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Aboveground Phytomass and Rate of Plant Debris Decomposition in Herbaceous Communities Exposed to Soil Pollution with Heavy Metals

V. S. Bezel'[a], **T. V. Zhuikova**[a,b], **V. A. Gordeeva**[b], **E. V. Meling**[b], **A. B. Trubyanov**[c], **and N. V. Glotov**[c]
[a] *Institute of Plant and Animal Ecology, Ural Branch, Russian Academy of Sciences, ul. Vos'mogo Marta 202, Yekaterinburg, 620144 Russia*
[b] *Nizhny Tagil State Social Pedagogical Institute, ul. Krasnogvardeiskaya 57, Nizhny Tagil, 622031 Russia*
[c] *Mari State University, pl. Lenina 1, Yoshkar-Ola, Mari El Republic, 424000 Russia*
e-mail: bezel@ipae.uran.ru

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Abstract—Consideration is given to production and decomposition processes in herbaceous communities exposed to chemical pollution with heavy metals in the Middle Urals. High variation in the aboveground phytomass of agrobotanical groups (legumes, forbs, grasses) is due to spatial heterogeneity of soil pollution levels and consequent changes in the species composition of plant communities in the areas studied. Therefore, nonparametric statistical methods have been used (Kruskal—Wallis test with subsequent pairwise comparisons by Wilcoxon—Mann—Whitney with Bonferroni correction for multiple comparisons). The phytomass of legumes remains unchanged in the increasing pollution gradient, while the contribution of forbs to the total phytomass decreases and that of grasses increases. Soils rich in nutrient elements can maintain a high rate of plant debris decomposition, counterbalancing the adverse effect of increased heavy metal concentrations on relevant processes. The balance between production and mineralization processes provides for the sustainable, long-term existence of herbaceous communities under conditions of intense pollution of the natural environment.

Keywords: herbaceous phytocenoses, biological productivity, decomposition processes, chemical pollution, heavy metals

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The fate of biogeocenosis (BGC) as a complex of living, nonliving, and inorganic components under any anthropogenic impact depends on the degree to which this system is capable of maintaining the turnover of matter (Vernadsky, 1934; Koval'skii, 1990). The problem of biological turnover has become especially acute in the context of chemical pollution of the environment. Technogenic impacts lead to change in the volume of evolutionarily conditioned biogenic fluxes and can affect functional stability of natural BGCs.

Numerous publications are available about the impact of chemical pollution on the state of plant communities of different composition growing under different ecogeographic conditions. However, their scope is usually limited to analysis of levels to which chemical elements have been accumulated by different components of natural ecosystems (Bezel' et al., 1998; Goryunova, 2001; Fedorova and Odintseva, 2005; etc.). Meanwhile, the sustainable functioning of natural BGCs depends on the balance between the synthesis of primary production and its subsequent decomposition and mineralization. The rate of these processes, in turn, depends on many factors, including edaphic conditions such as soil acidity and contents of aluminosilicates and humus, the composition and abundance of soil biota, and the effects of chemical pollution on these factors (Berg et al., 1991; Chew et al., 2001; Vorobeichik, 2002; Fischer et al., 2006; Parshina, 2007; Pomazkina, 2011; Kaznina and Titov, 2013; Zhuikova et al., 2013).

This paper deals with changes in the rates of phytomass production and decomposition in herbaceous ecosystems exposed to different levels of technogenic pollution with heavy metals. The differences revealed between these ecosystems appear to be contingent not only on the level of toxic impact but also on the composition of soil substrate and growing conditions.

MATERIAL AND METHODS

General characteristics of the study region. Studies were performed in the zone exposed to airborne emissions from the ferrous metal industries of the Middle

Urals (the city of Nizhny Tagil, Sverdlovsk oblast; 58° N, 60° E). The largest industry is the Nizhny Tagil Iron and Steel Works (OAO NMTK, Evraz Group S.A.), which has been in operation since 1938. Priority pollutants are fine dust particles containing oxides of heavy metals (Cr, Ni, Fe, Cu, Zn, Cd, Pb) and sulfur. The greatest excess over the background concentrations in the pollution gradient has been recorded for Cd (78-fold), Zn (29-fold) and Cu (10-fold). Mobile forms of heavy metals account for 70–90% of their total contents in the soil.

Based on the overall coefficient of heavy metal concentration in the soil (Z) expressed in relative units with respect to the background values, zones of toxic load were delimited and named according to the UNEP nomenclature (*Global...,* 1973): the background zone, where one plot (Bg) was established (Z = 1.44 rel. units); the buffer zone with two plots, B-1 (Z = 3.53 rel. units) and B-2 (Z = 9.03 rel. units); and the impact zone with two plots, I-1 (Z = 21.58 rel. units) and I-2 (Z = 29.53 rel. units).

The long-term industrial development of the study area has resulted in the formation of soils that largely differ in many parameters from its natural soddy podzolic soils. With regard to landscape and edaphic conditions, plots Bg and B-1 were classified as *agrozems,* and plots B-2, I-1, and I-2, as *technozems.*

Agrozems formed in agrolandscapes are agro-soddy podzolic soils with medium fertility and low to moderate base saturation (V = 50–95%) and contents of mobile phosphorus and potassium. The contents of readily hydrolyzable nitrogen compounds are medium to low.

Technozems are young soils developing in technogenic landscapes (on spoil banks aged over 45 years) into burozem and lithozem types. They are characterized by higher fertility, high base saturation (V > 95%), and high or very high contents of exchangeable phosphorus and potassium. The contents of nitrogen are low if sod is poorly developed and high if it is well developed.

The list of plants recorded in herbaceous communities of the study area includes 78 species from 60 genera and 19 families. Communities of the background and buffer plots belong to the class Molinio-Arrhenatheretea and correspond to the glycophytic variant of the meadow vegetation type. Communities of the impact zone are transitional between the classes Artemisietea vulgaris (ruderal communities of biennials and perennials) and Agropyretea repentis (ruderal communities with prevalence of perennial grasses representing the stage of progressive succession that precedes the meadow stage).

Detailed characteristics of pollution levels, soils, and species composition of herbaceous communities are given in previous publications (Kaigorodova et al., 2013; Zhuikova et al., 2015; Ivshina et al., 2014).

Assessment of primary productivity of communities. During the growing seasons of 2009–2012, ten 25 × 25-cm microplots were established in each of the studied phytocenosis at the peak of herb layer development. Samples were taken by the monolith method from a depth of 25 cm (Shalyt, 1960; Kharitonov and Boiko, 1999). Plants from each microplot were sorted by species, and the air-dry aboveground phytomass of each species in the microplot was determined in the laboratory. Further analysis of productivity was performed for three agrobotanical groups: legumes, grasses, and forbs.

Dominant species of these groups in the test plots were as follows. Plot Bg: legumes *Lathyrus pratensis* L. (9–31% of the total phytomass) and *Trifolium pratense* L. (7–9%); grasses *Poa angustifolia* L. (13–18%) and *Festuca pratensis* Huds. (8–10%); forbs *Pimpinella saxifrage* L. (9–22%), *Carum carvi* L. (7–10%), and *Tanacetum vulgare* L. (7–20%). Plot B-1: legumes *Lathyrus pratensis* L. (7–23%) and *Trifolium medium* L. (8–18%); grasses *Poa palustris* L. (4–14%), *Deschampsia caespitosa* (L.) Beauv. (10%), *Poa angustifolia* L. (4–9%), and *Festuca pratensis* Huds. (14–20%); forb *Alchemilla vulgaris* L. (33–52%). Plot B-2: legumes *Lathyrus pratensis* L. (4–15%) and *Trifolium pratense* L. (18–23%); grasses *Festuca pratensis* Huds. (6–20%) and *Poa palustris* L. (6–17%); forbs *Carum carvi* L. (10–17%) and *Achillea millefolium* L. (5–11%). Plot I-1: legumes *Lathyrus pratensis* L. (5–25%) and *Trifolium pratense* L. (9–20%); grass *Calamagrostis epigeios* (L.) Roth (35–56%); forbs *Tussilago farfara* L. (4–9%), *Chamaenerion angustifolium* (L.) Scop. (5–10%), and *Cirsium setosum* (Willd.) Bess. (4–6%). Plot I-2: legumes *Lathyrus pratensis* L. (11–28%) and *Carum carvi* L. (4–9%); grass *Calamagrostis epigeios* (L.) Roth (46–69%); forbs *Cirsium setosum* (Willd.) Bess. (5–16%) and *Picris hieracioides* L. (2–5%).

The rate of plant debris decomposition. A field experiment was performed in the same communities where primary productivity was studied. Ten air-dry phytomass samples from each of the three agrobotanical groups of plants (2.001 ± 0.009 g) were placed in bags made of 0.5-mm nylon mesh and inserted in the upper 3- to 4-cm soil layer at 30-cm intervals along transects laid in the five plots where the phytomass was collected (Bg, B-1, B-2, I-1, and I-2). The samples were exposed during 12 months (beginning from May 5–8, 2010), and then the contents of the bags were dried at 105°C and the decomposition rate was estimated from the loss of sample weight over the above period (Vorobeichik, 2002; Vorobeichik and Pishchulin, 2011).

Statistical analysis. Variation in the aboveground phytomass of each agrobotanical group per microplot within each phytocenosis during 1-year observation period was very high. The values of this parameter ranged from 0 to 843 g/m^2, and their distribution was J-shaped (Fig. 1).

The distribution of parameter "decomposition rate" at given sample sizes could not be described systematically (uni- or multimodality, high positive kurtosis, left- or right-sided asymmetry). Therefore, the data were analyzed by nonparametric methods: the Kruskal–Wallis test (*KW*) with subsequent pairwise comparisons by the Wilcoxon–Mann–Whitney test (*WMW*) with Bonferroni correction for multiple comparisons (Rebrova, 2002). The median was used as the position parameter.

The values of biomass of plants from different agrobotanical groups per microplot in a given community and year do not correlate with each other (only 3 out of 60 values of Spearman's rank correlation coefficients differ from zero at 5% significance level). Therefore, the analysis of results can be performed for each agrobotanical group separately.

RESULTS AND DISCUSSION

Aboveground phytomass. In most cases, the amount of phytomass collected in the period of its maximum development is used as a measure of primary production of herbaceous communities. This parameter does not take into account the phytomass that dies off during the growing season. A detailed analysis of the composition of a herb–legume–reed grass meadow community (similar to those considered here) has shown that the production of herbaceous phytocenoses estimated from the maximum harvest is 1.5–2.5 times lower than its actual value (Titlyanova, 1977, 1979). However, since direct determination of the annual primary production of herbaceous phytocenoses is methodologically difficult, we considered it possible to estimate the total aboveground phytomass production of phytocenosis from the phytomass collected at the peak of its development.

The phytomass of forbs in each plot do not differ significantly between years (*KW*: $p = 0.10–0.78$). The sum of data over 4 years show that the median values monotonically decrease with an increase in toxic load (*KW*: $p = 1.4 \times 10^{-8}$) (Fig. 2). In pairwise comparisons, Bg and B-1 differ from I-1 and I-2 (*WMW*: $p = 1.0 \times 10^{-6}–5.8 \times 10^{-4}$), and B-2 differs from I-2 (*WMW*: $p = 1.6 \times 10^{-4}$); in both cases, the difference (with Bonferroni correction) is significant at 1% level.

The phytomass of legumes proved to differs between years in plots Bg (*KW*: $p = 6.4 \times 10^{-3}$), B-2 (*KW*: $p = 1.1 \times 10^{-2}$), and I-1 (*KW*: $p = 4.7 \times 10^{-3}$); therefore, its dependence on toxic load was analyzed separately by years. The results showed that the phytomass of legumes was independent of pollution level in 2009 (*KW*: $p = 0.13$), 2010 (*KW*: $p = 0.28$), and 2012 (*KW*: $p = 0.54$). The effect of pollution manifested itself in 2011 (*KW*: $p = 0.0076$), but it was not systematic: the phytomass in I-1 was lower than in B-1 (*WMW*: $p = 7.6 \times 10^{-4}$; the difference with Bonferroni correction is significant at 1% level) and lower than in I-2 (*WMW*: $p = 4.7 \times 10^{-3}$; the difference with Bonferroni correction is significant at 5% level), because legumes in plot I-1 were absent in nine out of ten microplots. It may be concluded that the total phytomass of legumes over the observation period is independent of toxic load (see Fig. 2).

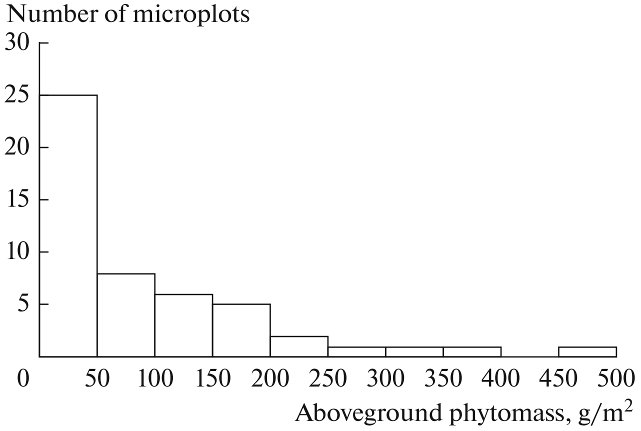

Fig. 1. Distribution of legume phytomass by microplots in 2012 (distribution pattern does not differ between pollution zones).

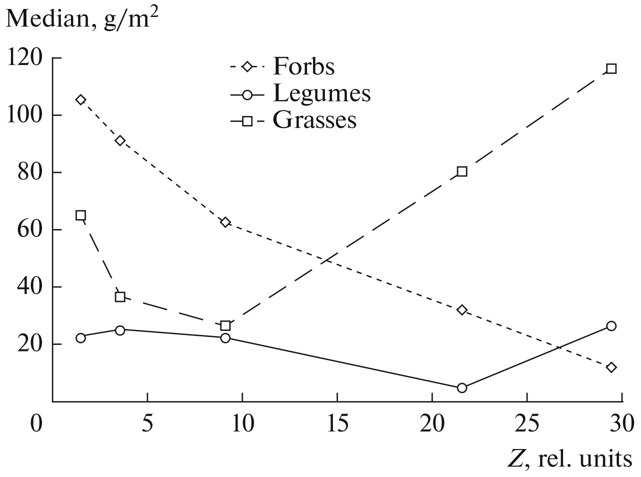

Fig. 2. Dependence of phytomass on toxic load for different agrobotanical groups.

The phytomass of grasses differed from year to year in plots B-1 (*KW*: $p = 3.2 \times 10^{-2}$) and I-2 (*KW*: $p = 1.8 \times 10^{-3}$), and its dependence on toxic load was analyzed separately by years. Changes in the phytomass between the plots were significant in 2009 (*KW*: $p = 0.0057$; in multiple comparisons by WMW with Bonferroni correction, only the difference between B-1 and I-2 was significant at 5% level, $p = 0.0028$), in 2010 (*KW*: $p = 0.0005$; in multiple comparisons by WMW with Bonferroni correction, the difference of B-1 and B-2 from I-2, with higher values in the latter plot, is significant at 5% level; the difference between

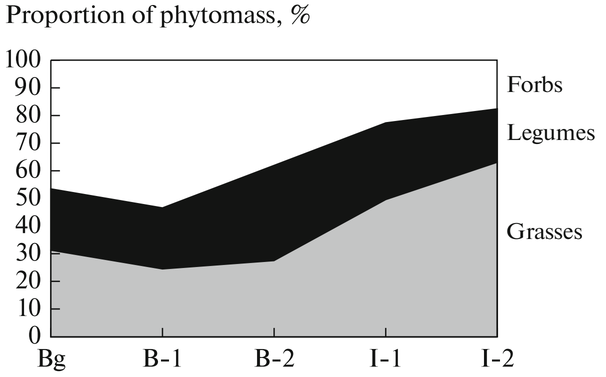

Fig. 3. Proportions of phytomass of different agrobotanical groups in the total aboveground phytomass.

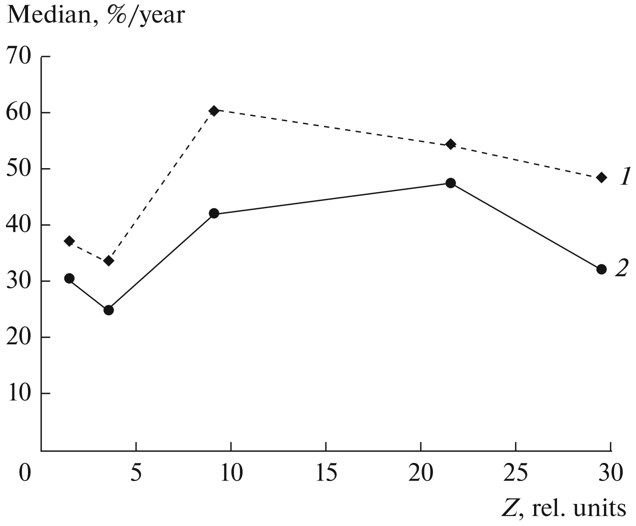

Fig. 4. Decomposition rates of (*1*) forbs and (*2*) legumes + grasses under different technogenic loads.

Bg and B-1 is also significant, but the values are higher in the former plot; $p = 1.0 \times 10^{-3}$–3.6×10^{-3}), and in 2011 (*KW*: $p = 0.004$, in multiple comparisons by WMW with Bonferroni correction, the difference between B-2 and I-2 is significant at 5% level; $p = 2.8 \times 10^{-3}$). Differences in the phytomass of grasses along the gradient of toxic load in 2012 lacked statistical significance ($p = 0.54$). Its values tended to increase in I-2 and decrease in B-1 and B-2, compared to Bg (Fig. 2).

Figure 3 shows the proportions of phytomass of different agrobotanical groups in the total aboveground phytomass. The forbs : legumes : grasses ratio changes along the gradient of chemical soil pollution from 46.8 : 21.3 : 31.9 in plot Bg to 17.7 : 19.1 : 63.2 in I-2.

Thus, the amount of phytomass per unit area decreases along the gradient of toxic load in forbs, increases in grasses, and remains unchanged in legumes, with the total phytomass of all agrobotanical groups on agrozems does not differ between the plots. The phytomass of grasses on technozems at small loads ($Z = 9.03$ rel. units) is lower than on agrozems. In our opinion, the specific J-shaped distribution patterns of aboveground phytomass per unit area and its individual irregular values in different years under different loads are indicative of heterogeneity of soil pollution levels and consequent irregularity in the distribution of herbaceous plant species within the identified phytocenoses. This conclusion is in agreement with data obtained by other researchers (Vorobeichik, 2002).

The rate of plant debris decomposition. Many authors have noted that this rate decreases in soils exposed to pollution with heavy metals and sulfur compounds (Vorobeichik, 2002; Berg et al., 1991; etc.). However, the opposite effect is also possible: mineralization processes may be accelerated in agroecosystems with polluted soils (Pomazkina, 2011). Thus, the role of metal-tolerant decomposers (bacteria and fungi) increases at high concentrations of trace elements in soils, with consequent intensification of organic matter decomposition (Ivshina et al., 2014).

The decomposition rates of legumes and grasses did not differ from each other in any of the plots (*WMW*: $p = 0.12$–0.78), and this allowed us to compare the decomposition rate of forbs with that of a pooled sample of legumes and grasses. As shown in Fig. 4, all points of the decomposition curve for forbs are located above the curve for the pooled sample Comparison of ten median values shows differences in

Results of statistical analysis of decomposition rates (p values according to Wilcoxon–Mann–Whitney test)

Comparison of agrobotanical groups (forbs and legumes + grasses) at different technogenic loads				
Bg	B-1	B-2	I-1	I-2
1.8×10^{-2}	0.11	6.5×10^{-4}*	3.0×10^{-3}	2.4×10^{-4}*
Comparison of zones with increasing technogenic loads				
Agrobotanical groups	Bg and B-1	B-1 and B-2	B-2 and I-1	I-1 and I-2
Forbs	0.21	5.8×10^{-4}*	0.21	1.1×10^{-2}
Legumes + grasses	0.30	9.7×10^{-6}**	3.0×10^{-3}	2.4×10^{-6}**

Significance level (with Bonferroni correction): *$p < 0.05$, **$p < 0.01$.

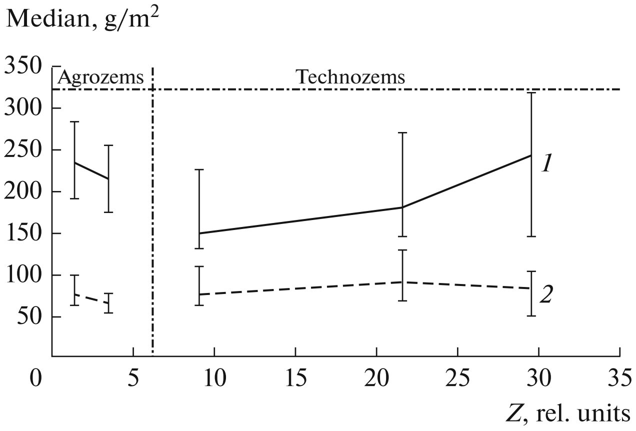

Fig. 5. Changes in (*1*) aboveground phytomass and (*2*) phytomass decomposed over 1 year in the gradient of soil pollution with heavy metals. (bars show 95% confidence interval for the median).

pairs forbs vs. legumes + grasses are statistically significant (*KW*: $p = 7.4 \times 10^{-13}$). Statistical analysis of pairwise comparisons is given in the table.

Differences between groups "forbs" и "legumes + grasses" are statistically significant in plots B-2 and I-2. The decomposition rate of both groups in B2 significantly increases, compared to B-1. A significant decrease in the decomposition rate of legumes + grasses is observed in I-2 compared to I-1, while this decrease in case of forbs lacks statistical significance.

Thus, the rate of plant debris decomposition in agrozems (Bg and B-1) is similar for all agrobotanical groups and remains unchanged. This rate increases upon transition to technozems (from B-1 to B-2), especially for forbs. The decomposition rate of legumes + grasses significantly decreases upon transition from I-1 to I-2.

Our data show that, regardless of the group of soils and the gradient of their chemical pollution, the amount of annually decomposed aboveground phytomass changes only slightly and is sufficient for the level of biogenic turnover necessary for sustainable (over many years) functioning of the herbaceous communities studied (Fig. 5). This specific adaptation of communities to toxic stress is provided for by changes in their species composition (Zhuikova et al., 2015) and spectra of decomposers in the pollution gradient (Ivshina et al., 2014).

Since the species composition of plants and their average productivity in all the plots remain stable over a long period of time, the amount of annually decomposed and mineralized aboveground plant parts is sufficient for the sustainable biogenic turnover of carbon and ash elements even under conditions of chemical pressure.

CONCLUSIONS

It is shown that studies on productivity of plant communities and decomposition rate of plant remains under conditions of high spatial variability of pollution fields require adequate nonparametric methods for analyzing the collected material.

The balance between the processes of organic matter production and degradation is maintained at different levels of chemical pollution and related changes in the species composition and productivity of plant communities growing on soils of different genesis, which allows the maintenance of biogenic turnover at the adequate level and thereby ensures sustainable functioning of herbaceous communities.

The results presented above have been obtained in the southern taiga subzone of the Urals and concern herbaceous communities of certain species composition growing on soils of certain groups and exposed to chemical pollution of certain kind and intensity. Multiplicity of biotic and abiotic factors influencing the rate of biogenic turnover suggests the necessity of cautious approach to wide generalizations and attempts to directly extrapolate the above data to different ecological situations.

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