deposits causes a great variation in HM content in soils, in the illuvial horizon in particular. The acid soil reaction and reduction conditions favor the high mobility of Fe, Mn, and organic matter. The soil profile is characterized by a combination of gleyic, humus, and illuvial horizons (OBH, BT, BTG, and others).

The chemical composition of soils is mainly determined by natural factors: soil-forming rocks and soil texture. The landscape structure of the area also plays a great role: the regularities of migration and accumulation of metals vary upon the transition from polygonal tundra to typical tundra and forest tundra. The content of Mn, Zn, Cu, Ni, Hg, and Co in organic soil horizons drops from polygonal peatlands to flattened and large hummocky peat bogs. The content of Pb and Cd in peat remains practically stable, while Cr and V content rises in polygonal peatlands (Opekunova, 2013). Adverse regularity is typical for Ba: its content in large hummocky peat bogs is two and three times higher when compared to flattened peat bogs and polygonal peatlands, respectively. Under natural conditions of the Urengoi tundra, Ba, V, Cu, Ni, and Cd are mainly accumulated in soils of autonomic facies, while in subordinate positions their content drops.

The content of HM in illuvial soil horizons in general increases from polygonal tundra to forest tundra,

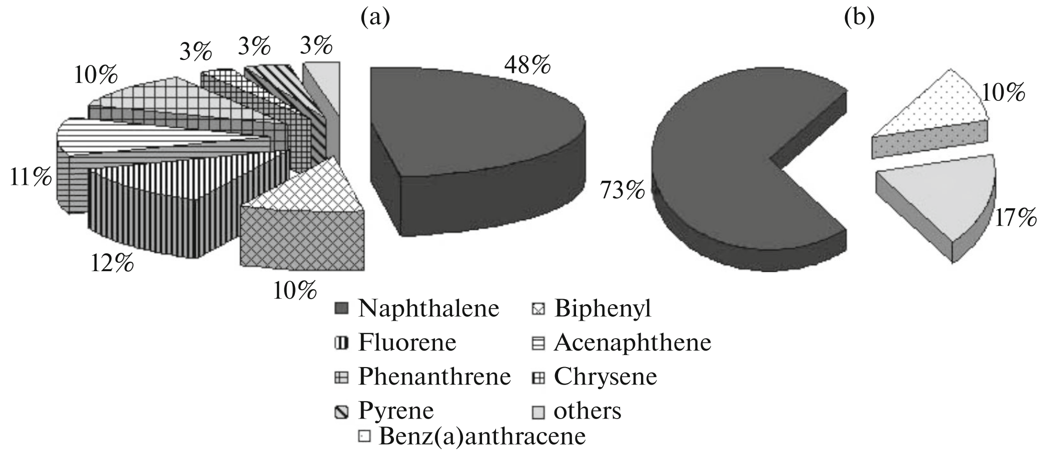


Fig. 2. Ratio between the main substances of the PAH group in bottom sediments (a) and soils of disturbed areas (b).

Table 2. Content of HC and microelements in soils of technogenically disturbed and background areas in the investigated region, mg/kg

	HC	Ba	Mn	Zn	Cu	Ni	Co	Pb	Cd	Cr	Hg	Fe	V
Accumulative horizon													
Disturbed areas, *n* = 180	96 ± 13.5	216 ± 53.6	191 ± 36.4	28.5 ± 3.18	8.1 ± 1.21	16.0 ± 6.08	4.1 ± 0.53	11.3 ± 1.49	0.36 ± 0.07	22.3 ± 3.2	0.084 ± 0.009	1.19 ± 0.16	18.2 ± 2.5
Background areas, *n* = 219	75 ± 8.5	178 ± 17.3	476 ± 113	34.7 ± 2.4	7.7 ± 0.6	11.2 ± 2.3	6.03 ± 1.1	11.7 ± 0.9	0.39 ± 0.04	17.2 ± 2.3	0.088 ± 0.009	1.18 ± 0.19	20.7 ± 3.1
Illuvial horizon													
Disturbed areas, *n* = 117	21.4 ± 5.4	402 ± 28.0	266 ± 45.5	28.0 ± 3.28	7.80 ± 0.92	11.0 ± 1.48	7.29 ± 1.24	8.75 ± 0.65	0.09 ± 0.02	42.1 ± 4.61	0.018 ± 0.002	2.23 ± 0.22	53.7 ± 5.7
Background areas, *n* = 180	15.5 ± 3.5	460 ± 19.9	405 ± 49.7	33.8 ± 2.44	9.0 ± 0.77	13.6 ± 1.48	10.5 ± 1.10	9.5 ± 0.51	0.14 ± 0.02	42.2 ± 3.98	0.022 ± 0.003	2.18 ± 0.232	61.0 ± 5.0

but greatly depends on the composition of soil-forming rocks. Among the studied metals, Mn, Cd, Pb, and Hg are characterized by a greater content in the top organic horizon when compared to the illuvial layer. This may be related both to the low content of these elements in soil-forming rocks and to their fixation at the geochemical barrier as components of organomineral complexes.

The correlation analysis of HM contents in soils of disturbed and background areas has shown that the difference between them is insignificant (Table 2). At the local level near the pollution sources, Ba is used as a reliable indicator. The disturbed landscapes of some license areas are characterized by an increased content of Ni, Co, Pb, Cr, and V. This corresponds to the data by Vodyanitskii et al. (2011), which testify to the fixation of V, Cr, Ni, and Ba in the top peat layer upon oil contamination. Nevertheless, the indication role of these elements is only pronounced within one lithological–geochemical area.

At the regional level, the technogenic impact is accompanied by the contamination of the topsoil by HC. The accumulative horizons undergo modern surface contamination, while the illuvial layers are characterized by old pollution of the period of geologic exploration. Naphthalene is a reliable indicator of soil pollution. Its portion among 16 polyarenes is 50–90% (Fig. 2), which is caused by the input of formation water to the surface upon drilling.

The content of HM in plants of the Nadym–Pur–Taz interfluve is determined by their biological features and environmental factors. The leading role belongs to soil cover, the composition and structure of plant communities, and moistening of habitats. The comparison of HM accumulation in the studied plant species have revealed two main indicators recommended when monitoring the environment status in the development areas of OGCF: *Cladonia alpestris* and *Ledum decumbens*. They are characterized by different capabilities of accumulating metals. Siderophile elements Ni, Co, Cr, V, and Fe, as well as Pb, are accumulated in *Cladonia alpestris*, while the increased accumulation of Ba, Mn, Zn, and Cu is seen in *Ledum decumbens*. With respect to the decrease in the content in *Cladonia alpestris* in comparison with *Ledum decumbens*, the metals may be arranged in the following series: Fe (4.5) > Co (3.9) > Cr (2.9) > V (2.6) > Pb (2.3) > Ni (1.25) > Cd (1.0) > Zn (0.65) > Cu (0.45) > Ba (0.19) > Mn (0.08). Our investigations have shown the reliable differences in the accumulation of microelements by plants with respect to their classification position, life form, accumulative organ, and phenological stage (Table 3, Fig. 3).

A comparison of chemical composition of plant samples taken in different periods shows that HM content considerably varies upon active growth. For example, the content of elements of biological uptake (Ba and Pb) in plants is higher in June than in July, contrary to biogenic elements (Zn and Mn) (Fig. 3).

The technogenic impact upon OGCF development is accompanied by an increase in the concentration of metals in indicator plant species parallel to the variability of HM content and the biological absorption coefficient (BAC). The main mechanisms of plant-cover pollution include the uptake of microelements by plants from the disturbed soil cover in the areas of intensive OGCF development and aerotechnogenic transmission. Secondary swamping of the area as a result of the mechanical disturbance of the soil cover makes HMs more mobile and favors their uptake by plants. A comparative analysis of the content of metals in background and disturbed habitats (Table 4) testifies to the statistically significant rise in the concentration of metals in plants under the technogenic impact. For example, there is a rise in the concentration of Ba, Zn, Cu Cd, and Fe in *Cladonia alpestris* and of Ba, Cu, Ni, Co, Cd, Pb, Cr, and V in *Ledum decumbens*. No variation in Mn concentration in plants at the regional level is revealed.

Table 3. Content of HMs in plants of the north of Western Siberia

Plant species, number of samples (*n*)	Ba	Mn	Zn	Cu	Ni	Co	Pb	Cd	Cr	V
Cladonia alpestris, *n* = 201	38 ± 1.5	83 ± 9	15.1 ± 0.4	2.0 ± 0.1	3.1 ± 0.1	0.71 ± 0.08	1.8 ± 0.11	0.06 ± 0.01	3.0 ± 0.2	1.6 ± 0.2
Ledum decumbens, *n* = 300	97 ± 4	1100 ± 67	22 ± 1	3.9 ± 0.4	2.0 ± 0.2	0.19 ± 0.17	0.88 ± 0.1	0.07 ± 0.01	1.2 ± 0.2	0.6 ± 0.04
Vaccinium vitis-idaea, *n* = 206	72 ± 5	1447 ± 70	27 ± 2	7 ± 1	0.9 ± 0.2	0.12 ± 0.02	0.67 ± 0.1	0.04 ± 0.01	0.4±0.02	<0.3
Vaccinium uliginosum, *n* = 120	94 ± 6	1067 ± 60	50 ± 3	7 ± 0.5	2.8 ± 0.3	0.1 ± 0.01	1.4 ± 0.2	0.21 ± 0.02	0.6±0.04	<0.3
Larix sibirica, *n* = 45	149 ± 28	140 ± 37	17 ± 2	4 ± 0.5	1.6 ± 0.6	0.3 ± 0.1	6.1 ± 1	0.08 ± 0.01	0.9 ± 0.4	0.7 ± 0.1
Salix lanata, *n* = 30	7 ± 3	270 ± 100	84 ± 33	23 ± 4	10.5 ± 3	1.8 ± 1.0	1.0 ± 0.5	0.3 ± 0.1	0.5 ± 0.2	1.5 ± 0.5
Betula nana, *n* = 38	21 ± 5	610 ± 114	113 ± 19	6.7 ± 1.4	2.7 ± 0.3	0.6 ± 0.1	1.5 ± 0.4	0.014 ± 0.001	0.43 ± 0.41	0.75 ± 0.3
Clarke according to V.V. Dobrovol'skii, 2003	**22.5**	**205**	**30**	**8**	**2**	**0.5**	**1.25**	**0.035**	**1.8**	**1.5**

Floristic and phytocenotic changes. An analysis of geobotanical descriptions of natural phytocenoses of the Urengoi tundra performed by the approach by P.V. Terent'ev has shown a close correlation between plants of different habitats (Neshataev, 1987; Arestova, 2003). Only two species of sphagnum mosses (*Sphagnum balticum* (Russow) C.E.O. Jensen. and *Sph. lenense* H. Lindb.) and one species of cotton grass (*Eriophorum scheuchzeri* Hoppe) were isolated from the total composition of species pleiads at a significance level of 5%. This is explained by the relatively uniform environmental conditions of the Urengoi tundra: plain area, high percentage of swamps, and the similarity of the structure of geocomplexes. At a higher significance level, 20 correlation pleiads, reflecting geographical centers of flora formation and specific features of habitats, were specified.

The central place in the system of correlation relationships in the plant cover pattern is occupied by three groups of phytocenoses of undisturbed NTC (Fig. 4). The first group includes mesocomplexes of dry stony tundra on watersheds with the participation of *Salix phylicifolia*, *Juncus arcticus*, *Pedicularis labradorica*, and other species (pleiada *VII*), which are replaced by sphagnum willow communities (pleiada *VIII*).

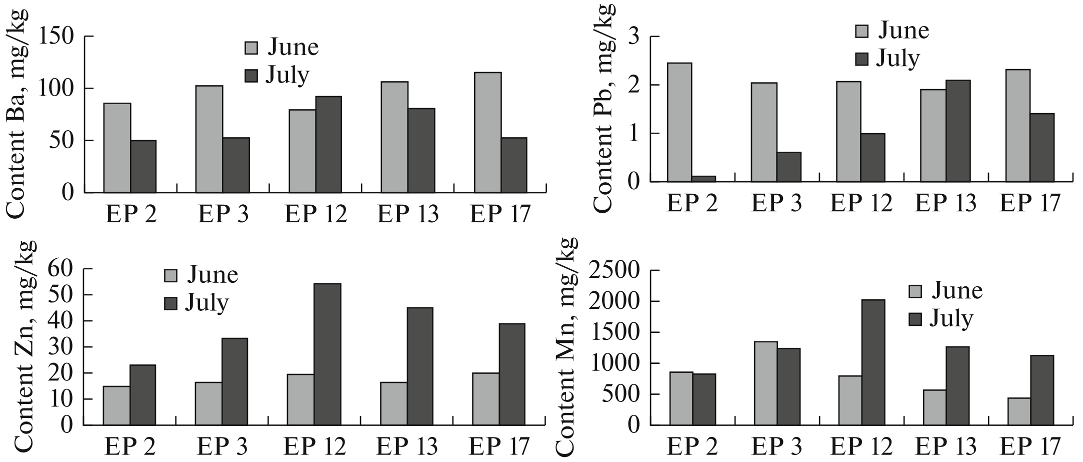


Fig. 3. Variations in chemical composition of *Ledum decumbens* in the growing period (growth starts in June and maximal vegetation activity in July) according to investigations on etalon plots (EPs).

Table 4. Content of microelements and BAC in plants of disturbed and background areas of the investigated region

	Ba	Mn	Zn	Cu	Ni	Co	Pb	Cd	Cr	V	Fe
Cladonia alpestris, concentration, mg/kg of dry matter											
Disturbed areas, *n* = 90	56.2 ± 19.7	78 ± 10.7	16.4 ± 1.67	2.35 ± 0.40	4.34 ± 1.76	0.80 ± 0.21	1.86 ± 0.24	0.07 ± 0.01	3.1 ± 0.5	1.75 ± 0.28	867 ± 112
Background areas, *n* = 111	16.5 ± 2.5	87 ± 29	14.0 ± 0.84	1.69 ± 0.15	2.12 ± 0.30	0.63 ± 0.18	1.72 ± 0.17	0.05 ± 0.01	2.94 ± 0.47	1.49 ± 0.24	410 ± 92
Ledum decumbens, concentration, mg/kg of dry matter											
Disturbed areas, *n* = 129	115 ± 5.92	1100 ± 91	22.8 ± 1.59	4.13 ± 0.24	2.44 ± 0.32	0.22 ± 0.04	1.06 ± 0.22	0.08 ± 0.02	1.49 ± 0.19	0.70 ± 0.08	63 ± 9
Background areas, *n* = 171	85.4 ± 4.0	1100 ± 94	21.4 ± 1.16	3.77 ± 0.18	1.7 ± 0.17	0.16 ± 0.02	0.74 ± 0.11	0.05 ± 0.01	1.01 ± 0.10	0.57 ± 0.05	91 ± 28
Cladonia alpestris, BAC											
Disturbed areas, *n* = 85	0.4 ± 0.1	0.8 ± 0.2	0.7 ± 0.1	0.4 ± 0.1	0.5 ± 0.1	0.5 ± 0.2	0.4 ± 0.3	0.4 ± 0.1	0.3 ± 0.1	0.2 ± 0.1	Not determined
Background areas, *n* = 111	0.12 ± 0.02	0.5 ± 0.11	0.45 ± 0.06	0.27 ± 0.03	0.4 ± 0.08	0.27 ± 0.06	0.2 ± 0.07	0.16 ± 0.03	0.25 ± 0.05	0.18 ± 0.04	Not determined
Ledum decumbens, BAC											
Disturbed areas, *n* = 119	0.9 ± 0.1	12 ± 2	1.0 ± 0.13	0.8 ± 0.2	0.5 ± 0.4	0.2 ± 0.23	0.2 ± 0.13	0.5 ± 0.3	0.2 ± 0.16	0.11 ± 0.09	Not determined
Background areas, *n* = 125	0.7 ± 0.1	9 ± 2	0.7 ± 0.08	0.6 ± 0.06	0.33 ± 0.07	0.06 ± 0.01	0.08 ± 0.02	0.08 ± 0.02	0.13 ± 0.02	0.08 ± 0.02	Not determined

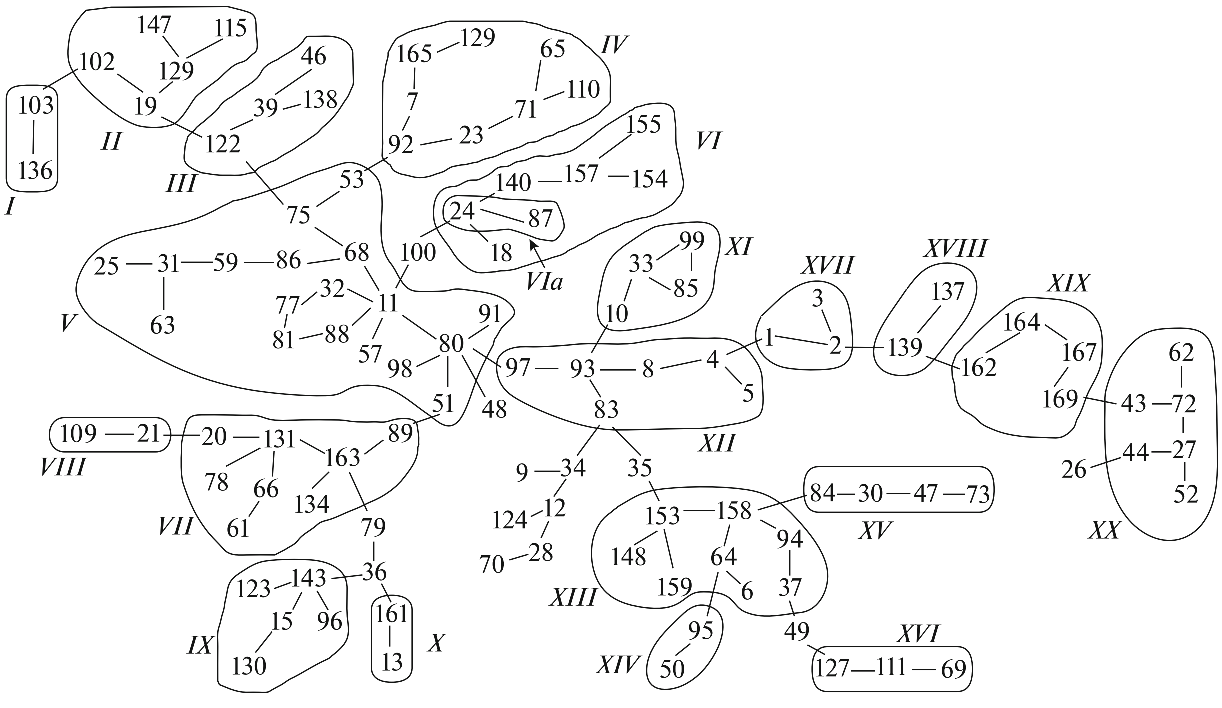


Fig. 4. System of correlation pleiads of plant communities in the Urengoi tundra. (1–169) Species number, (*I–XX*) pleiada number. Plant species of the Urengoi tundra: (*1*) *Betula tortuosa* Ledeb., (*2*) *Larix sibirica* Ledeb., (*3*) *Picea obovata* Ledeb., (*4*) *Pinus sibirica* Du Tour., (*5*) *Sorbus sibirica* Hedl., (*6*) *Betula nana* L., (*7*) *B. tundrarum* Perf., (*8*) *Duscheckia fruticosa* (Rupr.) Pouzar, (*9*) *Juniperus communis* L., (*10*) *Rosa cinnomomea* Herr., (*11*) *Salix arbuscula* L., (*12*) *S. dasyclados* Wimm., (*13*) *S. glauca* L., (*15*) *S.x hastata* L., (*19*) *S. myrtilloides* L., (*20*) *S. phylicifolia* L., (*21*) *Salix phylicifolia L.x S.myrsinifolia*, (*23*) *S. lanata* L., (*24*) *S. stipulifera* Flod., (*25*) *S. viminalis* L., (*26*) *Arctagrostis latifolia* (R.Br.) Greust., (*27*) *Arctophila fulva* (Trin.) Anderss., (*28*) *Arctostaphylos uva-ursi Spr.*, (*29*) *Arctous alpina (L.) Niedenta*, (*30*) *Andromeda polipholia* L., (*31*) *Aster sibiricus* L., (*32*) *Botrychium multifidum Rupr.*, (*33*) *Cacalia hastata L.*, (*34*) *Calamagrostis lapponica* Harm., (*35*) *C. langsdorffii* (Link) Trin., (*36*) *Carex arctisibirica* (Jatr.) Crev., (*37*) *C. aquatilis* Wahlenb., (*39*) *C. capitata* L., (*43*) *C. rariflora* (Wahlenb). Somth., (*44*) *C. rostrata* L., (*46*) *C. rupestris*, (*47*) *Chamaedaphne calyculata* L., (*48*) *Chamaerion angustifolium* (L.) Holub., (*50*) *Empetrum subholarcticum* V.Vasil., (*51*) *Equisetum arvense* L., (*52*) *E. fluviatile* L., (*53*) *E. palustre* L., (*57*) *Festuca ovina* L., (*59*) *Hieracium umbellatum* L., (*61*) *Juncus arcticus* Wild., (*62*) *J. casteneus* Sm., (*63*) *J. filiformis* L., (*64*) *Ledum decumbens*, (*65*) *Diphasiastrum alpinum* (L.) Holub, (*66*) *Lycopodium clavatum* L., (*68*) *Luzula multiflora* (Retz.) Les., (*69*) *L. parviflora* (Ehrh.) Dew., (*70*) *L. arctica* Blytt, (*71*) *Majanthemum bifolium* (L.) F.M.Schmidt., (*72*) *Menyanthes trifoliata* L., (*73*) *Oxycoccus microcarpus* Turcz. ex Rupr., (*75*) *Pedicularis hyperborea* Wed., (*77*) *P. palustre* L., (*78*) *P. labradorica* Wirsing., (*79*) *Petasites frigidus* (L.) Coss., (*80*) *Polygonum viviparum* L., (*81*) *Pyrola rotundifolia* L., (*83*) *Rubus arcticus* L., (*84*) *R. chamaemorus* L., (*85*) *Senecio nemoralis* L., (*86*) *Solidago lapponica* With., (*87*) *Stellaria graminea* L., (*88*) *St. humifusa* Rotfb., (*89*) *St. pedunculus* Bunge, (*91*) *Tanacetum bipinnatum* (L.) Sch.-Bip., (*92*) *Trichophorum caespitosum* (L.) C.Hurm., (*93*) *Trientalis europaea* L., (*94*) *Vaccinium minus* (Lode) Worosch., (*95*) *V. uliginosum ssp. microphyllum* Lange, (*96*) *V. myrtillus* L., (*97*) *Veratrum lobelianum* Bernh., (*98*) *Viola canina* L., (*99*) *V. biflora* L., (*100*) *V. epipsiloides* A. et D. Löve., (*102*) *Sphagnum acutifolium* Schrad., (*103*) *Sph. balticum* (Russow) C.E.O. Jensen., (*109*) *Sph. lenense* H. Lindb.;, (*110*) *Sph. subsecundum* Nees, (*111*) *Sph. squarrosum* Cramn., (*115*) *Sph. warnstorfii* Russ., (*122*) *Calliergon stramineum* (Brid.) Kindb, (*123*) *Dicranum angustum* Brid., (*124*) *D. congestum* Brid., (*127*) *Drepanocladus fluitans*, (*129*) *Gymnocolea inflata* (Huds.) Dum.s.b., (*130*) *Hypnum cupressiforme* Hedw., (*131*) *Lophozia ventricosa* (Wees.) Molonn., (*134*) *Pohlia nutans* (Hedw.) Lindb., (*136*) *Polytrichum piliferum* Hedw., (*137*) *P. commune* Hedw., (*138*) *P. jensenii* Hag., (*139*) *P. strictum* Brid., (*140*) *P. gracile* Bryk., (*143*) *Ptilium cristo-castrensis* (Hedw.) DeNot, (*147*) *Cetraria andrejevii* Oxn., (*148*) *C. cucullata* (Bellardi) Randl., Saag, (*153*) *Cl. alpestris* (L.) Rubh., (*154*) *Cl. cenotea* (Ach.) Schaer., (*155*) *Cl. deformis* (L.) Hoffm., (*157*) *Cl. pleurota* (Fel.)Schaer., (*158*) *Cl. rangiferina* (L.) Web., (*159*) *Cl. arbuscula* (Wallr.) Flot., (*161*) *Nephroma arcticum* (L.) Tuckm., (*162*) *Peltigera variolosa*, (*163*) *P. canina* (L.) Willd., (*164*) *P. leucophlebia* (Nyl.) Quel., (*165*) *Stereocaulon paschale* (L.) Hoffm., (*167*) *Cladonia macrophylla* (Schoer.) Stenh., and (*169*) *Cl. phyllophora* Hoffm.

The second group consists of Eurasian boreal species of relatively warm habitats: *Rosa cinnomomea*, *Cacalia hastata*, and others (pleiada *XI*); Siberian boreal species *Sorbus sibirica*, *Duscheckia fruticosa*, and others (pleiada *XII*); and tree plants of Siberian thin and open forests closely related to them: *Betula tortuosa*, *Larix sibirica*, and *Picea obovata* (pleiada *XVII*). The lichen moss cover is represented by *Polytrichum commune* and *P. strictum* (pleiada *XVIII*).

The third group is represented by boreal vegetation of river valleys on relatively warm soils, which includes *Salix viminalis*, *Aster sibiricus*, *Polygonum viviparum*, *Pyrola rotundifolia*, *Solidago lapponica*, *Tanacetum bipinnatum*, and others (pleiada *V*). At higher soil wetness, hydrophilic sedges (*Carex aquatilis* and *C. capitata*) and sphagnum mosses (*Sphagnum balticum* and *Sph. squarrosum*) appear in phytocenoses, and meadows give way to hypnum–sedge (pleiada *III*) and sedge–sphagnum (pleiada *IV*) bogs. The meadow communities are replaced by lichen willow forests (pleiada *VI*) on residual flattened hillocks in river valleys and on the slopes of river valleys, where soil wetness is not high.

The three main groups of pleiads are closely related to several mesocomplexes: hypoarctic low willow-stand mesocomplexes (pleiada *X*), shrub–green mosses willow-stand mesocomplexes (pleiada *IX*), and typical shrubby–lichen tundras on drained soils (pleiada *XIII*). The last is closely related to widespread shrubs of northern phytocenoses: *Empetrum subholarcticum* and *Vaccinium uliginosum* ssp. *microphyllum* (pleiada *XIV*).

In addition, independent pleiads are formed by dominants and codominants of peat bogs (pleiada *XV*), frost mounds (pleiada *XVI*), overmoist valleys on the permafrost (pleiada *I*), and the mesocomplex of transitional mire with closely located over-frozen waters (pleiada *II*). It is important that a group of species—*Peltigera variolosa*, *P. leucophlebia*, *Cladonia macrophylla*, and *C. phyllophora* (pleiada *XIX*)—of the areas of old fires and closely related to the species of Siberian open and thin forests was also specified as an independent pleiada on the correlation dendrogram (Fig. 4).

DISCUSSION OF RESULTS

The natural differentiation of the lithogenic basement is now the main factor determining the chemical composition of bottom sediments and soils. It consists of variations in the substance (the composition of Late Pleistocene rocks) and sedimentogenic (texture of sediments and soils) parameters. The calculated mean contents of metals in soils and bottom sediments at the regional level have shown that none of them may be used as an indicator of pollution. Only the content of OH and PAHs in bottom sediments and soils of disturbed landscapes reliably exceeded their background concentrations.

Significant changes in the content of Ba, Cu, V, and Pb in bottom sediments and of Ba, Cu, Ni, and Pb in soils were revealed at the local level near objects of the oil and gas industry (Fig. 5). In general, analysis has shown that the plant cover is the best indicator among the studied geographical components under the modern development conditions of the Nadym–Pur–Taz interfluve. The accumulation of mineral substances in plants and the intensity of their biogenic migration are determined by a combination of habitat factors and biological features of plants. They should be taken into consideration upon diagnostics of the technogenic pollution of NTC.

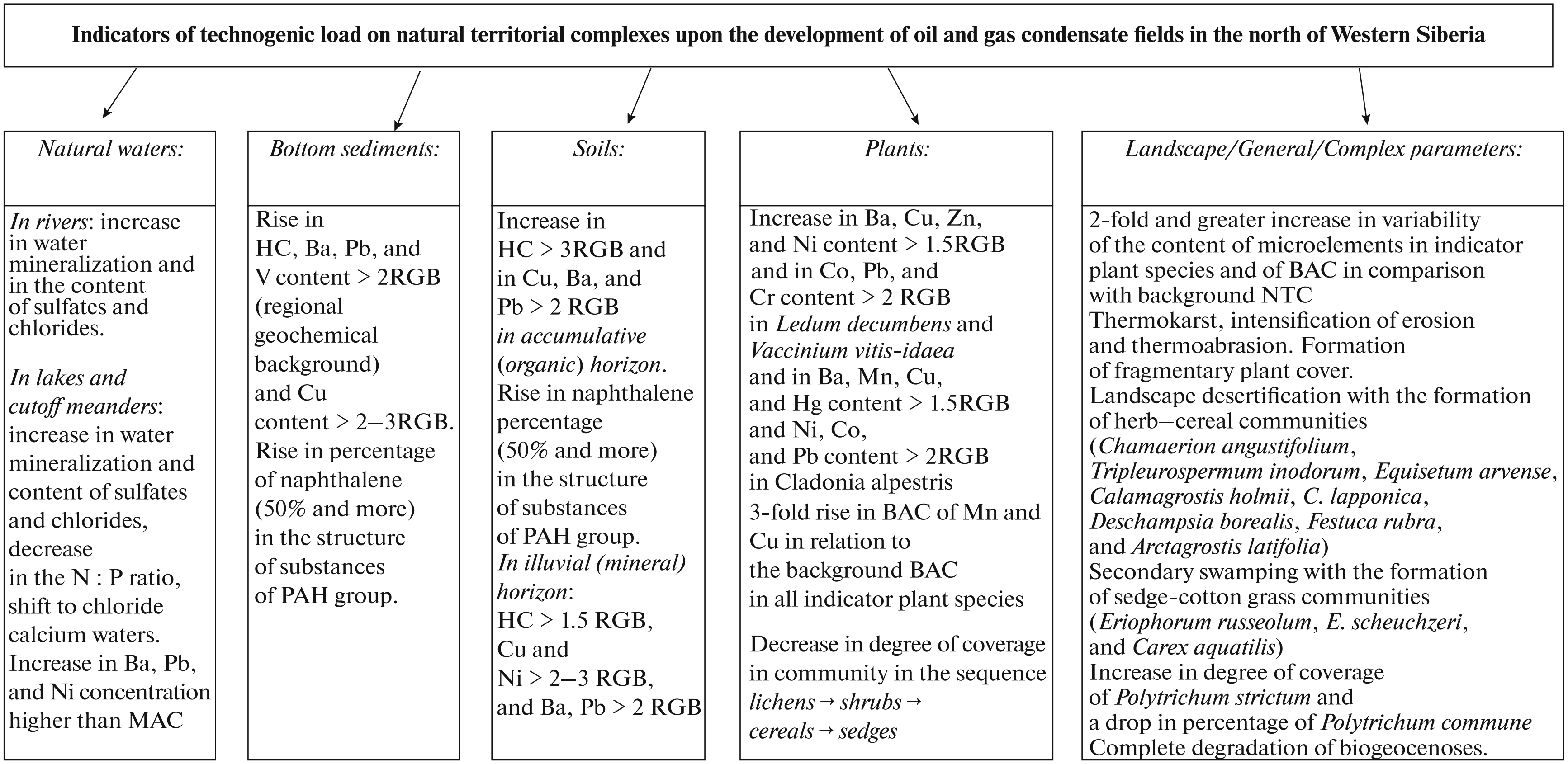
The plants under study are characterized by well-pronounced individual biogeochemical features. The chemical composition of plants depends slightly on the lithological–geochemical structure of the area, but, on the contrary, quickly responds to even the slight technogenic impact. This is especially the case for *Ledum decumbens* and *Cladonia alpestris*, which allows one to assign them to atypical concentrators and use them as indicators of technogenic pollution of the Nadym–Pur–Taz interfluve by HMs upon oil and gas extraction (Fig. 5). The floristic and phytocenotic parameters are efficient for indicating complex geomechanical disturbances and for the prognosis of the development of an area. The status of the most studied license areas is now close to the natural one, but evidences of technogenic disturbance of landscapes are present.

According to the data of floristic and phytocenotic investigations, the plant cover pattern of the studied area is typical for natural complexes of the north of Western Siberia (Kobeleva, 2012; Il'ina et al., 1989). Apophytes, the species of preferential development upon increased technogenic impact and indicating the succession trend—*Betula tortuosa*, *Calamagrostis lapponica*, *Polytrichum strictum*, *Cladonia deformis*, and others—are present in each of the specified correlation groups.

The plant cover of NTC is regenerated by the resources of the local flora and as a result of the invasion of boreal species. In technogenic habitats, where the role of mosses and hypoarctic shrubs becomes smaller, the boreal species *Chamaerion angustifolium*, *Festuca ovina*, *Equisetum ravense*, and others are widespread.

The regeneration rate of the plant cover and the type of secondary phytocenoses are determined by soil wetness and disturbance rate. Upon the development of an OGCF, the disturbance of plant cover is accompanied by secondary swamping and the formation of secondary meadows or desertification of NTC. The formation of meadows in tundra is evidenced by spread of cereals *Calamagrostis holmii*, *C. langsdorffii*, *Arctagrostis latifolia*, and others. It is seen in drained areas with sandy soils near nonoperational drilling stations, around trigonometric points, and along the routes of cross-country vehicles. Upon the complete clearing of the plant cover, as well as on sand dumps and in pits, the main cenosis-forming plants are represented by *Chamerion angustifolium*, *Tripleurospermum phaeocephalum* (Rupr.) Pobed., *Artemisia tilesii*, *Tanacetum bipinnatum*, *Polemonium boreale*, *Cerastium maximum*, and others. Secondary meadow phytocenoses in the areas of technogenic disturbance are very resistant and are preserved for many years (Sumina, 2011).

When vegetation is destructed in overmoist habitats or upon strong disturbance of the soil cover of dry microcomplexes, where permafrost rocks begin to melt, the regeneration of phytocenoses is related to secondary swamping and they are predominated by *Eriophorum angustifolium*, *E. scheuchzeri*, *Carex aquatilis*, *C. rostrata*, *Arctophila fulva*, *Equisetum fluviatile*, and other species (Fig. 4, pleiada *XX*). These plant communities are formed in the Nadym–Pur–



Indicators of technogenic load on natural territorial complexes upon the development of oil and gas condensate fields in the north of Western Siberia

Natural waters:	*Bottom sediments:*	*Soils:*	*Plants:*	*Landscape/General/Complex parameters:*
In rivers: increase in water mineralization and in the content of sulfates and chlorides. *In lakes and cutoff meanders*: increase in water mineralization and content of sulfates and chlorides, decrease in the N : P ratio, shift to chloride calcium waters. Increase in Ba, Pb, and Ni concentration higher than MAC	Rise in HC, Ba, Pb, and V content > 2RGB (regional geochemical background) and Cu content > 2–3RGB. Rise in percentage of naphthalene (50% and more) in the structure of substances of PAH group.	Increase in HC > 3RGB and in Cu, Ba, and Pb > 2 RGB *in accumulative* (*organic*) *horizon*. Rise in naphthalene percentage (50% and more) in the structure of substances of PAH group. *In illuvial (mineral) horizon*: HC > 1.5 RGB, Cu and Ni > 2–3 RGB, and Ba, Pb > 2 RGB	Increase in Ba, Cu, Zn, and Ni content > 1.5RGB and in Co, Pb, and Cr content > 2 RGB in *Ledum decumbens* and *Vaccinium vitis-idaea* and in Ba, Mn, Cu, and Hg content > 1.5RGB and Ni, Co, and Pb content > 2RGB in Cladonia alpestris 3-fold rise in BAC of Mn and Cu in relation to the background BAC in all indicator plant species Decrease in degree of coverage in community in the sequence *lichens* → *shrubs* → *cereals* → *sedges*	2-fold and greater increase in variability of the content of microelements in indicator plant species and of BAC in comparison with background NTC Thermokarst, intensification of erosion and thermoabrasion. Formation of fragmentary plant cover. Landscape desertification with the formation of herb–cereal communities (*Chamaerion angustifolium*, *Tripleurospermum inodorum*, *Equisetum arvense*, *Calamagrostis holmii*, *C. lapponica*, *Deschampsia borealis*, *Festuca rubra*, and *Arctagrostis latifolia*) Secondary swamping with the formation of sedge-cotton grass communities (*Eriophorum russeolum*, *E. scheuchzeri*, and *Carex aquatilis*) Increase in degree of coverage of *Polytrichum strictum* and a drop in percentage of *Polytrichum commune* Complete degradation of biogeocenoses.

Fig. 5. Complex of indication parameters of changes in NTC status under the effect of the oil and gas industry.

Taz interfluve on disturbed low banks of rivers, streams, and lakes, as well as along the routes of cross-country vehicles in swamped areas, where the moss cover is completely destroyed (Ishbirdin et al., 1999).

According to our investigation data, the consequences of NTC disturbance at oil and gas extraction depend on the initial disturbance of the area. Fires of mainly anthropogenic origin are one of the main reasons for the destruction of tundra vegetation. Pleiada *XIX*, specified on the dendrogram of interspecies conjugation (Fig. 4), includes species of the lichen moss layer of the secondary successions after a fire. It is known that phytocenosis regeneration depends on fire intensity and particular physicogeographical conditions (Moskalenko, 1991; Sumina, 2011). After slight ground fires in forest tundra NTCs, most trees are preserved, and the initial plant cover is regenerated. When fire completely destroys the vegetation, the large areas of open ground that form—sand blowings—are not overgrown for a long time. The effect of environmental pollution and disturbance as a result of oil and gas extraction in these areas will be quite different.

Birch forests widespread in the south of the investigated area are assigned to secondary communities of larch and dark coniferous forests. They are only indirectly related to the effect of oil and gas extraction and reflect dynamic stages of short-term secondary forests of after-fire succession (*Polevaya geobotanika*, 1976).

Contamination of deposit environment and landscape-destruction disturbance related to the geomechanical effect, fires, and overgrazing by deer are accompanied by flora vulgarization. The area of lichen tundra in general decreased two times within the last 25-year-long period, and the degradation of deer pastures is seen in one-fourth of their area. Anthropogenic cereal communities are often developed in places of typical moss–shrub vegetation (Moskalenko, 1991; Andreyashkina, 2013).

Therefore, the complex of bioindicational marks is informative for evaluating NTC transformation under the effect of the development of OGCFs. It is specified on the basis of an analysis of the chemical composition of geographical components and floristic and phytocenotic parameters (Fig. 5).

CONCLUSIONS

(1) Long-term investigations have shown that, at the regional level, the studied area is now characterized by low chemical pollution and its status is close to natural. The correlation analysis of water, bottom sediments, and soils in the background landscapes and in disturbed areas testifies to the fact that they are not contaminated by metals. A rise in the concentration of HMs (V, Cu, Pb, Ni, Co, and Zn) in surface water, bottom sediments, and soils is revealed at the local level upon the direct impact of objects of oil and gas industry.

(2) Oil hydrocarbons and PAHs characterized by a sharply increased percentage of naphthalene play the leading indicative role for the bottom sediments and soils at the regional and local levels.

(3) Plants (*Cladonia alpestris* and *Ledum decumbens*) are the most sensitive indicators of pollution among all studied components. Statistically significant differences in the content of metals in them in the background and disturbed areas (of Ba, Zn, Cu Cd, and Fe in *Cladonia alpestris* and of Ba, Cu, Ni, Co, Cd, Cr, and V in *Ledum decumbens*) are revealed at the regional level.

(4) Floristic and phytocenotic investigations substantiate the indicative role of plants upon the significant disturbance of an area. The Nadym–Pur–Taz interfluve is characterized by the preservation of natural NTCs with the active participation of Hypoarctic Siberian and Eurasian plant species. Nevertheless, the active development of OGCFs results in the gradual transformation of landscapes. This is confirmed by the shift of boreal vegetation to the north and the gradual replacement of lichens by herbs.

(5) An analysis of the correlation dendrogram of the plant cover of Western Siberia has shown that mechanical impact on vegetation and soils results in two directions of NTC succession. Tundra on drained sandy soils undergoes meadow formation, while the areas with strongly disturbed plant cover and runoff undergo secondary swamping with the formation of sedge–cotton grass communities. This is accompanied by a decrease in species diversity of phytocenoses and, hence, in the resistance of the north landscapes to technogenesis and climate changes.

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