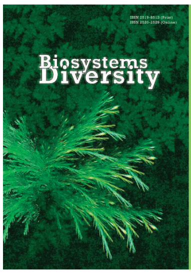

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Accumulation of heavy metals in birch and pine forest roadside phytocenoses in the south of Tyumen region

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We conducted a complex investigation of anthropogenic roadside phytocoenoses. For the study, 8 plots (birch and pine forests) were selected, close to roads in the south of Tyumen region within the five administrative districts: Uporovsky, Zavodoukovsky, Yalutorovskiy, Yarkovsky, and Tobolsk. As a result of the studies, 75 species of vascular plants from 21 families were noted in the plant communities. It was found that the majority of the total projective cover of the plant communities was provided by synanthropic species. In the synanthropic fraction of the flora, 33 species belonging to 11 families were identified, those with the most species being: Scrophulariaceae, Compositeae, Rubiaceae, Poaceae, Fabaceae, Polygonaceae, Umbellíferae. The index of synanthropization of the flora of the studied phytocenoses is in the range from 43% to 64%. Among the identified pollutants accumulated in the phytocenoses, the group of heavy metals was identified (Cr, Cu, Ni, Pb, Sr, Zn). Needles of *Pinus sylvestris* L. mainly accumulate Cr, Cu, Ni, Sr. The greatest concentration of Pb and Zn was found in the leaves of *Betula pendula* Roth. The content of other heavy metals in the leaves of *Betula pendula* Roth. during the growing season was relatively stable. Accumulation of heavy metals in the studied components of forest ecosystems can be displayed structurally: soil > leaves < phytomass (birch forests), soil < needles > phytomass (pine forests). Methodological approaches to conducting a complex of long-term observations of natural ecosystems have been formulated, substantiated and justified. To evaluate the absorption efficiency of heavy metals, the biological absorption coefficient was calculated. The obtained results can be used as a control in the study of migration and accumulation of heavy metals and for assessing the degree of anthropogenic load on phytocenoses of roadside ecosystems and predict the extent of probable changes in them. The forecast of the results will facilitate the elaboration of a necessary system of measures aimed at increasing the stability of plant communities.

Keywords: phytocenosis; anthropogenic ecosystems; synanthropization index; *Betula pendula* Roth.; *Pinus sylvestris* L.

Introduction

Autotransport is one of the main sources of anthropogenic environmental pollution. In large cities and oblasts, iincluding Tyumen oblast, over a half the volume of harmful emissions were caused by the motor vehicles. The literature on the pollution with heavy metals of phytocenoses by roads in the south of Tyumen oblast is quite limited. A study on the accumulation of heavy metals in the soil of the region was conducted by Ilyin (1987, 1991) and Guseynov (2001).

Intense development of the road network and a clear tendency towards increase in the number of motor vehicles on the roads has made the roads one of the most powerful sources of environmental pollution.

The total motorization taking place in the present time clashes fundamentally with the ecological requirements of the environment around the whole world. Massive resort to motor-driven vehicles leads to significant pollution of the environment and a sharp deterioration in the ecological situation in many countries.

The impact of heavy metals on the components of the environment is studied by researchers in many countries. A large number of publications, especially recent ones, indicate a significant and still high interest to this topic (Kul'bachko et al., 2015; Martynov & Brygadyrenko, 2018). In particular, much attention is paid to the influence of heavy metals on the main physiological processes and productivity of plants, which involves studying the mechanisms of metal-resistance of plants, which operate at different levels of organisation (Zimmer et al., 2011; Sikdar & Kundu, 2018).

Technogenic impact on the ecosystem of a roadside zone causes changes in physical-chemical properties of soils, pollution, particularly with heavy metals, leading to increase in their phytotoxicity (Antonova & Safonova, 2007; Zimmer et al., 2011; Kosobrukhov et al., 2018). Pollutants are constantly washed out into open water bodies and groundwater which could be used by humans. The most negative effect manifests particularly in the roadside zone. Vegetation in this strip is in inhibited condition, its physiological activity is reduced and it cannot perform its ecological functions fully (Bargalya, 2005; Gibbs et al., 2006). One of the most promising objects for such studies is the system "soil – tree – plant". Therefore, over the past decade, some of the most topical research has been work focused on distribution of heavy metals in the environment and their accumulation in plants.

Therefore, the objective of our study was the peculiarities of accumulation of heavy metals in the commonest types of forest in the studied area, birch and pine forests, in roadside phytocenoses in the south of Tyumen oblast.

Materials and methods

To determine the extent of anthropogenic impact, we selected study plots with different intensity of technogenic loading. The plots of birch (B1, B3, B5, B7) and pine (P2, P4, P6, P8) forests were located near the roads (15 meters from the side) in the south of Tyumen oblast within five administrative districts: Uporovsky, Zavodoukovsky, Yalutorovsky, Yarkovsky (Fig. 1). Description of the vegetation was made according to the methods accepted in geobotanical studies on sample plots of 20×20 m^2 (Mirkin et al., 2000).

To determine the extent of anthropogenic transformation of the flora and particular vegetative communities, we used the index of synanthropization – share of synanthropic species (both apophytes and anthropophytes) in relation to the total number of species.

Plot B1. Gramineous birch forest. Association of plants – Betuletum gramineous-varioherbosum. Geographical coordinates – 56.35520 N, 66.32950 E. General projective cover of live ground cover – 100%. Average height of the grass stand – 70 cm. The phytocenose is located by the road between the villages Chernoe and Shashova, Upirovsky district. The phytocenose has characteristics of steppe, which is proven by growth of *Centaurea sibirica* L., *Phleum phleoides* L., *Thalictrum minus* L., *Trifolium montanum* L. The most abundant were *Vicia sepium* L., *Achillea millefolium* L., *Vicia cracca* L., *Calamagrostis epigeios* (L.) Roth., *Poa pratensis* L.

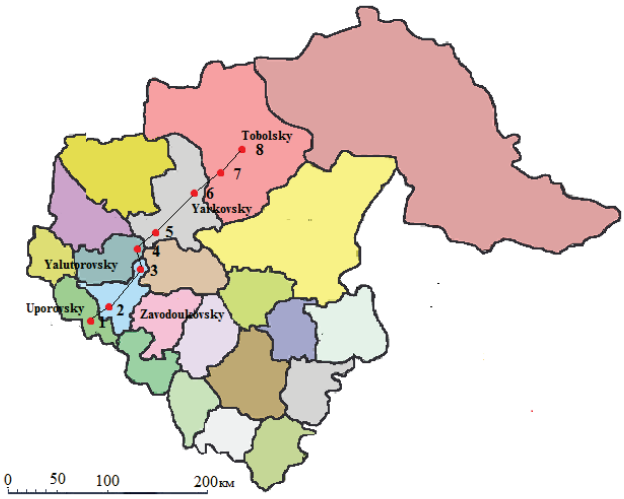

Fig. 1. Map scheme of locations of the plots 1–8 in Uporovsky, Zavodoukovsky, Yalutorovsky, Yarkovsky and Tobolsky administrative districts of Tyumen oblast

Plot P2. Pine-birch forest. Association of plants – Pineto-betuletum colamagrosto-varioherbosum. Geographic coordinates – 56.51030 N, 66.45680 E. Total projective cover of live ground cover – 60%. Average height of the grass stand – 60 cm. The phytocenose is formed on the terrace of the Iset River by the Uporovo-Zavodoukovsk road. The most abundant plant is *Calamagrostis arundinacea* (L.) Roth. Apart from birch, the common species are *Chimaphila umbellata* (L.) W. Barton), *Rubus saxatilis* L. Sometimes *Polygonatum odoratum* (Miller) Druce occur. The phytocenose is steppelike, which is proved by growth of *Trifolium lupinaster* L., *Veronica spicata* L., *Pulsatilla flavescens* (Zucc.) Juz.

Plot B3. Birch forest. Association of plants – Betuletum gramineous-fabacetosum. Geographic coordinates – 56.52840 N, 66.26550 E. Total projective cover of live ground cover – 70%. Average height of the grass stand – 60 cm. The roadside phytocenose is located in the above-floodland terrace of the Tobol River 1 km west from Zavodoudokovsk. The dominant species in the community are *Agrostis tenuis* Sibth., *Poa pratensis* L., *Trifolium pratense* L. Grasses are represented by *Brachypodium pinnatum* (L.) Beauv., *Dactylis glomerata* L., *Phleum pratense* L. Representatives of the bean family are rare compared to the dominants, but include *Lathyrus pratensis* L. and *Vicia cracca* L. Among the forbs, the abundant species are *Fragaria viridis* Duch., *Filipendula vulgaris* Moench, *Rubus saxatilis* L., *Viola hirta* L., *Ranunculus acris* L.

Plot P4. Pine forest. Association of plants – Pinetum chimaphilo-eguisetosum. Geographic coordinates – 56.62510 N, 66.26550 E. Total projective cover of live ground cover – 100%. Average height of the grass stand – 60 cm. The plot is located near the road to the south-west of the town Yalutorovsk.

The dominant species in the phytocenose are *Chimaphila umbellata* (L.) W. Barton and *Equisetum hyemale* L. Out of grasses, there grow *Phleum pratense* L., *Calamagrostis arundinacea* (L.) Roth, *Agrostis tenuis* Sibth. and others. Out of bean family, there were observed *Vicia cracca* L., *Trifolium medium* L., *Astragalus danicus* Retz., *Trifolium repens* L. Among the forbs, there were *Fragaria vesca* L., *Pimpinella saxifraga* L., *Moehringia lateriflora* (L.) Fenzl., *Pulmonaria mollis* Wulfen ex Hornem. The community is steppelike, there often occur *Filipendula vulgaris* Moench, *Chimaphila umbellata* (L.) W. Barton, *Silene nutans* L.

Plot B5. Birch forest. Association of plants – Betuletum colamagrosto-rubisaxalitosum. Geographic coordinates – 57.00230 N, 66.65780 E. Total projective cover of live ground cover – 90%. Average height of the grass stand – 55 cm. The phytocenose is located by the road, 2.5 km to the south-west of Novoatialovo village. Among the grasses, there were observed *Calamagrostis epigeios* (L.) Roth, *Brachypodium pinnatum* (L.) Beauv., *Molinia caerulea* (L.) Monch., *Agrostis tenuis* Sibth. Out of the bean family, there rarely grew *Lathyrus pratensis* L., *Vicia cracca* L., *Astragalus danicus* Retz., *Trifolium lupinaster* L., *Trifolium pratense* L., *T. repens* L. Forbs were represented by *Filipendula vulgaris* Moench, *Veronica longifolia* L., *Moehringia lateriflora* (L.) Fenzl., *Inula salicina* L., *Geranium sylvaticum* L. and others. The presence of *Molinia caerulea* (L.) Monch. in the phytocenose indicates the fact that the birch forest was formed on a place where pine forest grew earlier.

Plot P6. Pine forest. Association of plants – Pinetum vaccino-colamagrostitosum. Geographic coordinates – 57.60230 N, 67.02990 E. Total projective cover of live ground cover – 100%. Average height of the grass stand – 60 cm. The phytocenose is located by the Yalutorovsk-Yarkovo road. In the shrub-herbaceous layer, abundant plants included *Vaccinium vitis-idaea* L., *Calamagrostis arundinacea* (L.) Roth. Grasses were represented by *Brachypodium pinnatum* (L.) Beauv., *Molinia caerulea* (L.) Monch., *Agrostis tenuis* Sibth. Often, there occurred representatives of the Fabaceae family: *Lathyrus pisiformis* L., *Trifolium medium* L., *Orobus vernus* L. Forbs were represented by *Geranium sylvaticum* L., *Sanguisorba officinalis* L., *Maianthemum bifolium* (L.) F. W., *Inula salicina* L. and others. The phytocenose is steppelike (*Filipendula vulgaris* Moench, *Trifolium lupinaster* L.).

Plot B7. Birch forest. Association of plants – Betuletum calamagrosto-brachiopodiosum. Geographic coordinates – 57.60230 N, 67.27440 E. Total projective cover of above ground cover – 90%. Average height of the grass stand – 70 cm. The phytocenose is located by the road Yarkovo-Tobolsk. The pattern of the associations was determined by *Brachypodium pinnatum* (L.) Beauv., *Calamagrostis arundinacea* (L.) Roth, which dominate in the herbaceous layer. Among the grasses, we observed growth of *Poa pratensis* L., *Molinia caerulea* L. The bean family was represented by *Orobus vernus* L. Common plants were *Trifolium medium* L., *Lathyrus pisiformis* L. We found the following species of forbs: *Cirsium heterophyllum* (L.) Hill, *Rubus saxatilis* L., *Fragaria vesca* L., *Angelica sylvestris* L. In this birch forest, *Artemisia latifolia* L. grows – a typical species for the birch forests of the southern part of Western Siberia. Significant steppification of this birch forest is related to growth of *Trifolium lupinaster* L., *Dracocephalum ruyschiana* L.

Plot P8. Pine forest. Association of plants – Pinetum vaccine-colamagrostitosum. Geographic coordinates – 58.00190 N, 68.15240 E. Total projective cover of the live ground cover – 100%. Average height of the grass stand – 65 cm. The phytocenose is located by the road, 1.300 km south-west of Karachino village. In the shrub-herbaceous layer, abundant plants are *Vaccinium vitis-idaea* L., *Calamagrostis arundinacea* (L.) Roth. Grasses are represented by *C. arundinacea* (L.) Roth. *Trifolium medium* L., *Vicia cracca* L. are reasonably common.

The leaves and the needles were collected from around the perimeter of the lower third part of the crowns from 10 trees of average age, generative condition, washed with distilled water, dried and fixated in a drying cabinet at the temperature of 105 °C over 15 minutes with following additional drying at the temperature of 6 °C during 2 hours. The samples of phytomass were prepared similarly. Selection of samples of soil and preparation of the samples for quantitative chemical analysis were conducted according to the National Standard (National Standard, 2008). Five mixed samples were taken from each plot.

The samples were prepared using the system of microwave digestion speedwave MWS-2 manufactured by PerkinElmer (USA).

Soil samples of m = 4.0 g was put into a plastic tube, and then $HNO_3 : HCl = 1 : 3$ was added. The tube was put into a microwave oven for decomposition of the sample, using the programme recommended by the oven's manufacturer, and using the following regime of heating: raising the temperature up to 200 °C over 5 min, maintaining at 200 °C temperature during 5 min, cooling to 45 °C. The dissolved sample was transferred to a 15 ml test tube, increasing the volume of distilled water up to 10 ml, following which the analysis was conducted.

For decomposition of plant samples, m = 0.3 g samples were put in a tube, then $H_2SO_4 : H_2O_2 = 1 : 3$ was added. The following stages of decomposition were performed in the order described earlier. Quantitative chemical analysis of the accumulation of heavy metals Cr, Cu, Ni, Pb, Sr, Zn in the samples was conducted using the method of inductively coupled plasma on an atomic emission spectrometer Optima-7000DV manufactured by PerkinElmer (USA). For graduation, we used standard solutions manufactured by PerkinElmer (USA).

For calculation of the efficiency of absorption of heavy metals, we used the coefficient of biological absorption (K_i^{bp}), which is the content of a microelement in the ash of plant material to its content in the root-rich layer of soil:

$$K_i^{bp} = C_i^r / C_i^p \quad (1)$$

where C_i^r – content of the studied heavy metal in the plant (mg/kg), C_i^p – content of the studied heavy metal in soil (mg/kg). The value of index from 1 to 10 indicates intense accumulation of the element in a plant; 0.1 to 1.0 – average accumulation, 0.01 to 0.10 – insignificant absorption, 0.001 to 0.010 – absence of biological accumulation of an element (Neverova, 2001).

The results were statistically analyzed in Statistica 10.0 package (StatSoft Inc., USA). The differences between the selections were considered reliable at P < 0.05, calculated using ANOVA. The text and the tables provide mean and standard error (x ± SE).

Results

To identify and confirm the anthropogenic loading, we calculated the index of synanthropization of the flora, which ranged from 43% to 64%. This indicates that synanthropic species cover the greater part of the plots, i.e. dominate, forming the general environment, where all other plant species are dispersed. In the soil of the studied plots, the accumulation of heavy metals ranged as follows Cr 1.37–6.58, Cu 4.35–11.82, Ni 2.00–5.18, Pb 6.18–16.61, Sr 3.25–11.32, Zn 5.22–15.23 mg/kg. The results of pair comparisons using the Tukey test demonstrated confidence intervals for difference of mean values (Table 1).

It was observed that the highest amount of heavy metals accumulates in the soil of birch forests, and the lowest in pine forests. In order of increase in the anthropogenic loading, the plots could be arranged in the following order: B3 > B1 > B5 > B7 > P2 > P4 > P8 > P6.

To examine the accumulation of the heavy metals in plant objects, we determined their concentration in the needles of *Pinus sylvestris* L. and leaves of *Betula pendula* Roth. Content of the heavy metals in the needles of pine forests ranged as follows: Cr 1.89–5.52, Cu 8.45–13.50, Ni 3.30–8.50, Sr 8.15–12.08 mg/kg and decreased in the leaves of birch forests Cr 1.30–3.60, Cu 3.21–7.90, Ni 2.33–4.18, Sr 4.15–7.32 mg/kg, the results are reliable at P < 0.05. Therefore, the order of the plots redistributed in relation to the increase in anthropogenic load is as follows: P2 > P4 > P8 > B1 > P6 > B7 > B3 > B5. Accumulation of heavy metals can be expressed schematically: soil > leaves (birch forests), soil < needles (pine forests). Pb in leaves of *B. pendula* accumulated the most on the plot B1 at 9.59 mg/kg and on the plot B3 at 7.66 mg/kg.

Content of Zn in leaves of *Betula pendula* Roth. ranged from 5.22 to 10.50 mg/kg. Its highest value was observed on the first plot, and the lowest – on the fifth. Total Zn content in the soil was twice as high as its content in leaves of *B. pendula*. The needles of *P. sylvestris* were observed to have significantly less Zn – 4.58–6.23 mg/kg.

The obtained results allow us to determine certain species peculiarrities of trees related to the accumulation of heavy metals. The leading position for Cr, Cu, Ni, Sr belongs to the needles of *P. sylvestris*. As a result of the studies, we determined that in pine forests, the main load affects the dominant species of tree *P. sylvestris*, and the plants react to anthropogenic stress by manifesting different types of necrosis. Herbaceous plants of these forests are affected the least, in contrast to birch forests. Leaves of *B. pendula* were found to have the highest concentration of Pb and Zn (B1). Content of other heavy metals in the leaves of *B. pendula* during vegetation was relatively stable. Comparison of the obtained data demonstrates certain differences between the species in accumulation of heavy metals (Table 2).

During the study, we determined the accumulation of ecotoxicants in the general phytomass of roadside plots. The element sequence of the heavy metals can be arranged in relation to decrease of their concentrations in the total phytomass: Zn > Cu > Sr > Pb > Cr > Ni. We determined the differences in accumulation of heavy metals in phytomass of birch and pine forests. Unlike pine forests, plant samples of phytomass of birch forests concentrated a large amount of the pollutants. The dominant position in accumulation of heavy metals belongs to the phytomass of birch forests for Cr, Cu, Ni, Sr, Zn, Pb. Accumulation of heavy metals in the studied components of forest ecosystems can be presented structurally: soil > leaves < phytomass (birch forests), soil < needles > phytomass (pine forests) (Table 3).

Table 1
Accumulation of heavy metals in soil of the studied plots, mg/kg (X ± SE; n = 15)

Plots	Cr	Cu	Ni	Pb	Sr	Zn
B1	6.50 ± 0.08 [e]	10.50 ± 0.32 [d]	5.50 ± 0.06 [b]	11.37 ± 0.08 [b]	9.08 ± 0.05 [c]	15.23 ± 0.07 [d]
P2	4.61 ± 0.08 [d]	7.82 ± 0.08 [c]	4.18 ± 0.05 [b]	8.12 ± 0.06 [b]	7.32 ± 0.11 [b]	7.58 ± 0.08 [b]
B3	6.58 ± 0.24 [e]	11.82 ± 0.05 [d]	5.17 ± 0.08 [c]	16.61 ± 0.09 [c]	11.32 ± 0.07 [d]	13.50 ± 0.13 [c]
P4	3.68 ± 0.10 [c]	7.81 ± 0.04 [c]	3.67 ± 0.05 [b]	8.05 ± 0.11 [b]	7.35 ± 0.11 [b]	6.58 ± 0.07 [a]
B5	5.56 ± 0.12 [e]	9.02 ± 0.05 [c]	4.52 ± 0.07 [c]	9.58 ± 0.15 [b]	8.90 ± 0.03 [c]	12.50 ± 0.17 [c]
P6	1.37 ± 0.03 [a]	4.35 ± 0.06 [a]	2.03 ± 0.05 [b]	6.18 ± 0.12 [b]	3.25 ± 0.10 [a]	5.21 ± 0.08 [a]
B7	4.82 ± 0.05 [d]	8.54 ± 0.06 [c]	4.32 ± 0.06 [b]	8.91 ± 0.03 [c]	8.60 ± 0.06 [c]	11.69 ± 0.04 [c]
P8	2.89 ± 0.01 [b]	6.46 ± 0.06 [b]	2.32 ± 0.06 [b]	7.18 ± 0.05 [b]	6.15 ± 0.06 [b]	5.70 ± 0.06 [a]

Note: [a–e] – differences in soil, demonstrated by different letters, were statistically reliable, P < 0.05 (Tukey test).

Table 2
Accumulation of heavy metals in the needles of *P. sylvestris* (C2, C4, C6, C8) and the leaves of *B. pendula* (B1, B3, B5, B7) on the study plots, mg/kg (X ± SE; n = 10)

Plots	Cr	Cu	Ni	Pb	Sr	Zn
B1	3.60 ± 0.05 [b]	7.90 ± 0.11 [b]	4.18 ± 0.07 [b]	9.59 ± 0.15 [c]	7.32 ± 0.11 [c]	10.50 ± 0.12 [c]
P2	5.52 ± 0.08 [c]	13.50 ± 0.11 [c]	8.50 ± 0.06 [c]	7.36 ± 0.11 [b]	12.08 ± 0.19 [d]	6.23 ± 0.05 [a]
B3	2.92 ± 0.09 [a]	3.21 ± 0.06 [a]	3.31 ± 0.07 [a]	7.66 ± 0.05 [b]	5.97 ± 0.09 [b]	5.53 ± 0.07 [a]
P4	4.60 ± 0.07 [b]	11.81 ± 0.07 [c]	5.18 ± 0.03 [b]	7.61 ± 0.06 [b]	11.32 ± 0.07 [d]	5.08 ± 0.14 [a]
B5	1.30 ± 0.09 [a]	3.35 ± 0.07 [a]	2.33 ± 0.06 [a]	5.24 ± 0.07 [a]	4.25 ± 0.04 [a]	5.22 ± 0.04 [a]
P6	1.89 ± 0.07 [a]	8.45 ± 0.06 [b]	3.32 ± 0.07 [a]	5.18 ± 0.08 [a]	8.15 ± 0.06 [c]	4.69 ± 0.09 [a]
B7	2.10 ± 0.07 [a]	3.45 ± 0.06 [a]	3.30 ± 0.08 [a]	4.18 ± 0.08 [a]	4.15 ± 0.07 [a]	7.69 ± 0.05 [b]
P8	4.62 ± 0.07 [b]	10.80 ± 0.11 [c]	5.67 ± 0.06 [b]	6.05 ± 0.05 [a]	9.36 ± 0.13 [c]	4.58 ± 0.06 [a]

Note: [a–e] – see Table 1.

To compare average values, we used single-factor dispersal analysis (ANOVA). The factor was a scale "soil", dependant variables were "needles of *P. sylvestris* × phytomass", "leaves of *B. pendula* × phytomass". The main indicator of this analysis was F criterion of Fisher and its significance level. Therefore, we determined the differences for Cr (C2: $F_{9;5} = 4.2$ (P = 0.004); C4: $F_{8;8} = 5.2$ (P = 0.016); C8: $F_{10;6} = 6.4$ (P = 0.021), Cu (C2: $F_{8;8} = 3.6$ (P = 0.004); C4: $F_{6;10} = 9.4$ (P = 0.001); C6: $F_{12;4} = 5.6$ (P = 0.043), Ni (C2: $F_{8;8} = 15.5$ (P = 0.0004); C4: $F_{6;10} =$

10.2 (P = 0.0008); C8: $F_{12;4}$ = 29.7 (P = 0.002), Zn (C2: $F_{6;12}$ = 12.1 (P = 0.0002); C4: $F_{10;8}$ = 6.9 (P = 0.005); C8: $F_{12;6}$ = 4,5 (P = 0.03). Analysis of the impact of chemical composition of soil indicated that the "soil" factor was significant for Cr, Cu, Ni and Zn on the plots P2, P4, P6, P8. To check the dispersions for homogeneity, we used Levene's test for homogeneity. In this case, it proves the insignificance of differences between dispersions because the values were 0.91–0.95 > 0.05. Therefore, the results obtained using dispersal analysis can be considered correct.

An opposite situation was observed for these elements on the plots B1, B3, B5. The results of a single-factor ANOVA analysis indicate absence of a significant impact for Cr (C6: $F_{10;6}$ = 1.2 (P = 0.422), Cu (C8: $F_{12;4}$ = 2.8 (P = 0.163), Ni (C6: $F_{14;2}$ = 3.2 (P = 0.260), Zn (C6: $F_{12;2}$ = 7.3 (P = 0.126). Absence of significant impact was determined for Pb and Sr in birch and pine forests on all plots. Exclusion of these plots does not affect the conclusion about significant impact of chemical composition of soil on the ecosystem components.

To characterize the intensity of absorption of the elements by plants from the soil, we calculated the coefficient of biological absorption (K_i^{bp}), as the ratio of metal content in a plant to its total content in soil. Transition of the heavy metals from soil to plant occurs through biological consumption of these elements by biomass. The more the coefficient is higher than one, the higher the danger of pollution. On all of the plots, *P. sylvestris* accumulated the largest amount of heavy metals. The coefficient of biological absorption in the needles from the studied plots in relation to Cr (C2 – 1.2, C4 – 1.3, C6 – 1.4, C8 – 1.6), Cu (C4 – 1.5, C6 – 1.9, C8 – 1.7), Ni (C2 – 2.0, C4 – 1.4, C6 – 1.6, C8 – 2.4) and Sr (C2 – 1.7, C4 – 1.5, C6 – 2.5, C8 – 1.5) indicates intense accumulation of the elements in *P. sylvestris* (>1). The content of pollutants in the needles directly depends on the extent of anthropogenic load.

Regarding Pb and Zn in the needles, leaves and phytomass, the coefficient of biological absorption indicates average accumulation and ranges from 0.5 to 0.9. In the leaves of *B. pendula* from all plots, the coefficient of biological absorption had average accumulation in the interval between 0.2 and 0.8. However, for Cr, Cu, Ni and Sr in phytomass of birch forests, it was significantly higher – 1.1 to 1.2, which indicates the most significant pollution (Table 4).

Table 3
Accumulation of heavy metals in the total phytomass in the studied plots, mg/kg (X ± SE; n = 10)

Plots	Cr	Cu	Ni	Pb	Sr	Zn
B1	7.51 ± 0.08[c]	12.50 ± 0.04[d]	6.51 ± 0.06[c]	10.36 ± 0.07[c]	11.08 ± 0.13[d]	14.23 ± 0.05[e]
P2	3.61 ± 0.05[b]	5.89 ± 0.05[a]	3.18 ± 0.04[a]	7.62 ± 0.06[b]	6.32 ± 0.05[b]	6.52 ± 0.07[b]
B3	7.22 ± 0.06[c]	12.20 ± 0.05[d]	6.30 ± 0.05[c]	15.23 ± 0.05[d]	12.36 ± 0.05[e]	12.31 ± 0.05[d]
P4	2.60 ± 0.06[b]	5.82 ± 0.05[a]	2.67 ± 0.06[a]	6.05 ± 0.12[a]	6.35 ± 0.06[b]	5.58 ± 0.08[a]
B5	6.08 ± 0.10[c]	10.45 ± 0.06[c]	5.31 ± 0.09[b]	8.18 ± 0.07[b]	9.15 ± 0.09[c]	11.69 ± 0.04[d]
P6	0.89 ± 0.02[a]	4.84 ± 0.05[a]	2.91 ± 0.09[a]	5.68 ± 0.10[a]	4.25 ± 0.03[a]	4.22 ± 0.03[a]
B7	5.28 ± 0.06[c]	9.23 ± 0.11[c]	5.34 ± 0.06[b]	7.82 ± 0.08[b]	10.60 ± 0.07[d]	9.19 ± 0.04[c]
P8	3.12 ± 0.07[b]	7.30 ± 0.05[b]	3.91 ± 0.10[a]	6.18 ± 0.08[a]	8.15 ± 0.06[c]	4.11 ± 0.04[a]

Note: [a–e] – see Table 1.

Table 4
Coefficient of biological absorption of elements (K_i^{bp}) by the needles (N) of *P. sylvestris*, leaves (L) of *B. pendula* and phytomass (F)

Plots	Cr		Cu		Ni		Pb		Sr		Zn	
	NL	F	NL	F	NL	F	NL	F	NL	F	NL	F
B1	0.61	1.21	0.83	1.21	0.84	1.22	0.81	0.91	0.81	1.21	0.70	0.9
P2	1.20	0.83	1.71	0.82	2.02	0.81	0.92	0.90	1.72	0.92	0.80	0.9
B3	0.42	1.10	0.33	1.01	0.62	1.21	0.51	0.91	0.51	1.11	0.41	0.9
P4	1.30	0.71	1.52	0.72	1.41	0.72	0.93	0.82	1.54	0.92	0.82	0.8
B5	0.21	1.11	0.41	1.21	0.51	1.21	0.53	0.91	0.52	1.01	0.40	0.9
P6	1.41	0.63	1.90	1.12	1.60	1.40	0.82	0.90	2.51	1.32	0.90	0.8
B7	0.43	1.12	0.43	1.11	0.81	1.21	0.51	0.90	0.50	1.21	0.71	0.8
P8	1.60	1.10	1.72	1.13	2.41	1.72	0.82	0.91	1.50	1.31	0.80	0.7

Analysis of the obtained results allowed us to conditionally divide the plants into two groups by the property of accumulation of heavy metals. Accumulator plants (accumulate metals mainly in above-ground organs, both at low and high content of them in soil) *P. sylvestris* (K_i^{bp} > 1) and excluder plants (introduction of the metals into the shoots is limited, despite their high concentration in the environment) *B. pendula* (K_i^{bp} < 1). According to the indicators of the coefficient of biological absorption in the system "soil – leaves (needles) – phytomass", zinc and lead are included to the group of an insignificant range (K_i^{bp} = 0.4–0.9). Perhaps, accumulation of the heavy metals in these plants occurs in the barrier type.

Distribution of the heavy metals in the studied components of forest ecosystems of birch and pine forests in the south of Tyumen oblast in the system "soil – leaves (needles) – phytomass" is presented in Figure 2. The dendrogram (method of pair average) indicates the extent of similarity of the plots by accumulation of the heavy metals, and also graphically demonstrates the order of their bonding or division in relation to accumulation in the forest ecosystems. First of all, the plots grouped into clusters B1, B2, B5, B7 (birch forests) and P2, P3, P6, P8 (pine forests) by Cr, Cu, Ni, Sr, Zn. Accumulation of Pb united the plots B1, B3 and P2, P4, P6, P8, B5, B7 into clusters.

To describe the mathematical dependency of the concentration of the heavy metals in soil and total biomass in the studied plots, we obtained the regressive equation (Table 5).

Table 5
Dependence of the content of heavy metals in soil, leaves of *B. pendula* and needles of *P. sylvestris*

TM	Formula of approximating function		Significance coefficient of approximation R^2
	birch forests	pine forests	
Cr	y = 0.9278x – 3.0242	Y = 1.0760x + 0.8147	0.92
Cu	y = 0.2761x + 1.7242	Y = 1.2275x + 3.0300	0.93
Ni	y = 0.9803x – 1.5038	Y = 1.6264x + 0.7191	0.97
Pb	y = 0.3830x + 2.2071	Y = 1.2411x – 2.6065	0.85
Sr	y = 0.4439x + 1.2195	Y = 0.8523x + 5.0964	0.98
Zn	y = 0.9791x – 5.7264	Y = 0.6872x + 0.8315	0.98

These formulae approximate the initial dependence of accumulation of heavy metals in soil and the leaves of *B. pendula* and the needles of *P. sylvestris* with a high extent of closeness, i.e. R^2 = 0.85–0.98. On the basis of the data on the content of heavy metals in the soil and the regression equation developed earlier, the theoretical significance of the concentration of metals in the leaves and needles is calculated. In the case, when the difference between factual and theoretical values exceeds the mean error of approximation, a conclusion about pollution can be drawn.

Discussion

Many authors think that in performing a defensive function plants extract and concentrate different chemical elements in their organs and tissues, therefore preventing distribution of pollutants in the environment (Bruins et al., 2000; Lin et al., 2010; Vodyanitsky, 2014). In many experiments, it was determined that practically all plants to a particular extent are able to protect against hazardous excess of the heavy metals. Different mechanisms of such protection are described (Foyer & Harbinson, 2005; Clemens, 2006). Other authors (Kodirov & Shukurov, 2009; Conn & Gilliham, 2010) examine the adaptive strategy both at the level of species and between them.

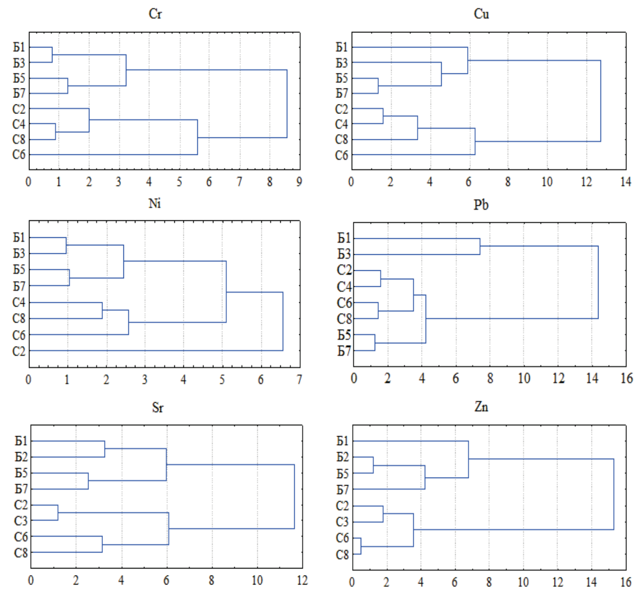

Fig. 2. Distribution of the heavy metals in the studied components of the forest ecosystem of birch and pine forests of the south of Tyumen oblast in the system "soil – leaves (needles) – phytomass" (mg/kg)

This article mentions that the heavy metals accumulate more in the soil of birch forests, and less in pine forests. The determined differences correspond to the existing perception (Sikdar & Kundu, 2018) that selective ability and intensity of absorption of the metals by the assimilating organs of plants is determined in relation to species. Data on the distribution of heavy metals in organs and tissues of plants are contradictory. Some authors mention high accumulation of heavy metals in the aboveground organs (Yan et al., 2016), other authors – in the roots (Chen et al., 2007). Certainly, the ratio of concentration of elements in the organs and tissues of plants is highly variable due to species specificity of plants, and properties of the elements themselves (Kim et al., 2010).

According to the literature data (Kabata-Pendias & Pendias, 1989), the tissues of leaves of birch have a certain selective ability to accumulate heavy metals.

Due to fall of leaves in autumn, trees are able to get rid of a large amount of toxic compounds accumulated in them, which allows significant reduction in the extent of negative impact of heavy metals and, therefore, contributes to survivability of plants which grow in similar environmental conditions. This method is considered a defense mechanism which protects the plant organism against intoxication and death. But, as a result, the toxicants become introduced to the soil and accumulate mainly in herbaceous vegetation of phytocenoses (Antonova & Safonova, 2007).

In the leaves of *B. pendula*, we found the highest concentration of Pb and Zn (B1). Pb concentration in the leaves of *B. pendula* was the highest on the plots B1 at 9.59 and B3 at 7.66 mg/kg. The content of Zn ranged from 5.22 to 10.50 mg/kg. The content of other heavy metals in the leaves of *B. pendula* during vegetation was observed to be stable. However, herbaceous vegetation in these forests suffers the highest load of accumulation of Cr, Cu, Ni, Sr, Zn and Pb. The different level of involvement of heavy metals in biogenic cycles by herbaceous phytocenoses, first of all, is determined by their content in the soil. In the gradient of chemical pollution and in combination with selectiveness of accumulation of the elements by different species, all this leads to a complex structure of their participation in the general biogenic cycle and change in the species composition of herbaceous vegetation, and appearance of synanthropic species. The index of synanthropisation of the flora of studied plots ranges between 43% and 64%.

In pine forests, increased levels of accumulation of metals in assimilating organs cause dying of trees, destruction of tree stands and total death of forest ecosystems. One of the factors which reduce the maintenance of the needles is accumulation of heavy metals in them up to the levels which exceed the toxic effect, leading to damage to particular needles in the form of chlorosis and necrosis, and full death of the needles. Some researchers think that the critical threshold, the overcoming of which leads to death of coniferous species, is reached after maximum permissible heavy metal concentrations in the needles are exceeded by several times (Kabata-Pendias & Pendias, 1989). The critical threshold of heavy metal concentrations in assimilating organs of pines is followed by death of trees (Bargalya, 2005).

As a result of the study, it was determined that in pine forests, the main load pressurizes the dominant species of tree *P. sylvestris*, at the same time, herbaceous vegetation in these forests is pressurized by the lowest load. The plants react to the anthropogenic load by necrosis of different type. The leading position in accumulation belongs to Cr, Cu, Ni, Sr. Broad variations of mean values for the studied heavy metals indicate a high level of adaptation of *P. sylvestris* to pollution and presence of unstudied mechanisms of blocking the toxic effect of the absorbed metals.

The results of the study enlarge the knowledge on the conditions of pollution of forests in the region and can be the beginning of creating a data base for a complex ecological assessment of the region's environment.

Conclusion

In the soil of the studied plots, the heavy metals ranged within the following: Cr 1.37–6.58, Cu 4.35–11.82, Ni 2.00–5.18, Pb 6.18–16.61, Sr 3.25–11.32, Zn 5.22–15.23 mg/kg. Among the studied tree species, there was determined a species specificity in accumulating heavy metals. *P. sylvestris* specialized in Cr – Cu – Ni – Sr and *B. pendula* in Pb – Zn. Accumulation of heavy metals in the studied components of forest ecosystems can be demonstrated structurally: soil > leaves < phytomass (birch forests), soil < needles > phytomass (pine forests). The element sequence of heavy metals can be arranged in relation of decrease in their concentration in the total phytomass Zn > Cu > Sr > Pb > Cr > Ni. It was determined that the dependence of concentrations of heavy metals in soil and vegetation can be expressed in the equation y = ax + b, a and b – value of element. The index of synanthropization of the flora of the studied phytocenoses ranges within the interval between 43% and 64%. Analysis of the obtained results allowed conditional division of the plants into two groups in terms of their abilities to accumulate heavy metals. Accumulator plants (accumulate metals mainly in above-ground organs, both at low and high content of them in soil) *P. sylvestris* ($K_i^{bp} > 1$) and excluder plants (introduction of the metals into shoots is limited, despite their high concentration in the environment) *B. pendula* ($K_i^{bp} < 1$). Such data can be used for recovering forests on large areas polluted by heavy metals.

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