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Dependence of Phytomass of Herbaceous Cenoses on Weather Factors in Anthropogenically Impacted Areas

T. V. Zhuikova[a, b] *, V. S. Bezel'[b], I. E. Bergman[b], V. A. Gordeeva[a, *], and E. V. Meling[a, *]

[a]*Nizhny Tagil State Social Pedagogical Institute of Russian State Vocational Pedagogical University,*
Nizhny Tagil, 622031 Russia

[b]*Institute of Plant and Animal Ecology, Ural Branch, Russian Academy of Sciences,*
Yekaterinburg, 620144 Russia

**e-mail: hbfnt@rambler.ru*

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Abstract—This paper is concerned with the phytomass of herbaceous phytocenoses growing in anthropogenically impacted areas in the Middle Urals at different stages of succession along the heavy-metal pollution gradient. Cenoses of young soils of dumps have less resistance and higher sensitivity to changes in weather factors, in contrast to the phytocenoses of the deposits. It is shown by general regression models that the epiterranean and subterranean biomass of cenoses on technozems depends on Selyaninov's hydrothermic coefficient for September and the amount of precipitation in October–November of the previous year and in January–May of the current year. The degree of this dependence for cenoses under research is determined by edaphic conditions that affect the species diversity and dominance structure.

Keywords: herbaceous phytocenoses, epiterranean and subterranean biomass, weather factors, anthropogenically impacted areas, heavy metals

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The steady functioning of living things is ensured by specific habitat conditions, e.g., soil substrate composition, phytocenotic relationships, weather factors, etc. Organisms have evolved a spectrum of responses to adequately react to possible changes in these "traditional" environmental factors. The same mechanisms are involved in stressful situations caused, for example, by anthropogenic impacts on soils, including intense chemical contamination. In plants, this leads to the adjustment of physiological, biochemical, and other suborganismal processes, as well as possible shifts in the species composition and productivity of plant communities.

The response of phytocenoses to altered edaphic conditions has been discussed in detail in extensive publications (Glazunov, 2005; Igosheva, 2007; Dymova, 2009; Morozova, 2009; Andreyashkina, 2012; Prasad et al., 2001; Khudsar et al., 2004; Kosobrukhov et al., 2004; Laidinen et al., 2013; Belykh et al., 2015; Kaznina et al., 2015). Exposure to aerogenic pollution from industrial plants transforms vegetation, along with changes in the structure of communities and a decline in taxonomic diversity and productivity of phytocenoses. In a number of cases, the change in the conditions of the growing season has been emphasized to induce a mixed response in plant communities (Kurkin, 1996; Pozolotina and Antonova, 2017; Gorchakovskii and Korobeinikova, 1975; Mirkin et al., 2001; Kayumov et al., 2014; Kryuchkov, 2016). However, studies on phytocenoses that grow in anthropogenically impacted areas under changeable weather factors are few in number and rather fragmentary (Zhuikova, 2009; Meling and Zhuikova, 2012, 2015; Gordeeva and Zhuikova, 2014; Zhuikova et al., 2010) because they require a long-term conditions-gradient monitoring of species composition and productivity in communities.

The goal of this paper is to examine the phytomass of herbaceous phytocenoses growing in anthropogenically impacted areas at different stages of succession during different growing seasons along the gradient of heavy-metal (HM) soil contamination. The assumption is that the communities give a mixed response to the main weather factors and are dependent on edaphic conditions and phytocenotic factors.

MATERIALS AND METHODS

We explored the productivity of herbaceous phytocenoses in the Tagil zone of the Middle Urals (60° E and 58° N, boreal geographical zone, and southern boreal forest subzone). The area is characterized by anthropogenically transformed natural systems as a result of 300 years of activities in the mineral industry and metallurgy that led to changes in soil physico-

Table 1. Concentrations of labile forms of HMs in soil samples under research ($M \pm m$) (as of 2011)

Plots	Z, rel.units.	Soil group	Type of phytocenosis	Available microelements, μg/g								
				Cd^{2+}	Co^{2+}	Cr^{3+}	Cu^{2+}	Fe^{3+}	Mn^{2+}	Ni^{2+}	Pb^{2+}	Zn^{2+}
BG	1.0	agrozem	meadow	0.2 ± 0.96	6.5 ± 0.85	13.1 ± 0.78	12.6 ± 0.89	788.9 ± 50.9	291.6 ± 27.2	13.0 ± 0.86	8.1 ± 0.91	17.5 ± 1.61
B-1	3.3			1.3 ± 0.00	16.8 ± 0.21	20.0 ± 0.46	38.6 ± 0.59	964.5 ± 1.65	359.0 ± 9.37	18.0 ± 0.32	13.2 ± 0.18	58.1 ± 1.10
B-2	6.2	technozem		0.9 ± 0.08	14.5 ± 3.63	7.8 ± 1.08	101.6 ± 11.13	841.1 ± 13.23	375.2 ± 54.02	7.4 ± 1.37	38.8 ± 4.91	262.7± 39.56
I-1	22.8		grasses	1.5 ± 0.47	124.2 ± 17.79	7.1 ± 2.26	951.5± 236.10	–	2364.9 ± 93.52	7.8 ± 1.30	12.4 ± 3.88	391.0± 125.92
I-2	30.0			2.8 ± 0.44	–	51.9 ± 3.44	194.6 ± 6.60	2736.6± 85.36	–	–	–	850.4 ± 18.26

Z is the total toxic load, M is the arithmetic mean, m is the error of the arithmetic mean, $n \geq 10$; and "–" denotes missing data.

chemical properties, including the deposition of HMs in soils.

The chemical composition of soils was examined in accordance with the certified methods of analysis in the laboratory at the Institute of Plant and Animal Ecology, Ural Branch, Russian Academy of Sciences (Certificate to Accreditation no. *ROSS* RU. 0001.515630). Soil sampling and analysis of HM content in soils was conducted in accordance with *GOST* 17.4.3.01 and methodological requirements (*Metodicheskie rekomendatsii...*, 1981; *Vremennye metodicheskie rekomendatsii...*, 1983; *RD 52.18.191–89 Metodicheskie ukazaniya...*, 1990). The level of HM concentration was measured in acid-digested samples (5 M HNO_3 as an extracting agent (soil : acid proportion is 1 : 5)) (Table 1) with a flame Atomic Absorption Spectrometry procedure using an AAS Vario 6 spectrometer of Analytik Jena AG.

Anthropogenically transformed zones were established based on HM contents in soils and a calculated index of toxic load (Bezel' et al., 1998):

$$Z = \frac{1}{n}\sum_{i}^{n}\frac{C_i}{C_{\hat{o}}}, \text{ rel. units,}$$

where C_i and $C_{\hat{o}}$ are concentrations of toxic elements on metal contaminated plots and background plot and n is the number of chemical elements involved.

Names of the zones (background, buffer, and impact zones) are used in accordance with the UNEP nomenclature (Global..., 1973). The following plots were set up within the zones: background plots (BG: Z = 1 rel. unit), buffer plots (B-1: Z = 3.3 and B-2: Z = 6.2 rel. units), and impact plots (I-1: Z = 22.8 and I-2: Z = 30 rel. units).

Along with the levels of toxic load, the studied gradient is conjugate to a set of soil physicochemical properties, which allow assigning them to two groups, namely, *agrozem*s (BG and B-1) and *technozem*s (B-2, I-1, and I-2).

Agrozems are found on "deposits" (arable land not cultivated for over 25 years) and characterized by an intermediate base saturation (V = 76%), as well as an intermediate and low supply of labile phosphorous and sodium compounds and intermediate and low concentration of easily hydrolysable nitrogen. Technozems are found in anthropogenic landscapes (industrial dumps of 45 years and more). These young soils are formed by *burozem* and *lithozem* types of soil-forming processes. The soils exhibit high base saturation of up to 99%; the exchange complex is dominated by calcium. The supply of exchangeable forms of phosphorous and sodium is high and very high; the nitrogen supply is low under weakly developed sod and high with the presence of sod.

By successional status, the herbaceous cenoses were identified as *meadow* type (BG, B-1, and B-2) and *grasses* type (I-1 and I-2). There are 78 species occurring in plant communities of the studied territory, which are members of 60 genera and 19 families. The communities on the plots in the background and buffer zones belong to Molinio–Arrhenatheretea class and correspond to a glycophytic variant of meadow vegetation type. Cenoses of the impact zones are transitional between the classes of Artemisietea vulgaris (ruderal biennial and perennial plants) and Agropyretea repentis (ruderal communities of perennial grasses, predominantly representative of a premeadow stage of progressive succession). We have previously elaborated on the edaphic conditions and phytocenoses of the area under research (Kaigorodova et al., 2013; Ivshina et al., 2014; Zhuikova et al., 2015; Bezel' et al., 2016).

The phytomass of the herbaceous cenoses was studied during the growing seasons of 2006 and 2009–2012 and the period of the maximum stand development. There were ten 25 × 25 cm quadrants set up at

Table 2. Phytomass of the cenoses in anthropogenically impacted areas during different growing seasons ($M \pm m$)

Growing season	Plots				
	agrozems		technozems		
	BG	B-1	B-2	I-1	I-2
	Epiterranean biomass, g/m^2				
2006	280.0 ± 46.3	360.2 ± 83.0	235.6 ± 34.5	176.4 ± 60.7	–
2009	215.0 ± 30.4	226.2 ± 27.9	196.1 ± 34.3	336.0 ± 92.4	371.4 ± 54.8
2010	310.8 ± 35.5	204.5 ± 15.3	279.6 ± 32.3	193.4 ± 29.6	334.1 ± 49.3
2011	252.7 ± 56.8	249.7 ± 56.5	113.7 ± 23.1	112.9 ± 19.0	115.7 ± 17.2
2012	277.0 ± 23.0	206.7 ± 46.8	198.3 ± 42.6	333.1 ± 44.7	206.7 ± 49.9
$M \pm m$	267.11 ± 15.96	249.44 ± 28.87	204.65 ± 27.35	230.36 ± 44.60	257.00 ± 58.84
	Subterranean biomass, g/m^2				
2006	385.9 ± 41.9	401.9 ± 82.5	366.7 ± 62.2	237.7 ± 27.8	–
2009	364.3 ± 45.2	350.1 ± 56.6	219.3 ± 56.6	221.6 ± 50.3	351.0 ± 51.9
2010	310.6 ± 44.9	284.5 ± 59.4	173.0 ± 32.8	90.8 ± 9.5	458.0 ± 50.5
2011	285.9 ± 51.5	334.4 ± 66.7	108.5 ± 22.7	78.4 ± 12.6	85.1 ± 12.5
2012	270.8 ± 46.2	204.4 ± 45.5	123.4 ± 19.7	187.5 ± 23.2	199.0 ± 49.2
$M \pm m$	321.71 ± 22.60	315.03 ± 33.45	198.16 ± 46.43	163.21 ± 33.16	273.24 ± 82.19

M is the arithmetic mean, m is the error of the arithmetic mean, and "–" denotes missing data.

3-m intervals in the studied phytocenoses. The method of monolith collection was used for sampling from a depth of 25 m (Shalyt, 1960; Kharitonov and Boikov, 1999; etc.). The plants within each quadrant were sorted by species. An air-dried epiterranean and subterranean biomass of all species from within the boundaries of the quadrants was evaluated in the laboratory.

For the weather factors that affect phytomass, we took the monthly average air temperatures, the sums of precipitation by months (mm), and Selyaninov's hydrothermic coefficient (HTC) (Romanova et al., 1993; The Encyclopedia..., 2005). The currently acting weather factors were analyzed starting from August of the previous year until July of the current year. We utilized data from the automated atmospheric condition monitoring of air and precipitation in Nizhny Tagil (station 2 in Sukholozhskii *poselok* of Dzerzhinskii district and station 4 in *Techposelok* of Tagilstroevskii district).

Statistical Analysis of the Results

The dependence of phytomass on the edaphic condition gradient was analyzed using the Spearman rank correlation coefficient (R_S); annual genetic variability was accessed through the Mahalanobis distance or generalized squared interpoint distance (SMD); a proportion of effect that the growing-season conditions and edaphic conditions produce on phytomass was determined using the analysis of variance.

The principal component analysis assisted in identifying the leading climatic factors that affect the epiterranean and subterranean biomass. For each contaminated zone, we determined its dependences on the climatic parameters, i.e., monthly average temperatures, amount of precipitations, and Selyaninov's hydrothermal coefficient (HTC). General regression models (GRMs) were used to estimate the combined effect of "plot × weather parameter" factors.

Statistical processing of data and illustration graph plotting was performed using standard Microsoft Excel 2007 and STATISTICA 8.0 software packages.

RESULTS

Change in epiterranean and subterranean biomass along a soil condition gradient during different growing seasons. The soil condition-gradient changes in phytomass of three main groups of herbaceous cenoses (forbs, legumes, and graminoids) have been analyzed in depth previously (Bezel' et al., 2016). In the present report, the same gradient is utilized to study the effects of weather factors on epiterranean and subterranean biomass of the communities while growing (Table 2). The epiterranean biomass of the considered herbaceous cenoses results from the production process and corresponds to their primary productivity. The subterranean biomass is reflective of the results of production process, along with the survival rate of the perennial parts of plants, and indicates the phytomass stock in total.

It has been established that a change in phytomass along the gradient of edaphic conditions differs with the growing season. In some years (2006 and 2011) this indicator, in terms of the studied gradient, decreases (epiterranean $R_S = -0.58$ and -0.38, $p < 0.01-0.001$ and subterranean $R_S = -0.62$ and -0.46; $p < 0.001$); in other years (2009) it significantly increases (epiterranean $R_S = 0.30$; $p < 0.05$) or slight changes are observed (2010 and 2012: epiterranean $R_S = -0.03$ and -0.02; $p > 0.05$ and subterranean $R_S = 0.06$ and 0.01; $p > 0.05$). This fact can probably be explained by the different response of herbaceous cenoses growing in different edaphic conditions to the weather factors during the growing season.

The influence of edaphic factors and growing conditions on the phytomass of the cenoses was assessed using the two-factor analysis of variance (Table 3). Among the two factors analyzed, varying growth conditions (year) produce a stronger effect on epiterranean biomass, whereas subterranean biomass is, to a greater degree, affected by edaphic conditions. The effect of both factors is stronger on the subterranean sphere, as is indicated by the proportion of explained variation, than on the epiterranean one. It is an interaction between edaphic factors and growth conditions that largely contributes to the explained variation.

Squared Mahalanobis distances (SMDs) were calculated to estimate the annual genetic variability of phytomass of different cenoses. Each studied cenosis was analyzed separately; year was used as a grouping variable (Fig. 1).

It has been found that the communities on agrozems are characterized by a low level of annual genetic variability and by the similarity of epiterranean and subterranean biomass sensitivity to the weather factors, as indicated by MSD values. The phytocenoses on technozems are more sensitive, with the sensitivity of the subterranean biomass being higher than the epiterranean. This difference is likely due to the direct contact of soil with the subterranean sphere of plants, which is exposed to the toxic effect to the maximum degree. As the chemical contamination progresses, the sensitivity of herbaceous cenoses (as expressed by the phytomass indicator) to the weather factors increases and peaks in the community of the I-2 plot.

Communities on technozems display a nonlinear dependence of the phytocenoses' sensitivity to the weather factors on a toxic load level. For example, the B-2 and I-2 plots share a similar level of annual genetic variability of their phytomass, which does not significantly differ from the phytomass on agrozems, notwithstanding a significant difference between them in contamination levels of soils and successional age of the phytocenosis. The dependence of phytocenosis on weather factors sharply rises on the I-2 plot. This suggests that the response of the communities to the growing season conditions is governed not only by the toxic load.

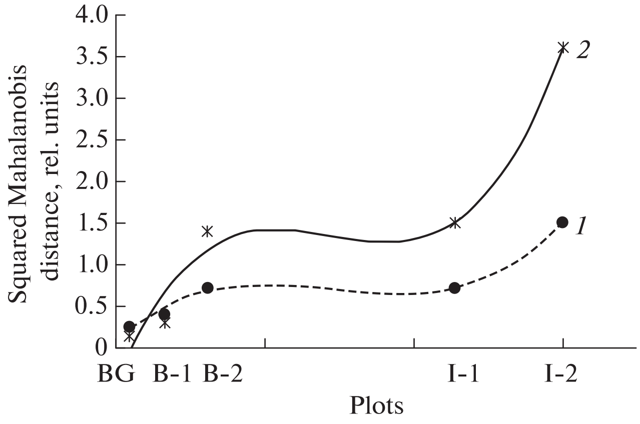

Fig. 1. Squared Mahalanobis distance describing the response of epterranean (*1*) and subterranean (*2*) biomass to the growing-season conditions.

The foregoing analysis does not provide answers as to which of the weather factors affect the phytomass and to what extent. The complexity of assessing such an influence of growing-season conditions on production processes in natural phytocenoses is linked to the cross correlation between multiple indicators (average monthly temperatures, precipitation, and HTC), making it difficult to identify the leading, statistically significant parameters. Principal component analysis was employed for the reduction of hydrometeorological data collected over a period of 20 years (1995–2015). Among the selected weather parameters, maximum factor loadings are associated with the fall and winter–fall precipitations (F1 and F2), which explain up to 39% of variance. Factor F3 includes the HTC for September (12.5% of variance). Further discussion is limited to investigating the effects of the outlined indicators, which explain up to a 52% of total growth condition variance, on phytomass (Table 4).

Throughout the time period under study (2006–2012), weather conditions on all plots corresponded to average climate norms; therefore, in accordance with the principal component analysis, the effects of three main parameters on epiterranean (Pa, g/m^2) and sub-

Table 3. Results of the two-factor analysis of variance with respect to the effect estimate of the growing season conditions (year) and edaphic factors of the plots on phytomass

Factor	*df*	*F*	*P*	% of explained variation
Epiterranean biomass				
Year (*1*)	3; 216	4.68	0.003	6.5
Plot (*2*)		4.30	0.006	6.0
Interaction (*1*) × (*2*)	15; 216	3.03	0.0002	21.6
Subterranean biomass				
Year (*1*)	3; 216	7.06	0.002	9.8
Plot (*2*)		15.37	≪ 0.001	21.4
Interaction (*1*) × (*2*)	15; 216	5.08	≪ 0.001	35.3

Table 4. Factor loadings of main weather factors on principal components over the period of 1995–2015

Indicators	Month	Principal components	
		1	2
Monthly average temperature	April	−0.427	0.076
	May	−0.325	0.285
	June	−0.293	0.660
	July	−0.581	−0.471
Monthly average precipitation	January	**−0.793**	0.110
	February	**−0.840**	−0.041
	March	**−0.956**	0.086
	April	**−0.816**	−0.190
	May	**−0.789**	0.172
	June	−0.355	−0.277
	July	−0.580	−0.509
	August	−0.544	0.464
	September	−0.505	0.441
	October	**−0.915**	−0.221
	November	**−0.825**	−0.057
	December	−0.657	−0.095
HTC	May	−0.612	−0.016
	June	−0.612	0.157
	July	−0.125	−0.038
	August	−0.437	−0.481
	September	−0.243	**0.775**
Eigenvalues		7.852	2.495
Proportion of the variance		**0.393**	**0.125**

Maximum-factor loading levels are typed in semibold.

terranean (Pr, g/m^2) biomass were assessed, namely, the sum of precipitation for October–November (S_1), the sum of precipitation for January–May (S_2), and Selyaninov's hydrothermal coefficient (HTC) for September. The relationship between biological productivity and weather factors is expected to be nonlinear (Odum, 1975); hence, the linearizing transformation (taking the logarithm of both parts of the model) was used prior to regression analysis:

$$\mathrm{LnP} = a_0 + a_1 \ln S_1 + a_2 \ln S_2 + a_3 \ln \mathrm{HTC}, \qquad (1)$$

where a_0, a_1, a_2, and a_3 are parameters of the model; S_1 is the sums of precipitation for October–November; S_2 is the sum of precipitation for January–May; and HTC is Selyaninov's hydrothermal coefficient for September.

Constants of the regression models are not statistically significant for the phytocenoses on agrozems (BG and B-1). The outlined weather parameters, though, have a significant effect on the technozem cenoses (B-2, I-1, and I-2), both on their epiterranean and subterranean biomass (Table 5). In addition, the epiterranean biomass is likely to change with the amount of precipitation by the periods and displays both positive and negative trends. The relationship of subterranean biomass with the winter–spring precipitation is positive for all plots and, with the fall amounts, is negative for the agrozem communities and positive for the technosem communities. Winter–spring precipitation is likely to have a weak (not statistically significant) effect on the subterranean biomass of the I-2 plot due to the absence in the vicinity of forest stands, which ensure snow retention. In contrast, the B1 and I-1 plots are surrounded by young forest cenoses, which do ensure the snow retention. A rise in HTC for September negatively impacts phytomass in all instances.

However, since in most cases the constants for the considered predictors are statistically insignificant (Table 5), they can only be indicative of a trend of the influence of the studied factors on phytomass.

We traced the combined effect of the edaphic conditions and weather parameters of the plots on phytomass using GRMs. Models for agrozems and technozems were calculated separately to factor out the possible effect of stages of succession of phytocenoses corresponding to the different plots. The type of model built is

$$\begin{aligned}\mathrm{LnPa} &= a_0 + a_1 Z + a_2 \ln S_1 \\ &+ a_3 \ln S_2 + a_4 \ln \mathrm{HTC},\end{aligned} \qquad (2)$$

(Z encodes a plot, while taking on values 1 or 0).

Constants, their statistical significance ($p < 0.05$, highlighted with semibold), and the coefficients of determination of regression models are presented below:

Agrozems

Epiterranean biomass

$$\begin{aligned}\mathrm{LnPa} &= 2.81 + 0.09\,Z(\mathrm{BG}) + 0.29 \ln S_1 \\ &+ 0.25 \ln S_2 - 0.18 \ln \mathrm{HTC};\ R^2 = 0.05.\end{aligned} \qquad (3)$$

Subterranean biomass

$$\begin{aligned}LnPr &= 4.89 + 0.07\,Z\,(\mathrm{BG}) - 0.94 \ln S_1 \\ &+ 0.90 \ln S_2 - 0.10 \ln \mathrm{HTC};\ R^2 = 0.1.\end{aligned} \qquad (4)$$

Technozem

Epiterranean biomass

$$\begin{aligned}\mathrm{LnPa} &= 2.51 - 0.01\,Z\,(\mathrm{I}-1) \\ &+ 0.06\,Z(\mathrm{I}-2) + \mathbf{2.06} \ln S_1 \\ &- \mathbf{1.21} \ln S_2 - \mathbf{0.75} \ln \mathrm{HTC};\ R^2 = 0.18.\end{aligned} \qquad (5)$$

Table 5. Characteristics of Eq. (1) for epiterranean and subterranean biomass

Plot	Constant; independent variable				R^2	p
	a_0	$a_1 \ln S_1$	$a_2 \ln S_2$	$a_3 \ln$ HTC		
			Epiterranean biomass			
BG	3.31	1.08	−0.48	−0.25	0.06	0.39
B-1	2.23	−0.49	1.00	−0.11	0.05	0.47
B-2	0.71	**1.82**	−0.66	**−0.73**	0.26	<0.003
I-1	1.00	**3.17**	**−1.82**	**−0.55**	0.23	<0.007
I-2	−8.41	−1.56	3.99	**−0.76**	0.30	<0.004
			Subterranean biomass			
BG	3.17	−0.44	0.84	−0.15	0.11	0.15
B-1	6.66	−1.49	1.00	−0.06	0.11	0.15
B-2	−7.12	0.36	**2.05**	**−0.69**	0.38	<0.001
I-1	−7.65	0.59	**1.98**	−0.20	0.40	<0.001
I-2	−2.65	1.37	0.39	**−1.37**	0.45	<0.001

Statistically significant constants ($p < 0.05$) are typed in semibold.

Subterranean biomass

$$\begin{aligned} \mathrm{Ln}\,\mathrm{Pr} &= \mathbf{-5.95} - \mathbf{0.19}Z(\mathrm{I}-1) \\ &+ \mathbf{0.32}Z(\mathrm{I}-2) + 0.76\ln S_1 + \mathbf{1.51}\ln S_2 \\ &\mathbf{-0.75}\ln \mathrm{HTC};\ R^2 = 0.33. \end{aligned} \quad (6)$$

The combined effects ($Z \times \ln S_1$; $Z \times \ln S_2$; $Z \times \ln$ HTC) were entered sequentially into each model (3–6). Further, we established their statistical significance and contribution to an improvement of the corresponding model (increase in the coefficient of determination).

After analyzing the phytomass of the agrozem communities, none of the studied combined effects "plot × weather parameter" were found to have a statistical significance ($p > 0.05$) or make any substantial contribution to improve models 3 and 4 ($R^2 < 0.12$). In contrast, an analysis of phytomass of the technozem communities revealed that combined effects "plot × sum of precipitation (October–November)" and "plot × HTC (September)" were statistically significant ($p < 0.001$) and improved the coherence of the theoretical data (obtained for models 5 and 6) with the factual data both for epiterranean ($R^2 = 0.24$) and subterranean ($R^2 =$ 0.37–0.43) biomass.

Thus, the effect of weather parameters (precipitation and HTC) on phytomass of the studied phytocenoses is manifested in different ways depending on edaphic conditions, including HM soil contamination.

DISCUSSION

Based on an analysis of the weather factors that affect the phytomass of herbaceous plant communities, the most significant proved to be precipitation for the period of October–November and the months of January–May, as well as Selyaninov's hydrothermal coefficient; however, their effect does not appear to be unique. It is specific characteristics of soils that seem to be responsible for the observed lack of statistically significant influence of these indicators on epiterranean and subterranean biomass of the agrozem plots (BG and B-1) and technozem plots (B-2, I-1, and I-2). The first two plots are characterized by agricultural soddy–podzolic soils prograded by "sod" soil-forming process. These plots feature rocky "heavy" loam (alphitite content of 40% and more) and clay soils formed on the diluvium of calcareous clays with the pronounced horizons (O, AY, P, (EL), BEL, BT). The thickness of the matted humus horizon AY is 0–4 cm; the plow horizon (P) is 19–25 cm.

In contrast to agrozems, technozems are young soils formed on dumps of different types and subtypes; e.g., the B-2 is presented by silty loams on talc schist with anthropogenic inclusions; I-1 is presented by rocky clay loams with inclusions of iron ore agglomerate, concentrate, slag, limestone, talc, etc.; and I-2 is presented by rocky heavy loams with inclusions of slag, ore, crushstone, and crushed quartz and talc stone (Zhuikova et al., 2015). Only the O, AY, and Ctech horizons are clearly distinguished in the technozems. The thickness of the sod horizon does not exceed 6 cm; there is no plow horizon. The soil structuring and availability of the developed plow horizon seem to ensure the continued fertility of agrozems and less exposure of their productivity of cenoses to weather factors, as opposed to technozems, young soils of which are unable to sustain fertility. This is in concordance with the ideas about an increase in soil fertility resources as soil develops over time (e.g., Kukresh, 2011).

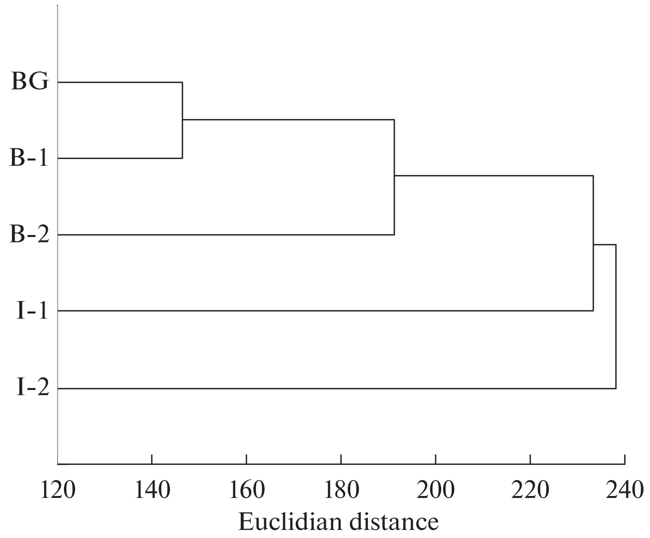

Fig. 2. Cluster analysis of epiterranean biomass of herbaceous cenoses on plots with different levels of chemical contamination.

The determined differences in response of phytocenoses to weather conditions cannot be narrowed down to edaphic conditions alone. A certain part can be undoubtedly attributed to the species composition and the dominance structure of herbaceous cenoses. The most remarkable differences are manifested on the technozem plots.

The B-2 community includes 47 species and is polydominant in structure. In different years (2006 and 2009–2011), its codominants were represented by the following species: *Trifolium pratense* L. (13–18%), *Festuca pratensis* Huds. (20%), *Poa palustris* L. (17%), *Lathyrus pratensis* L. (13–15%), *Carum carvi* L. (11–16%), *Achillea millefolium* L. (11%), *Leucanthemum vulgare* Lam. (10%), *Veronica chamaedrys* L. (12%), and *V. longifolia* L. (10%). A group of “other species” contributes 33–63% to the total structure of epiterranean biomass. Single dominant species *T. pratense* L. (23%) and two subdominant species *L. pratensis* L. (13%) and *C. carvi* (10%) occurred in the community in 2010. The annual genetic variability for epiterranean biomass of the dominant species is 42.5%.

There are 42 species growing in the I-1 plot cenosis. The species structure is characterized by the stability of *Calamagrostis epigeios* (L.) Roth. dominance with a 35–53% participation in epiterranean biomass. The absolute dominance of this species was noted only for 2011 and 2012. The species was relatively dominant in 2006 and 2010. Subdominants were represented by *T. pratense* L. (11–20%) most of the time and *Chamerion angustifolium* (L.) Holub (10%) and *Melilotus albus* Medik. (11%) in some years. Two codominants were present in the cenosis in 2009, namely, *C. epigeios* (L.) Roth. (45%) and *L. pratensis* L. (25%). Other species accounted for 29–53%. The annual level of genetic variability for the epiterranean biomass of the dominant species was 48.6%.

Phytocenosis of the I-2 plot contains 32 species and features a stable dominance of bushgrass with 46–69% participation. Its absolute dominance was recorded in 2009–2011. Subdominants are represented by *L. pratensis* L. (11%) or *Cirsium setosum* (Willd.) Bess. (16%). In 2012, the share of *C. epigeios* (L.) Roth. in the total phytomass was slightly under 50% (46.4%). Along with it, *L. pratensis* L. (28%.) was gaining phytomass, corresponding to the dominant status. Other species accounted for 15–26% of the structure of dominance. The annual genetic variability level for the epiterranean biomass of the dominant species was 48.6%.

It has been established that the total phytomass of a cenosis is correlated with a phytomass of the dominant ($R_S = 0.61$; $N = 20$; $p = 0.004$). The degree of variation of the latter increases along the gradient of contamination from 26.0–26.5% on agrozems to 42.5–53.5% on technozems and is correlated with values of squared Mahalanobis distance ($R_S = 0.8$), which reflect the response of epiterranean biomass to conditions of the growing season (Fig. 1). The sensitivity of the cenoses to weather factors in terms of the phytomass indicator is also associated with species richness. Within the entire contamination gradient under investigation, we observed a decline in species richness from 55 species on agrozems to 32 on the I-2 ($R_S = -0.9$; $N = 5$; $p = 0.0037$), which is inversely related to the annual genetic variability of the phytomass ($R_S = -0.8$).

Distinctions in species richness between agrozems and technozems become evident when clustering the 5 years of observations over the phytomass of plants growing on the studied plots (Fig. 2).

It is possible to group into the same cluster the communities of BG and B-1 plots, which are similar in agrochemical features of the soils they are growing on and successional age (meadow-type cenoses); communities on technozems (B-2, I-1, and I-2) do not form a single cluster. This appears to be governed by the aforementioned differences in soils of the plots and the species richness of their phytocenoses.

The established dependence of phytomass on the sum of precipitation for October–November and January–May on the given plots can be attributed to two important periods defined in the development of herbaceous perennials, which have an impact on their productivity, that is, the spring period associated with the onset of growing and active processes of phytomass gain and the fall period, whereby the formation of vegetative and reproductive buds occurs, the quantity and quality of which affects the yield of the next year (Kuperman, 1977; Mustafaev, 2007). Perennial meadow graminoid species display spring and summer–fall periods of tillering, the intensity of which is influenced by the moisture regime; type, dose, and timing of fertilizer application; and other factors (Mustafaev, 2007).

Precipitation in October–November performs the moisture-accumulation function and positively impacts the epiterranean biomass. This is closely associated with preventing winter desiccation and the springtime lack of moisture that control the onset of growth. On the other hand, the heat capacity of wet soil is higher than that of dry soil; therefore, sufficiently moistened soil retains heat longer and freezes and thaws more slowly. Hence, with January thaws, the temperature variation will be smoothed out, which is favorable for plants (Yudaev and Bulanova, 2013; Lyashevskii and Tishchenko, 2017; Umarova et al., 2011).

According to our model, it is the sum of precipitation for January–May that positively impacts subterranean biomass. This is probably related to snow-cover depth, which does not only protect the root zone from frost penetration but also supplies the soil with the necessary reserve of soil moisture during the spring melt period.

The negative impact of the winter–spring precipitation on epiterranean biomass determined for the I-1 plot can likely be explained by the asphyxiation effect (Podgornyi, 1971). This primarily concerns nonhardy plants, including, for example, *T. pratense* L. (Mustafaev, 2007). The position that this species (occurring on the I-1 plot) occupies in the cenosis structure varies. During the seasons with dry winter conditions, it builds up the maximum phytomass (up to 68 g/m^2) and acts as a subdominant species with a relative dominance of 20% and more, which promotes the total phytomass gain up to 333 g/m^2. During growing seasons with snowy winters, its phytomass drops to 4–20 g/m^2 and the participation in the total phytomass of the community is reduced to 1–11% or is excluded from the dominant group altogether

Rather surprisingly, no direct effect on productivity in the studied herbaceous cenoses is observed from monthly average temperatures. This weather parameter is taken into account only by means of Selyaninov's hydrothermal coefficient, the effect of which is negatively correlated with phytomass (Table 5). The impact that the HTC for September has on productivity arises from an excessive accumulation of water in the soil and low air temperature. In this setting, water viscosity increases; this results in a decrease in its mobility, the permeability of cytoplasm, and rates of all metabolic processes. Such a "physiological drought" can inhibit the development of subterranean and epiterranean organs of plants (Yakushkina and Bakhtenko, 2005). Fall periods with a small amount of precipitation and high effective temperatures are favorable for the formation of epiterranean and subterranean biomass.

The seemingly surprising excessive sensitivity to weather factors displayed by subterranean biomass of technozem cenoses through an increased annual genetic variability when compared to the epiterranean biomass appear to be due to the direct contact of the subterranean sphere of plants with the soil, which is exposed to the maximum toxic effects from the presence of high concentrations of HMs in soils of these plots.

CONCLUSIONS

(1) In the conditions of the Middle Urals, among the selected parameters (monthly average temperatures, the sum of precipitation by months, and Selyaninov's hydrothermal coefficient), the maximum factor loading were found to correlate with the fall and winter–spring precipitation, as well as HTC for September, based on 20 years of hydrometeorological observations using the principal component analysis.

(2) As was shown by the results of regression analysis, anthropogenically impacted but structured soils of the deposits that feature a sufficiently developed plow horizon (agrozems) assure the continued productivity of herbaceous cenoses and reduce their dependence on the growing conditions.

(3) The cenoses that are formed on young soils of dumps (technosems) are in marked contrast to the phytocenoses of the deposits (agrozems) and display less resistance and higher sensitivity to changes in weather factors. The sensitivity of the herbaceous cenoses (as expressed by the phytomass indicator) is observed to increase along the soil-contamination gradient, while being more pronounced for the subterranean sphere. However, the dependence is nonlinear, since it is determined by a broad range of factors.

(4) The degree of manifestation of a response of some technozem phytocenoses to the leading weather factors is determined by edaphic conditions that impact the species diversity and the dominance structure in the communities. Fall periods with a small amount of precipitation and high active temperatures were found to be the most favorable for the formation of epiterranean and subterranean biomass on such soil.

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