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Specific Features of Soils and Herbaceous Plant Communities in Industrially Polluted Areas of the Middle Urals

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Abstract—Anthropogenic transformation of soils and specific features of herbaceous plant communities have been studied in areas polluted with heavy metals. With regard to landscape and edaphic conditions, all test areas have been divided into two groups: agrozems and technozems. Phytocenoses in test areas of the background and buffer zones belong to the glycophytic variant of meadow vegetation type and to the pre-meadow stage of progressive succession, respectively. Chemical pollution leads to a decrease in coefficients of similarity between communities and an increase in taxonomic diversity due to reduction in species saturation of genera and families, with a rise in the proportion of monotypic taxa. The influence of chemical pollution on the species saturation of plant communities is stronger than that of community type and coverage of species.

Keywords: heavy metals, agrozems, technozems, herbaceous phytocenoses, syntaxonomic characteristics, taxonomic richness and diversity, species saturation, coverage of species

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Anthropogenic impact can upset the homeostasis of natural ecosystems and cause various disturbances to vegetation and soils, up to their complete degradation. This fully applies to regions affected by the metallurgical and mining industries (Rosenberg et al., 1979; Folkson, 1984; De Vries, 1988; Sienhiegwieg, 1989; Kozlov and Vorobeichik, 2012; Purtova et al., 2013).

In the Middle Urals, the Nizhny Tagil Iron and Steel Works (EVRAZ NTMK), which has been in operation since 1938, is the largest source of airborne pollutants, which include fine dust particles containing metal ions (Cu, Ni, Pb, Cd, Zn, Cr, As, Hg) as well as SO_2, NO_2, CO_2, and dihydrosulfide.

The purpose of this study was to analyze specific features of anthropogenically degraded soils and herbaceous plant communities formed along the gradient of chemical pollution.

MATERIAL AND METHODS

Biotopes in agrogenic and technogenic landscapes where the communities of interest had been formed were studied in 2009 to 2012.

Description and diagnosis of agrogenically transformed natural soils were made on the basis of their morphological analysis in 2012, following the corresponding methodological guidelines (Shishov et al., 2004). Young soils on waste rock dumps were diagnosed taking into account the results of previous studies on waste dumps from the mining industry in the Urals (Makhonina, 2003; Zabaluev et al., 2007).

The chemical composition of soil samples was analyzed at the Laboratory of Ecotoxicology of Populations and Communities, Institute of Plant and Animal Ecology (Ural Branch, Russian Academy of Sciences), accredited in the State System of Analytical Laboratories (certificate no. ROSS.RU0001.515630). Test parameters included pH of water and saline extracts (pH_{water}, pH_{saline}), hydrolytic acidity (H_{hydr}), exchangeable calcium and magnesium, base saturation degree, mobile potassium and phosphorus, readily hydrolyzable nitrogen (N_{rh}), total carbon, and nitrates (*Teoriya i praktika...*, 2006). Analysis for heavy metals was performed following the official guidelines (*RD 52.18.191-89...*, 1990). Concentrations of Fe, Ni, Cu, Zn, Cd, and Pb in acid extracts were measured with an AAS Vario 6 atomic absorption spectrometer (Analytik Jena, Germany).

Based on the recorded concentrations of heavy metals and the calculated pollution index Z (the overall concentration coefficient expressed in relative units with respect to the background values), we distinguished zones with different levels of industrial pollution, i.e., the background, buffer, and impact zones (*Global...*, 1973). Background test areas were in agrogenic landscapes (in abandoned plowed fields), and impact areas, in technogenic landscapes such as waste dumps of iron ore mining and smelting works. In the buffer zone, one area was in an agrolandscape, and the other, on the spoil bank built of magnesian rocks dumped from the mining industries operating in the city of Nizhny Tagil, which provided a bridge between the contrasting soil-ecological conditions of the background and impact zones.

Descriptions of species composition and coverage of species in herbaceous communities were made in July, when plants were at the peak of development. We selected areas where the composition and structure of vegetation were typical for a given region and compiled complete species lists of herbaceous plants, as described (Ponyatovskaya, 1964). Plant names are given according to Cherepanov (1995). Coefficients of taxonomic saturation (Vtorov and Vtorova, 1983) were calculated for supraspecific taxa to characterize their taxonomic diversity.

Within test areas, permanent sampling plots were laid to assess the coverage of species in communities (20 plots of 0.25 m^2) and their species saturation (5 plots of 1.0 m^2). The assessment was made every year by standard methods (Mirkin and Rozenberg, 1978; Makhnev et al., 1990). Below, the data generalized over 4 years (2001–2012) are presented.

Statistical data processing involved calculation of arithmetic means (M), errors (m), and standard deviations (S). The Czekanowski–Sørensen coefficient (I_{SC}) was used to compare species composition between communities. Multiple comparisons were made by Scheffe's S method. The influence of relevant factors on the coverage and species saturation of communities was evaluated by one-way ANOVA using the Statistica v. 10.0 program package (StatSoft, Inc., 2012).

RESULTS AND DISCUSSION

Characteristics of chemical soil pollution. The soil–plant cover of the study region has been formed under conditions of the southern taiga subzone. The soddy podzolic soils natural to this territory have been transformed in the course of its industrial development. Thus, agro-soddy podzols developed in agrolandscapes and, after plowed fields were withdrawn from tillage, they have transformed into fallows at the initial stages of sod-forming process. Initial soils with specific properties are being formed on spoil banks of copper and iron ore mining works.

The levels of soil pollution in the test areas were described in detail previously (Ivshina et al., 2014). The concentrations of mobile forms of heavy metals in the soil reach 288 μg/g for copper, 23 μg/g for lead, 2 μg/g for cadmium, 343 μg/g for zinc, and 16185 μg/g for iron. The concentrations of cadmium, copper, and zinc exceed the background level by factors of 78, 10, and 29, respectively. The toxic load (Z) in technogenically disturbed areas is increased 30-fold, compared to the background area (Table 1).

Characteristics of soils and landscapes in test areas. In the background zone (57°57′50″ N, 60°15′11″ E), test areas are in fallow fields withdrawn from tillage 17–20 years ago (Table 1). During this period, the sod-forming process has developed to different extents in their agrogenic soils. Morphologically, these soils have retained distinct attributes of plowed horizon (P), which is underlain by eluvial (EL) or subeluvial (BEL) horizons. The soil of Background-1 area is gleyey, with signs of seasonal overmoistening. Morphological features allow these soils to be classified as agro-soddy podzolic, derived from soddy podzolic heavy loam clay soils on diluvial clay marl as a result of their agricultural development. They are prograded by the soil-forming process, with the soil of Background-1 being gleyey and that of Background-2, typical.

The soils of both these areas are weakly acidic or circumneutral (pH_{water} 5.8–6.6), have low hydrolytic acidity (Table 2), and are base-saturated (57–95%), primarily with calcium. Signs of calcium and magnesium removal from the eluvial part of the soil profile can be noted. The contents of nutrient elements (readily hydrolyzable nitrogen and mobile phosphates) are low or very low, because initially poor soddy podzolic soils have been further depleted by plowing and crop cultivation. Mobile potassium content is relatively high, that of total carbon is low, and nitrates are practically absent (0.3–1.6 mg/kg).

Test areas in the buffer zone have highly contrasting soils (Table 1). Area Buffer-1 (57°52′18″ N, 59°59′39″ E) is in a 20-year fallow, where the natural landscape has been only slightly transformed by agricultural activities. This area is used as a hayfield. There is a cohesive sod layer covered by dead grasses; the plowed horizon is distinct, and the underlying layer shows signs of podzolization and gleying. The soil is classified as agro-soddy podzolic, gleyey, formed on diluvial talc schist and prograded by the sod-forming process. This soil is weakly acidic, with exchangeable and hydrolytic acidity being manifested in the lower part of its profile. Its exchangeable complex is base-saturated (70–90%), primarily with calcium, but magnesium content is also high, because talc schist is a magnesian rock. The content of nutrient elements is high only in the upper organic horizon. Nitrogen and phosphorus concentrations sharply drop down the soil profile and are very low in deeper horizons, while potassium concentration gradually decreases to medium or low values (Table 2).

Test area Buffer-2 (57°58′13″ N, 59°58′35″ E) is in a technogenic landscape, in eluvial position on the upper terrace of a waste rock dump built of fine earth, landwaste, talc schist rubble, and technogenic inclusions. The soil is young; its development is provided for by the sod-forming process on crushed talc schist and fine earth. There are morphologically distinct horizons O (dead meadow herbage and, at the forest

Table 1. Characteristics of landscapes and soils in test areas

Zone	Plot/*Z*, rel. units;	Area	Landscape element	Landscape		Soil		
				geographic	geochemical	type	subtype	genus/species
Background	Backround-1/1.0	Agrolandscape, a fallow aged more than 20 years	Very flat slope of low hill	Agrogenic	Transelluvial, transition to transaccumulative	Agro-soddy podzol	Gleyey	Heavy loam clay soil prograded by sod-forming process, on diluvial clay marl
	Backround-2/1.44	Agrolandscape, a fallow aged less than 20 years	Very flat slope of low hill	Agrogenic	Transeluvial	Agro-soddy podzol	Tongued	Heavy loam clay stony soil prograded by sod-forming process, on diluvial clay marl
Buffer	Buffer-1/3.53	A fallow aged about 20 years	Lower part of a flat hill slope descending to a valley (probably, a river terrace)	Natural, agrogenically transformed	Transaccumulative	Agro-soddy podzol	Gleyey	Silty loam, crushed-stony soil prograded by sod-forming process, on diluvial talc schist
	Buffer-2/9.03	Upper terrace of an old waste rock dump near an open pit (over 25–30 years) and an old mine	Technogenically transformed, leveled upper terrace of waste rock dump	Technogenic	Eluvial	Young soil developing on spoil bank built of magnesian rock and talc schist (lithostrat)	Sodded	Silty loam on talc schist with technogenic inclusions
Impact	Impact-1/21.58	Midslope terrace on waste rock dump of Vysokogorsky Ore Mining and Processing Plant (VGOK)	Technogenically transformed, midslope terrace on a steep slope of waste rock dump	Technogenic	Transelluvial	Young soil developing on waste rock dump of Vysokogorsky Iron Ore Mine (VGOK)	Sodded	Stony clay loam with inclusions of iron ore sinters and pellets, slag, limestone, talc, etc.
	Impact-2/29.53	Upper terrace of NTMK cinder dump in its old part, technically recultivated	Technogenically transformed, upper terrace of waste rock dump	Technogenic	Eluvial	Young soil developing on filled-up recultivated substrate underlain with rock waste, cinders, etc. (artiindustrat–replantozem)	Sodded	Stony heavy loam with inclusions of cinders, ore, and quartz and talc rubble

Table 2. Agrochemical parameters of soils and grounds in test areas

Plot	Horizon	Depth, cm	pH_{water}	pH_{saline}	H_{hydr}	Ca + Mg	Ca	Mg	V, %	N_{rh}	P_2O_5	K_2O	C_{total}, %	NO_3, mg/kg
					mg-equiv/100 g					mg/100 g				
Background-1	AY	0–2	6.55	6.58	1.49	26.00	20.00	6.00	94.59	7.36	48.67	71.06	6.26	1.63
	P	2–37	6.55	6.48	2.10	20.00	16.00	4.00	90.50	5.10	19.31	22.05	3.59	0.57
	(EL)	37–42	6.59	6.28	2.01	15.00	13.33	1.67	88.17	6.17	14.40	13.65	1.60	0.29
	BELg	42–...	6.29	5.81	4.55	14.67	9.33	5.33	76.32	3.86	3.91	11.55	0.52	1.29
Background-2	P	0–19	6.32	6.19	3.15	17.33	16.00	1.33	84.62	5.61	3.67	22.39	4.48	1.07
	(EL)	19–32	6.28	4.02	6.04	8.00	5.33	2.67	56.99	2.60	0.88	12.45	0.46	1.27
	BEL	32–42	5.90	3.75	8.58	13.33	9.33	4.00	60.86	2.75	1.01	15.41	0.46	1.04
	BT	42–...	5.77	3.78	10.76	21.33	13.33	8.00	66.47	2.95	1.08	27.49	0.45	0.80
Buffer-1	O	0–1	5.66	6.31	21.00	51.00	45.00	6.00	70.83	61.38	49.70	418.00	29.14	0.91
	AY	1–4	6.34	6.05	3.85	30.00	20.00	10.00	88.63	6.75	3.41	34.62	6.59	0.86
	P	4–25	6.48	6.09	2.80	21.67	16.67	5.00	88.56	4.50	1.66	11.96	2.30	0.90
	(EL)	25–29	6.16	4.55	2.63	14.67	13.33	1.33	84.82	2.27	1.03	11.57	0.38	0.00
	BEL	30–44	6.24	4.09	2.63	25.33	13.33	12.00	90.61	1.60	6.61	11.31	0.21	0.55
	BT	44–59	6.08	4.01	8.40	32.00	22.67	9.33	79.21	1.57	30.05	12.98	0.13	0.11
Buffer-2	O	0–1	6.05	6.40	14.88	65.00	55.00	10.00	81.38	57.90	91.68	544.25	32.65	0.61
	AY	1–6	6.76	7.06	1.23	24.00	20.00	4.00	95.14	4.76	34.34	38.97	6.69	1.46
	Cur	6–15	5.89	4.67	2.80	6.67	5.33	1.33	70.42	2.86	11.28	11.31	0.52	0.00
Impact-1	O	0–1	5.28	6.51	11.38	37.50	30.00	7.50	76.73	29.13	82.60	230.95	20.53	0.53
	AY	1–5	7.63	7.48	0.70	38.00	30.00	8.00	98.19	4.14	69.59	57.79	3.57	1.58
	C1 tech	5–20	7.76	6.96	0.88	29.33	24.00	5.33	97.10	1.25	158.05	27.11	0.30	0.41
	C2 tech	20–37	6.61	6.30	0.96	40.00	30.67	9.33	97.65	1.17	117.90	26.12	0.17	0.15
Impact-2	AY	0–6	7.35	7.74	0.79	38.00	22.00	16.00	97.97	5.12	4.25	55.69	5.22	1.56
	Crr	6–27	8.57	7.68	0.09	35.00	21.00	14.00	99.75	4.47	10.77	26.47	1.59	0.68
	C2 tech	27–40	8.13	7.74	0.79	30.00	18.33	11.67	97.44	1.15	51.20	5.62	0.16	0.00

margin, forest litter at the initial stage of formation) and AY (sodded gray humus horizon); they are underlain by a mottled, ochreous, dense mass of structureless loam mixed with fine earth, landwaste, and talc schist rubble, which has been barely involved in soil-forming processes. Taxonomically, this substrate represents a transitional stage from technogenic surface formations (lithostrats and artiindustrats) to young soils developing into the burozem type (Table 1). The soil is weakly acidic, base-saturated (70–95%), primarily with calcium and, to a lesser extent, magnesium); the contents of nutrient elements (especially phosphorus and potassium) are high, and that of readily hydrolyzable nitrogen is very high, while nitrates are absent.

In the impact zone, soils occupying eluvial and transeluvial positions in technogenic landscapes have been studied (Table 1). They develop on overburden and enclosing rock dumps with technogenic inclusions (sinters, slag, etc.), which have been recultivated by forming terraces and, in places, covering their surface with fine earth. These young soils are at the stage of transition from technogenic surface substrates (ariindustrats and replantozems) to sodded stony soils of lithozem and burozem types.

The soil of area Impact-1 (57°54′14″ N, 59°54′41″ E) is young, with a poorly defined litter layer consisting mainly of dead grasses and a weakly sodded horizon AY (4.5–5.0 cm deep). They overlie the substrate of the dump, which consists of mottled loam (grayish brown with orange and crimson spots) with inclusions of cinders, ore, talc, limestone, sinters and pellets, iron dross, slug, coke, etc. Soil pH changes from weakly acidic in the litter to weakly alkaline in the mineral bulk. Base saturation degree reaches 98%, with calcium prevailing in the exchangeable complex. The contents of phosphorus and potassium are very high; that of nitrogen is also very high in the organic horizon but sharply decreases down the soil profile;

and nitrates are practically absent. The total carbon content is increased in the litter, due to the presence of undecomposed organic matter, but drops abruptly in mineral horizons (Table 2).

The soil of area Impact-2 (57°58′12″ N, 59°57′21″E) is also young (Table 1): the litter has not yet formed, gray humus horizon AY (6.0 cm deep) is weakly sodded but relatively rich in humus and has a crumbly–powdery structure. It is underlain by a 25-cm layer of recultivated dump substrate, which is whitish gray-brown and has a crumbly–powdery structure of loamy fine earth with inclusions of ultrabasic rock rubble, cinders, fritted ore, etc. This recultivated substrate has an even boundary with the underlying structureless mass of heavy loam with inclusions of quartzite, marble, limestone, cinders, iron-ore concentrate, etc. It appears that the recultivated substrate layer (20–30 cm) was applied at the stage of technical planning of the terrace. The soil is weakly acidic, base-saturated (97–99%), primarily with calcium. The content of nitrogen is low to very low (in deep horizons); that of phosphorus is low in the recultivated substrate but high in the underlying ground. The content of potassium is high in the humus horizon but decreases to very low values down the soil profile (Table 2).

Thus, the test areas can be divided into two groups with regard to landscape and soil conditions. The first group (below, referred to as agrozems) comprises areas Background-1, Background-2, and Buffer-1 located in agrogenic landscapes with agrogenically transformed soddy podzolic soils. These soils have developed under the taiga vegetation and have been differentiated by eluvial processes. They were first plowed about a century ago, and their composition and properties has subsequently changed depending on agrotechnology. The eluvial removal and incomplete replenishment of elements by cultivated crops has resulted in significant impoverishment of their macro- and trace element composition.

The second group (technozems) comprises areas Buffer-2, Impact-1, and Impact-2 located in technogenic landscapes, on industrial dumps over 45 years of age. Young soils in these areas develop into burozem and lithozem types on technogenic soil-forming rocks rich in exchangeable bases and nutrient elements. Both these soils are currently at different stages of sod-forming process, which leads to the enrichment of upper soil horizons with exchangeable bases and nutrient elements.

Syntaxonomic characteristics of phytocenoses. ***Background-1***: rankless community Pimpinella saxifraga–Poa angustifolia [Arrhenatheretalia]. Dominants: *Poa angustifolia*, *Lathyrus pratensis*. Syntaxonomic position: order Arrhenatheretalia R. Tx. 1931 of the class Molinio-Arrhenatheretea R.Tx. 1937 em. R.Tx. 1970. The community includes species of two unions: Festucion pratensis Sipajlova et al. 1985 (true meadows of European Russia and Siberia with dominance of *Trifolium pratense* and *Phleum pratense*) and Cynosurion R. Tx. 1947 (meadows under strong recreational and grazing impacts with dominance of *Taraxacum officinale* s.l. and *Trifolium repens*).

Background-2: rankless community Deschampsia caespitosa–Festuca pratensis [Arrhenatheretalia]. Dominants: *Festuca pratensis*, *Poa angustifolia*, *Deschampsia caespitosa*, *Trifolium pratense*. The community includes diagnostic species of the class Molinio-Arrhenatheretea and order Arrhenatheretalia—*Achillea millefolium*, *Phleum pratense*, *Taraxacum officinale* s.l., *Leucanthemum vulgare*—and relicts of preceding succession stages, such as *Cirsium setosum*, *Vicia hirsuta*, *Artemisia vulgaris*, and *Linaria vulgaris*.

Buffer-1: rankless community Alchemilla vulgaris–Festuca pratensis [Arrhenatheretalia/Carici macrourae-Crepidetalia sibiricae]. Species prevalent in the community belong to the glycophyte meadow order Arrhenatheretalia: *Festuca pratensis*, *Poa angustifolia*, *Galium mollugo*, *Lathyrus pratensis*, *Carum carvi*, etc. The order of forest glades and meadows, Carici macrourae-Crepidetalia sibiricae Ermakov et al. 1999, is represented by *Alchemilla vulgaris* and *Polygonum bistorta*.

Buffer-2: Rankless community Carum carvi–Festuca pratensis [Arrhenatheretalia]. Its composition is typical for communities of the order Arrhenatheretalia: *Festuca pratensis*, *Poa angustifolia*, *Carum carvi*, *Trifolium pratense*, etc. Synanthropic species are few, and almost all of them are also found in meadow communities (*Cirsium setosum*, *Melilotus albus*, *Linaria vulgaris*).

Impact-1: Rankless community Tussilago farfara–Calamagrostis arundinacea [Dauco-Melilotion/Agropyrion repentis]. A transitional community between the union Dauco-Melilotion Görs 1966 (xerothermic ruderal communities of annual and biennial plants; diagnostic species in the community: *Melilotus officinalis*, *Melilotus albus*, *Linaria vulgaris*) of the class Artemisietea vulgaris Lohm. et al. in Tx. 1950 (diagnostic species in the community: *Artemisia vulgaris* L.) and the union Agropyrion repentis of the class Agropyretea repentis Oberd. et al 1967 (diagnostic species: *Calamagrostis epigeios*, *Picris hieracioides*, *Seseli libanotis*). Succession on the dumps has progressed to the grass stage, retaining specific characteristic of weed stage. The community includes *Chamaenerion angustifolium*, a species of the class Epilobietea angustifolii R.Tx. et Prsg 1950 that comprises plants prevalent in felling and burned-out areas. The syntaxonomic status of this community has remained unchanged during the observation period.

Impact-2: Rankless community Latyrus pratensis–Calamagrostis arundinacea [Dauco-Melilotion/Agropyrion repentis], transitional between the union Dauco-Melilotion (diagnostic species in the community: *Melilotus albus*, *Berteroa incana*, *Linaria vulgaris*) of the class Artemisietea vulgaris (diagnostic species in the community: *Artemisia vulgaris*) and the union Agropyrion repentis (the grass stage of progressive suc-

Table 3. Taxonomic structure of communities and diversity of their taxonomic structure (2009–2012)

Plot	Number of taxa				Saturation coefficient of supraspecific taxa			Proportion of monotypic taxa	
	families (f)	genera (g)	species (s)	total	s/g	s/f	g/f	genera	families
Agrozems									
Background-1	11	33	42	86	1.27	3.82	3.00	0.76	0.27
Background-2	13	40	50	103	1.25	3.85	3.08	0.80	0.31
Buffer-1	15	44	55	114	1.25	3.67	2.93	0.77	0.33
Technozems									
Buffer-2	13	39	47	99	1.21	3.62	3.00	0.85	0.38
Impact-1	12	37	42	91	1.14	3.50	3.08	0.86	0.42
Impact-2	9	28	32	69	1.14	3.56	3.11	0.86	0.44

cession; diagnostic species: *Calamagrostis epigeios*, *Convolvulus arvensis*). The class Epilobietea angustifolii is represented by *Chamaenerion angustifolium*. Succession progresses toward a community of the class Molinio-Arrhenatheretea (diagnostic species: *Poa angustifolia, Trifolium pratense*, *Lathyrus pratensis*, *Vicia cracca*, *Stellaria graminea*, etc.). The syntaxonomic status of this community has remained unchanged during the observation period.

As follows from the above descriptions, communities of test areas in the background and buffer zones belong to the class Molinio-Arrhenathåretea and represent a glycophyte variant of meadow vegetation, while those of the impact zone are transitional between the classes Artemisietea vulgaris (ruderal communities of annual and biennial species) and Agropyretea repentis (ruderal communities with prevalence of perennial grasses that correspond to the premeadow stage of progressive succession). The next succession stage involves the development of grass communities. Despite the diversity of these communities with respect to syntaxonomic position and succession stage, they have a number of features reflecting their development on the aforementioned groups of soils (agrozems and technozems) in the total pollution gradient.

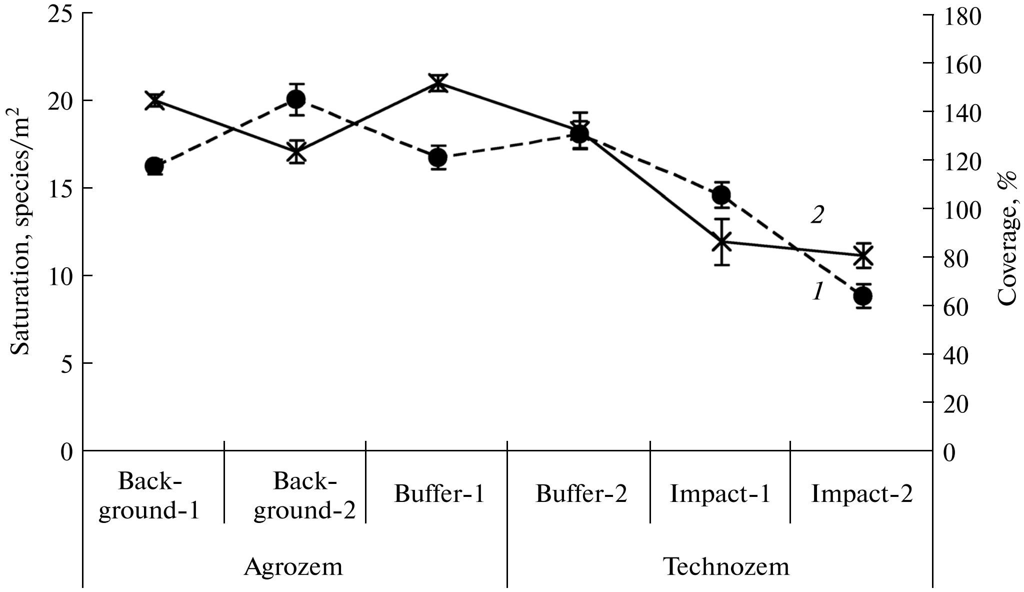
Evaluation of similarity in species composition between phytocenoses. Phytocenoses of the background zone show the highest degree of similarity in species composition (Background-1 and Background-2: $I_{SC} = 0.85$). As the toxic load increases, so does the difference between phytocenoses because of changes in species composition along the pollution gradient. Consequently, communities of test areas Background-1 and Impact-1–2 are the least similar to each other ($I_{SC} = 0.51$). Similarity between communities growing on agrozems is higher than between those on technozems (I_{SC} = 0.72–0.85 vs. 0.53–0.62). The toxic load on both soil types increases by a similar factor (3.5 for agrozems and 3.3 for technozems), and the decrease in I_{SC} is also the same in both cases (by a factor of 1.2).

Taxonomic richness and diversity of phytocenoses. The communities studied comprise 83 species belonging to 65 genera, 21 families, and 2 classes of the order Magnoliophyta Cronq., Takht. & W. Zimm. Table 3 shows data on the taxonomic diversity of individual communities. The total number of species in communities growing on agrogenic soils increases along the pollution gradient, while that in communities on technogenic soils decreases. This is especially clear under high pollution load (Impact-2).

The coefficients of species saturation (the numbers of species per genus and per family) are higher in communities on agrogenic than on technogenic soils, because the latter include greater proportions of monotypic genera and species (Table 3). Consequently, their taxonomic structure is more diverse.

Thus, the taxonomic richness of communities decreases, while their taxonomic diversity increases along the pollution gradient. Emel'yanov et al. (1999) have arrived at similar conclusions in studies on communities of mountain landscapes. According to these authors, the functional stability of biotic communities in ecosystems with a limited holding capacity (e.g., in the mountains) is maintained due to the presence of a multifunctional system of monotypic taxa, which is one of the strategies for the adaptation of biotic communities to specific ecological conditions.

It is noteworthy that the observed tendency is similar to the response of upland meadows to hay harvesting and cattle grazing in the Middle Urals. An analysis



Species saturation (*1*) and total coverage of species (*2*) in the communities studied.

of their floristic composition has shown that the number of species per genus in these communities varies within the ranges of 1.33–1.28 at the first stage of their transformation, 1.32–1.18 at the second stage, and 1.19–1.14 at the third stage, decreasing to 1.11 at the fourth stage (Gorchakovskii, 1999). Consequently, their taxonomic diversity increases, and the same takes place in communities exposed to chemical pollution. Therefore, the above changes may be regarded as a nonspecific response of herbaceous communities to increasing anthropogenic impact.

Species saturation and coverage of species. The species saturation of communities on agrozems and technozems varies from 16 to 20 and from 9 to 18 species per square meter, respectively (figure), with the difference being statistically significant (*S*-method: $F(5; 25) = 3.82$; $p < 0.05$). The total species coverage (TSC) over the observation period averages 123–144% in the background zone, 132–151% in the buffer zone, and 81–87% in the impact zone, with this parameter being higher in communities on agrozems than in technozems ($F(5; 25) = 15.72$; $p < 0.001$).

Considering the above parameters with regard to succession stages (meadow and grass communities), it may be noted that species saturation and coverage are higher in phytocenoses corresponding to the glycophyte variant of meadow vegetation that in communities representing the pre-meadow stage of progressive succession: for species saturation, $F(5; 25) = 5.73$; for coverage, $F(5; 25) = 44.24$; $p < 0.001$ (figure). It should be emphasized that meadow communities differ from grass communities in the direction of change in TSC and species saturation along the pollution gradient. These parameters in meadow communities remain almost unchanged under low or moderate toxic load, but those in grass communities decrease when the toxic load increases. A decrease in the species saturation and TSC of herbaceous communities at high levels of chemical pollution has been observed in several studies (Shilova and Luk’yanets, 1989; Makhnev et al., 1990).

A noteworthy fact is that the young meadow community on agrozems (Background-2, no sod horizon) is similar to more advanced meadow community on technozem (Buffer-2, well-developed sod horizon): both of them are characterized by low TSC and high species saturation, compared to well-developed meadow communities Background-1 and Buffer-1 (figure), being also similar in species composition ($I_{SC} = 0.82$). It appears that an increase in technogenic load along the gradient between the background and buffer zones leads to the retention of features indicative of immature community structure, which are observed at the early stage of meadow development. Communities of the impact zone are characterized by low species saturation and coverage, compared to those of the background and buffer zones, which indicates that they are at an earlier stage of successional development and suffer an increased toxic load.

The species saturation and TSC of communities differ not only along the pollution gradient but also depending on the group of soils (agrogenic or technogenic) and the stage of successional development of the community. The influence of these two factors was evaluated by means of one-way ANOVA (Table 4). The results show that species saturation and TSC depend mainly on the level of toxic load and the type of community, while the influence of factor “soil group” is relatively weak.

Table 4. Results of one-way ANOVA for the influence of chemical pollution, soil group, and succession stage on species saturation of communities and coverage of species

Factor	*df*	*F*	*p*	Relative influence of factor, %
Species saturation of community				
Toxic impact	5; 79	27.05	≤0.001	64.64
Soil group	1; 79	23.85	≤0.001	23.41
Community type	1; 79	51.37	≤0.001	39.71
Coverage of species				
Toxic impact	5; 79	22.39	≤0.001	60.21
Soil group	1; 79	52.34	≤0.001	40.2
Community type	1; 79	103.93	≤0.001	57.1

CONCLUSIONS

Parameters of phytocenoses (their species composition, taxonomic richness, diversity of taxonomic structure, species saturation of genera and families, and TSC) along the pollution gradient depend on the level of pollution, group of soils, and stage of successional development of the community. Chemical pollution is the leading factor, since the species composition of communities changes and differences between them increase along its gradient. This tendency is better manifested on technozems than on agrozems.

As the toxic load increases, so does the taxonomic diversity of communities, which is due to reduction in the species saturation of genera and families and consequent increase in the proportion of monotypic taxa. This is one of mechanisms providing for sustainable functioning of communities at high levels of chemical soil pollution.

Herbaceous communities in the test areas differ in species saturation and TSC, with these parameters being higher in communities on agrogenic than on technogenic soils. Moreover, they are also higher in meadow phytocenoses than in communities at the pre-meadow stage of progressive succession. On the whole, species saturation and TSC decrease along the pollution gradient.

The results of this study provide evidence that meadow communities can be formed in the test areas, regardless of soil group. The meadow phytocenosis on technozems has been formed long ago and has a well-developed sod layer, but it nevertheless retains certain features of young meadow communities on agrozems. Therefore, the increase in technogenic load along the gradient between the background and buffer zones leads to the retention of features indicative of immature community structure, which are observed at the early stage of meadow development. Communities of the impact zone are characterized by low values of the above parameters, which indicates that they are at an earlier stage of successional development and suffer an increased toxic load.

The observed changes in the parameters of phytocenoses are characteristic of serial herbaceous communities involved in progressive succession in fallows and on waste rock dumps where the soils are polluted with heavy metals. Although this study has been performed under particular conditions of the taiga zone of the Urals and deals with specific levels and type of pollution, its results may reflect some general trends and be applicable to other situations with chemical pollution of the environment.

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