Additive biomass models for *Quercus* spp. single-trees sensitive to temperature and precipitation in Eurasia

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**Abstract.** The analysis of the biomass of oak (genus *Quercus* spp.) trees on the aboveground component composition based on regression equations having the additive biomass structure is fulfilled. Two trends of changes in the tree biomass structure are revealed: due to the mean January temperature and due to the mean annual precipitation. It was shown for the first time that both trends are mutually determined: the intensity of biomass trend in relation to the temperature is changing when depending on the level of precipitation, and the intensity of biomass trend in relation to precipitation level is changing during to a transition from the cold zone to the warm one and vice versa.

**Key words:** oak trees, tree biomass, allometric models, additive biomass equations, mean January temperature, mean annual precipitation.

1. Introduction

Information about forest tree biomass can easily be derived through allometric equations, as it is done for example for biomass stock per ha, especially in many-species forests (Dahlberg et al., 2004; Zeng et al., 2018; Usoltsev et al., 2019a), for greenhouse gas reporting (de Miguel et al., 2014), for analysis of national forest inventories data, in ecological studies (Marklund, 1987; Riedel & Kändler, 2017), as well as in gas-exchange, nutrient and energy flow studying, forest growth and biomass allocation models (Zianis et al., 2005; Vonderach et al., 2018).

All above mentioned equations are usually internally contradictory, they are not harmonized by the biomass structure, i.e. they do not provide the additivity of component composition, according to which the total biomass of components (stems, branches, needles, roots) obtained by “component” equations would be equal to the value of biomass obtained by the total biomass equation (Kozak, 1970). The additivity methods can be divided into aggregative (Parresol, 2001) and disaggregative (Dong et al., 2015) approaches. It was recently showed that having in mind the result correctness, both approaches differ only slightly (Affleck & Diéguez-Aranda, 2016). The development
of regional allometric models of tree biomass sensitive to climate variables has shown both negative (Forrester et al., 2017) and positive (Zeng et al., 2017) results. The influence of climatic changes on the biomass of a particular tree species in the format of additive models according to transcontinental hydrothermal gradients was not been studied, with some single exceptions (Usoltsev et al., 2019a, b).

In the present study, the first attempt is made to simulate the changes in the additive component composition of tree aboveground biomass in oak forests on Trans-Eurasian hydrothermal gradients. In the simulation we used the database of the biomass of 530 sample trees (genus *Quercus* spp.), the distribution of sample plots of which in the territory of Eurasia is shown in Figure 1 (Usoltsev, 2016; Lakida et al., 2017).

2. Materials and methods

Of the above-mentioned two databases (Usoltsev, 2016; Lakida et al., 2017) containing data on biomass and dendrometric parameters, 530 trees were selected for the analysis, including 8 species-vicariants of the genus *Quercus* spp. Their distribution by regions, tree species and mensuration indices is presented in Table 1.

Each sample plot on which tree biomass estimating was performed is positioned relatively to the isolines of the mean January temperature (Fig. 2) and relatively to the isolines of mean annual precipitation (Fig. 3). The matrix of harvest data was compiled, in which the biomass component values and mensuration tree parameters were related with the corresponding values of mean January temperature and precipitation, then included in the regression analysis procedure.

It is known that a stem diameter is a main predictor that most explains the variation of tree biomass, and their relationship as the most common and biologically determined is described by the allometric function. Allometry determines how tree shape and function scale with each other, related through size. Allometric relationships help scale processes from the individual to the global scale and constitute a core component of vegetation models. Allometric relationships have been expected to emerge from optimization theory, yet they do not suitably predict empirical data (Fischer et al., 2019). On the allometry basis, several theories are proposed: the pipe model (Huber, 1925, 1927; Shinozaki et al., 1964a, b), the functional equilibrium model (Davidson, 1969), the fractal model (West et al., 1999), the metabolic scaling theory (when scaling exponent is constant) (West et al., 1997), the theory of adaptive mass distribution (when scaling exponent changes dynamically with size) (Poorter et al., 2015) and some of their modifications (Enquist & Niklas, 2001, 2002). However, when calculating allometric models of tree biomass there is always a residual variance, reflecting, in particular, the discrepancy between the annual dynamics of the crown.
Table 1. Distribution of the 530 oak sample trees by countries, regions, tree species and mensuration indices

| Regions                      | Species of the genus *Quercus* spp.                                                                 | Ranges:                                                                 | Data number |
|------------------------------|---------------------------------------------------------------------------------------------------|------------------------------------------------------------------------|-------------|
| Czech Republic, Switzerland  | *Q. robur* L., *Q. robur* subsp. *pedunculiflora* (K.Koch) Menitsky, *Q. petraea* (Mat.) Liebl., *Q. frainetto* Ten. | age, years 13÷104; diameter, cm 4.0÷69.7; number 16                  |             |
| Bulgaria                     | *Q. robur* L., *Q. rubra* L., *Q. robur* subsp. *pedunculiflora* (K.Koch) Menitsky, *Q. petraea* (Mat.) Liebl., *Q. frainetto* Ten. | age, years 17÷70; diameter, cm 1.5÷29.5; number 49                     |             |
| Hungary                      | *Q. petraea* (Mat.) Liebl.                                                                       | age, years 68; diameter, cm 15.8÷23.8; number 9                        |             |
| The Ukraine                  | *Q. robur* L.                                                                                     | age, years 6÷128; diameter, cm 2.5÷50.5; number 370                   |             |
| European part of Russia      | *Q. robur* L.                                                                                     | age, years 12÷130; diameter, cm 1.1÷46.9; number 66                    |             |
| Russian Far East             | *Q. mongolica* Fisch. *ex* Ledeb.                                                                 | age, years 56÷166; diameter, cm 9.5÷34.5; number 7                     |             |
| Japan                        | *Q. serrata* Murray, *Q. mongolica* Fisch. *ex* Ledeb.                                             | age, years 4÷40; diameter, cm 1.1÷16.5; number 13                      |             |

Figure 2. Distribution of biomass harvest data of 530 oak sample trees on the map of the mean January temperature, °C (World Weather Maps, 2007)

Figure 3. Distribution of biomass harvest data of 530 oak sample trees on the map of the mean annual precipitation, mm (World Weather Maps, 2007)
mass, especially of the foliage, and the relative conserva-
tivism of a stem diameter, as an accumulator of its annual
increments (Usoltsev, 1988), as well as differences of age
status, soil and climatic conditions.

Total tree height is not always available in field meas-
urements, and it may sometimes be better not to involve
it in biomass estimation procedure (Williams & Schreuder,
2000). In this study, the task is to extract the climatic com-
ponent from the residual dispersion of a model obtained
during to calculation of tree biomass by stem diameter.
To the share of climatic factors was predominant in this
“information noise”, it is necessary to take into account
in the model in addition to the diameter, also the tree age,
which is a factor largely determining the structure of tree
biomass (Nikitin, 1965).

A negative relationship between the crown biomass
of equal-sized trees and their age in forest stands is well
known. Thus, the crown mass of the tree with a diameter
of 12 cm at the age of 15 years exceeds that at the age
of 35 years at the birch by 1.5-2.0 times, and at the aspen –
by 2.4-4.4 times (Usoltsev, 1972) due to the age shift of the
cenotic position of equal-sized trees: at the age of 15 years
such tree is the leader, and at the age of 35 years it is the
depressed tree, a candidate for dying. The influence of age
on stem biomass in comparison with other components
is minimal due to the relative stability of the stem shape:
with the same stem shape and the corresponding volume,
its biomass changes with age mainly due to age-related
changes in the basic density related to a decrease in the
proportion of sapwood having a reduced dry matter content
compared to the heartwood (Usoltsev, 1988). Tree age, all
other conditions being equal, also affects the mass of roots
in terms of root-shoot relationships (Kazaryan, 1969).

We have in our database only 47 trees having both
aboveground biomass and root one, represented by Cen-
tral Europe, European part of Russia and Japan. Because
of small root experimental data, we do not involve the bio-
mass of roots into our additive biomass system. Root bio-
mass data are high labour-consuming, and therefore they
determined by researchers not at all sample plots, often
without specifying the method of their estimation. The
analysis of the world data of underground tree biomass has
showed that due to the imperfection of methods to estimate
fine root biomass, the total underground biomass of trees
and stands may be underestimated two to five times (Usol-
tsev, 2018).

We limited ourselves to the calculation of the coeffi-
cient of determination and the standard error. We have not
calculated additional characteristics of the equation ade-
quacy, such as the mean prediction error, the relative mean
prediction error, the mean absolute error, and the relative
mean absolute error, since they all are derived from the
determination coefficient.

The disaggregation method of two-step proportional
weighing, based on the principle “from general to par-
ticular” is developed as an alternative to the independent
(without additivity) fitting approach. It has been imple-
mented in two versions: as a sequential (Zheng et al., 2015)
and parallel (Zhang et al., 2016) disaggregating additive
systems of equations for aboveground biomass (Fig. 4).
According to the structure of the disaggregation model
of a two-step additive equation system (Zheng et al., 2015),
the aboveground biomass $P_a$, estimated by an initial equa-
tion, is divided into biomass components by means of pro-
portional weighting the corresponding component initial
equations (see: Dong et al., 2015; Usoltsev et al., 2019a, b).

The coefficients of the regression equations of all two
steps are evaluated simultaneously, that ensures the addi-
tivity of the biomass of all components (Dong et al., 2015).
Since the regression coefficients in the designed model
were calculated on the log-transformed data, a correspond-
ing correction is introduced in the equations to eliminate
the displacements caused by the logarithmic transforma-
tion of the variables (Baskerville, 1972).

![Figure 4. The pattern of the disaggregating two-step proportional weighting additive model of sequential (left) and parallel (right)
schemes. The schemes show relationship between each biomass component, where lines from left to right indicate disag-
gregation and from right to left indicate summation (Zheng et al., 2015; Zhang et al., 2016)](image-url)
We adhered to the concept that there is only one definite variant of stand (and tree) biomass structure corresponding to a given structure of taxonomic parameters (morphological structure) of a tree stand, determined by local forest growth conditions (Usoltsev, 2007). If in some region we find a forest stand of the same morphological structure, then the structure of its biomass is likely to be the same, provided there were no anthropogenous and other abiotic influences. But as the range of expansion of woody species (genus), this compliance will be increasingly violated as a result of increasing the diversity of forest growth conditions. This change in the diversity of forest environment has geographical causes and in the regression multiple model is expressed by an increase in residual dispersion (“information noise”). In terms of biogeography, the increase of variability of this residual variance as a consequence of increasing diversity of forest environment, is most likely due to climate and in the regression multiple model is expressed by an increase in residual dispersion (“information noise”). In terms of biogeography, the increase of variability of this residual variance as a consequence of increasing diversity of forest environment, is most likely due to climate variables, such as temperature and precipitation, which are included in our models as additional independent variables.

3. Results

Based on the above, the following structure of the regression model is suggested:

$$\ln P_i = a_0 + a_1 (\ln A) + a_2 (\ln D) + a_3 (\ln D)^2 + a_4 [\ln(T+20)] + a_5 (\ln PR) + a_6 [\ln(T+20)](\ln PR),$$  

(1)

where $P_i$ is biomass in dry condition of $i$-th component, kg; $A$ is tree age, yrs; $D$ is stem diameter at breast height, cm; $i$ is the index of biomass component: above-ground $(a)$, crown $(c)$, foliage $(f)$, branches $(b)$, stem above bark $(s)$, stem wood $(w)$ and stem bark $(bk)$; $T$ is mean January temperature, °C; $PR$ is mean annual precipitation, mm.

According to the theory of adaptive mass distribution, the scaling exponent (or exponent at the stem diameter in the allometric model) is not a constant, and in log-log coordinates the relationship has the nonlinear form (Poorter et al., 2015). To account for this nonlinearity, the stem diameter in the model (1) is introduced in the form of a second-order logarithmic polynomial:

$$\ln P_i = f(\ln D), (\ln D)^2.$$  

(2)

Since the mean January temperature in the northern part of Eurasia has negative values, the corresponding independent variable is modified to the form $(T+20)$ to be subjected to logarithmic procedure. The schematic map of the isolines of mean January temperature, rather than the mean annual temperature, is used, since climate warming is most pronounced in the cold half of the year (Golubyatnikov & Denisenko, 2009; Laing & Binyamin, 2013; Felton et al., 2016). In this regard, a similar parallel trend of another level is interesting: according to the report of National Oceanic and Atmospheric Administration (2017), warming in the Arctic is twice as fast as in other parts of the Earth, and “the Arctic is on the frontline of climate change” (https://www.noaa.gov/explainers/changing-arctic-greener-warmer-and-increasingly-accessible-region) (Blunden et al., 2018).

Characteristic of equations (1) is obtained by regression analysis, and after correcting on logarithmic transformation by Baskerville (1972) and anti-log transforming is given in Table 2.

| Biomass component | Regression coefficients of the model | $adjR^2*$ | $SE*$ |
|-------------------|------------------------------------|-----------|-------|
| $P_x$             | 3.49E-09 A 0.1008 D 1.9511 D 0.0823(\ln D) (T+20) 3.8805 PR 2.6377 (T+20) 1.8553(\ln PR) | 0.989 | 1.22 |
| $P_y$             | 2.10E-11 A 0.3144 D 1.7957 D 0.1310(\ln D) (T+20) 5.3197 PR 3.5835 (T+20) 1.0204(\ln PR) | 0.911 | 1.71 |
| $P_z$             | 3.32E-08 A 0.2113 D 1.9646 D 0.0733(\ln D) (T+20) 2.8111 PR 2.2139 (T+20) 0.7166(\ln PR) | 0.987 | 1.25 |
| $P_f$             | 9.41E-07 A 0.1925 D 1.6748 D 0.0862(\ln D) (T+20) 3.3779 PR 1.3893 (T+20) 1.6920(\ln PR) | 0.871 | 1.67 |
| $P_b$             | 3.47E-13 A 0.1857 D 2.0212 D 0.0966(\ln D) (T+20) 9.955 PR 4.0371 (T+20) 1.0841(\ln PR) | 0.901 | 1.84 |
| $P_s$             | 4.00E-08 A 0.3001 D 2.2722 D 0.01875(\ln D) (T+20) 4.4532 PR 2.0392 (T+20) 1.6546(\ln PR) | 0.984 | 1.28 |
| $P_{bk}$          | 2.17E-13 A 0.1151 D 1.3606 D 0.1655(\ln D) (T+20) 1.7468 PR 3.0457 (T+20) 1.1066(\ln PR) | 0.960 | 1.40 |

* $adjR^2$ – coefficient of determination adjusted for the number of parameters; $SE$ – equation standard error.
All regression coefficients of equations (1) are characterized by the Student’s significance level of 0.05 and better [including at variables (lnD) and (lnD^2)], and the resulting equations are adequate to the original values presented in the available database. Unlike of our previous result on larch tree biomass (Usoltsev et al., 2019a), where the combined effect of temperature and precipitation was not statistically significant (Student’s test t05 s from 0.08 to 1.33, which is below the standard value t05 s = 1.96), this model includes synergism [ln(T+20)][ln(PR)], which is significant (t05 s is from 2.04 to 6.49, which is higher than the standard value t05 s = 1.96) for all biomass components. When using a 3D-interpretation, this means a “propeller-shaped” surface of biomass in dependence upon temperature and precipitation, which was previously confirmed by the example of tree biomass of two-needled pines (Usoltsev et al., 2019b).

The designed initial equations (1) are then modified to the additive form according to the early published algorithm (see: Dong et al., 2015; Usoltsev et al., 2019a, b), structure of which is shown in Figure 4 (left), and the final form of the transcontinental additive model of the component composition of oak tree biomass is shown in Table 3.

Next, it is necessary to find out whether the additive model obtained is enough adequate and how its characteristics relate to the adequacy of initial equations. To do this, the first and the second models are tabulated on the empirical measurement data and the calculated values of biomass are compared with the empirical ones using the coefficient of determination. The comparison results shown in Figure 5, indicate that the adequacy of the two systems of equations is close to each other.

Due to the high complexity of obtaining the age of trees in comparison with the stem diameter measuring, one use specially designed equation or table that reflects the relationship of the tree age with the stem diameter. To this end, the equation (3) is calculated:

\[
A = \exp\{-1.6598 + 0.6774(\ln D) + 2.2621[\ln(T+20)] + 0.9003(\ln PR) - 0.4865[\ln(T+20)]\} \quad \text{adj}R^2 = 0.747; \quad SE = 1.42. \tag{3}
\]

Using the result of tabulating eq. (1) by the given values A, D, T and PR, 3D-dependences of biomass components on temperature T and precipitation PR for trees aged 100 years with D = 24 cm and H = 22 m were designed (Fig. 6).

To estimate climate-related changes in the total biological productivity of oak stands, the above equations, calculated only for aboveground tree biomass, are not sufficient. Because of the small experimental data of root biomass, we calculated the roots-to-shoot ratio in dependence upon the defining variables, having in mind the available 47 data. Of the morphology-caused variables, only age is statistically significant, and the following equation is obtained

\[
P_r \times P_a = \exp\{-21.6606 - 0.8536(\ln A) - 2.7020[\ln(T+20)] + 4.7564(\ln PR)\} \quad \text{adj}R^2 = 0.856; \quad SE = 1.20, \tag{4}
\]

where \(P_r\) is tree root biomass, kg. Equation (4) may be used in a rough estimation of underground biomass on tree and forest levels.

Table 3. Final three-step additive model of oak tree biomass

| Step 1 | \(P_s = 3.49E-09 \quad A \quad 0.1098 \quad D \quad 1.9891 \quad D \quad 0.0023(\ln 20) \quad (T+20) \quad 5.6803 \quad PR \quad 2.6737(T+20) \quad 0.8555(\ln PR)\) |
|--------|---------------------------------------------------------------|
| \(P_a\) | \(1303.6 \quad A \quad 0.5299 \quad D \quad 0.2003 \quad D \quad 0.0377(\ln 20) \quad (T+20) \quad -1.7067 \quad PR \quad -1.5694(T+20) \quad 0.3084(\ln PR)\) |
| \(P_s\) | \(0.0008 \quad A \quad 0.5299 \quad D \quad 0.2003 \quad D \quad 0.0377(\ln 20) \quad (T+20) \quad 1.7067 \quad PR \quad 1.5694(T+20) \quad 0.3084(\ln PR)\) |

| Step 2a | \(P_r = 0.4064 \quad D \quad 0.3464 \quad D \quad 0.0104(\ln 20) \quad (T+20) \quad 2.6556 \quad PR \quad 2.1476(T+20) \quad -0.33916(\ln PR)\) |
| \(P_a\) | \(1\) |
| \(P_c\) | \(P_c \times \) |

| Step 2b | \(P_s = 0.4064 \quad D \quad 0.3464 \quad D \quad 0.0104(\ln 20) \quad (T+20) \quad -2.6556 \quad PR \quad -2.1476(T+20) \quad 0.33916(\ln PR)\) |
| \(P_a\) | \(1\) |
| \(P_c\) | \(P_c \times \) |

| Step 2c | \(P_r = 0.1669 \quad D \quad 0.8216 \quad D \quad 0.1408(\ln 20) \quad (T+20) \quad 4.2616 \quad PR \quad -1.0064(T+20) \quad -0.6544(\ln PR)\) |
| \(P_a\) | \(1\) |
| \(P_c\) | \(P_c \times \) |
Figure 5. The ratio of the harvest biomass and its values obtained by calculating the initial (a) and additive (b) models of the oak tree biomass

| Observed data, kg | Predicted data, kg |
|-------------------|--------------------|
| Crown             |                    |
| Foliage           |                    |
| Branches          |                    |

Figure 6. Dependence of oak tree biomass upon the January mean temperature ($T$, °C) and precipitation ($PR$, mm). Designations: $P_a$, $P_s$, $P_f$, and $P_b$ are correspondingly biomass: aboveground, stems, foliage, and branches, kg
The obtained models of oak tree biomass make them possible to establish quantitative changes in the structure of tree biomass due to climatic changes, in particular, the mean temperature of January and mean annual precipitation. The percentage change in the structure of biomass is associated with the ratio of these two climatic variables.

In Figure 7 it is shown the change in the tree biomass ($\Delta \%$) with an increase in temperature by $1^\circ C$ in different ecoregions, characterized by different values of temperature and precipitation. It is assumed that climate change does not affect precipitation, which changes only geographically (by regions), and the temperature as a result of the expected climate change increases by $1^\circ C$ at different territorial (zonal) temperature levels, designated as $-15\Delta\ldots0\Delta$. Figure 7 shows the general pattern of increase of all the biomass components in moderate dry areas ($PR = 400$ mm) and decrease in water-rich areas ($PR = 700-900$ mm) with an increase in temperature by $1^\circ C$ in all temperature zones of Eurasia.

In Figure 8 it is shown the change of tree biomass ($\Delta \%$) with the increase in precipitation by $100$ mm in areas characterized by different values of temperature and precipitation. It is assumed that the January temperature changes only geographically, and precipitation as a result of the expected climate change increases by $100$ mm at different territorial levels of precipitation, designated as $400\Delta\ldots900\Delta$. Figure 8 shows the common pattern of increase of the all biomass components with an increase in annual precipitation by $100$ mm in all temperature zones of Eurasia and in all regions that differ in precipitation, with exception of foliage biomass that is decreasing in the regions of warm and moderate temperatures (from $0^\circ C$ to $-1^\circ C$).

4. Discussion

Analysis of the 3D-surfaces in Figure 6 allows us to draw some nontrivial conclusions. As we can see there, all of the biomass components vary according to approximately one overall scheme, but in different proportions. The dependence, common to all of the components: in cold climatic zones ($T = -15^\circ C$), any increase in rainfall leads to corresponding increase in the biomass value, and in moder-
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...ate warm zones \((T = 0^\circ C)\), leads to a decrease in foliage biomass value, to a slight decrease in branch biomass and remains unchanged in the aboveground and stem biomass.

Correspondingly, in water-rich areas \((PR = 900 \text{ mm})\), the rise in temperature causes a decrease of biomass values, and in moderate dry areas \((PR = 400 \text{ mm})\), in their increase. This pattern is opposite to the previously constructed analogous models for the aboveground biomass of two-needled pines (Usoltsev et al., 2019b) and larches (Usoltsev et al., 2019a). Perhaps this contradiction is due to the smaller ranges of temperature and precipitation in the areas occupied by oak stands, compared with pine and especially with larch ones, as well as due to biological features of coniferous and deciduous species. The regularities for pines and larches were previously confirmed by other authors on the local level (Glebov & Litvinenko, 1976) and some regional levels (Molchanov, 1976; Polikarpov & Chebakova, 1982).

Using the data of above- and underground biomass of 600 sample trees of eight larch species (genus *Larix* spp.) growing throughout China, the allometric model including the stem diameter and height as independent variables, was developed. After introduction into the allometric model the indices of the mean annual temperature and precipitation, as additional independent variables, it was established that the temperature increase by 1°C leads to an increase in the aboveground biomass of equal-sized trees by 0.9% and to a decrease in the underground one by 2.3%, and an increase in precipitation by 100 mm causes a decrease in the above- and underground phytomass by 1.5 and 1.1%, respectively (Zeng et al., 2017). Our results confirm the data by Zeng et al. (2017) related to the change in the aboveground biomass of larch trees with the increase in temperature by 1°C, but only partly, namely in the areas of low precipitations. With the increase in precipitation by 100 mm, we obtain the opposite result from Zeng’s conclusion, namely an increase rather than a decrease in aboveground tree biomass. As had been mentioned above, this contradiction may be due to the smaller ranges of temperature and precipitation in the areas occupied by oak stands, as well as due to biological features of coniferous and deciduous species.

Figure 8. Change of tree biomass with (+) (surface 1) and (-) (surface 2) when precipitation increasing by 100 mm due to the expected climate change at different territorial levels of temperature and precipitation. The symbols Δa, Δs, Δf and Δb along the ordinate axes represent the change (± %) of aboveground, stems, needles and branches biomass, respectively, with precipitation increase by 100 mm and at the constant mean temperatures of January.
In another study devoted to European forests (Forrester et al., 2017), there was no statistically significant effect of temperature and precipitation on the tree biomass of the most components. The reasons may be the following: a small range of temperature and precipitation variations within Europe, a study of species groups instead of a single species, the introduction of too many variables and their combined effects into the model, and the use of meta-data instead of harvest biomass indices.

The study of the regional variability of the allometric models of aboveground biomass of trees of Masson pine in southern China showed that diameter at breast height, together with the long-term average of growing season temperature, total growing season precipitation, mean temperature of wettest quarter, and precipitation of wettest quarter, had significant effects on values of aboveground biomass. Excessive precipitation during the growing season and high mean temperature in the wettest quarter reduced the aboveground biomass, while a warm growing season and abundant precipitation in the wettest quarter increased it (Fu et al., 2017). Thus, the reaction of pine biomass to the increase in precipitation in the subtropical conditions of China in the wettest quarter is negative, and in the wettest quarter at extremely high temperatures is positive. A similar differentiated reaction of biomass and net primary production to temperature and precipitation was shown earlier on the example of stands of two-needled pines in Eurasia (Usoltsev et al., 2019c). Apparently, any response of forests to climate change is species-specific and reflects the biological and ecological specificities of each tree species.

Our model obtained and the patterns shown are hypothetical: they reflect the long-term adaptive responses of forest stands to regional climatic conditions and do not take into account the rapid trends of current environmental changes, which place serious constraints on the ability of forests to adapt to new climatic conditions (Alcamo et al., 2007). Although modelling at the global level shows that the productivity of forest cover is mainly determined by temperature, other factors (salt stress, length of vegetative period, imbalance between air and soil temperatures, frost drought) limit the productivity to a much larger extent than just temperature. Besides, some experiments show clearly that the water status affects stomata opening and closing in very much degree, and our understanding of the adaptation to water shortage is still patchy (Schulze et al., 2005).

5. Conclusions

Thus, we have made the first attempt to simulate changes in the component composition of the aboveground biomass of oak trees by trans-Eurasian hydrothermal gradients, that revealed the presence of non-trivial regularities. The analysis of the aboveground biomass of oak trees on the basis of the component composition, using regression model method, showed changes in the structure of the biomass of trees, both in connection with the average temperature of January and average annual precipitation, namely: the intensity of changes in biomass due to temperature varies depending on the level of site moisture, and the intensity of changes in biomass due to the level of moisture changes during the transition from cold to warm temperature belts. The adequacy of the obtained regularities is determined by the level of variability 87-99% explained by the proposed regression models.

The obtained model of oak tree biomass make it possible to establish quantitative changes in the biomass structure due to climatic changes, in particular, the mean temperature of January and mean annual precipitation. The proposed additive model, adapted for use in the forest area of Eurasia, is designed for a more accurate assessment of the carbon-depositing ability of oak forests. However, this is a solution to the problem only in the first approximation, because it is based on a limited amount of harvest data.

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Elements distribution in soil and plants of an old copper slag dump in the Middle Urals, Russia

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Abstract. The elements concentration in soil and accumulation in plants growing spontaneously on an old copper slag dump were studied. The research object was a landfill site of the Polevskoy copper smelter (Middle Ural, Russia), which is about 200 years old. We investigated composite samples, consisting of soil blocks (20 x 20 cm) with growing plants. Samples were selected on a transect of 4-5 m at equal intervals. The composite sample was divided into slag fractions: stone, gravel, fine soil (particles smaller than 1 mm); plant fractions: moss and roots, stems and leaves. The microelement analysis of the samples was carried out at an analytical center of the Institute of Geology and Geochemistry, Ural Branch of RAS. The analyses were performed by inductively coupled plasma mass-spectrometry using Elan-9000 ICP mass-spectrometer. The formation of technogenic soil with a thickness of 10-15 cm on the dump of cast copper slag has begun two hundred years ago. Fine soil constitutes more than one third of the technogenic soil mass and acts as a sorption geochemical barrier. Fine soil accumulates elements mobilized from slag. The concentration of most elements in fine soil is 1-2 orders of magnitude higher than their concentration in slag stone. Pb, Cd, Bi are particularly effectively retained in fine soil: their content is 700-1000 times higher than in slag stone. In the conditions of unlimited supply of elements released from slag, plant reaches the upper threshold of accumulation. The aboveground plant parts compared to litter (roots and moss) have a lower concentration of all elements, but they show the stronger ability to accumulate selenium.

Keywords: industrial dump, heavy metals, technogenic soil, anthropogenic ecosystems, elements distribution.

1. Introduction

Extraction and processing of minerals leads to soil degradation, natural ecosystems and landscapes destruction, rivers and groundwater pollution, the industrial waste dumps formation (Chibrik et al., 2011; Mensah et al., 2015).

Mining and mineral processing wastes occupy vast areas around the world, disfigures the environment and are pollution sources. Soil and vegetation restoration in man-made landscapes occurs in two variants: reclamation and spontaneous revegetation. Studies of spontaneous revegetation are necessary for the development of man-made territories biological reclamation. The result of successful biological reclamation is a sustainable, productive and economically valuable ecosystems (Chibrik et al., 2011; Vymazal & Šklenicka, 2012).

Spontaneous revegetation of dumps occurs in most cases are extremely slow and with specific features of the soil and plants restoration, which depend on the dumps nature. It should be remembered that plants are able to concentrate certain elements in quantities that are dangerous when included in food chains. Therefore, it is necessary to evaluate the chemical composition of plants growing on dumps (Remon et al., 2005).

Industrial dumps are numerous and diverse. The basis of Russian classification (Tarchevsky, 1970) is the dumps...
origin (mining industry dumps, processing dumps or other), and the remaining features (age, shape, height, mechanical composition of the surface substrate, acidity, the recycling possibility) are explanatory and can be used to characterize all types of dumps.

The features of the soil formation process are quite well considered for the ash dumps of thermal power stations (Zikeli et al., 2002; Uzarowicz & Zagórski, 2015; Konstantinov et al., 2018) and mining waste (Sourkova et al., 2005; Bragina & Gerasimova, 2014; Santini & Banning, 2016; Dvurechensky et al., 2018), but significantly worse for the metallurgy slag dumps. We have found interesting studies of Polish scientists about old pyrometallurgical copper slags (Kierczak et al., 2013). The article considers mineralogical and chemical composition of slags, and the authors attempt to assess the elements migration into soils, river sediments and surface waters.

Vegetation formation is also much more detailed studied for the ash dumps (Makhnev et al., 2002; Glazyrina et al., 2016; Chibrik et al., 2018) and dumps of different deposits (Kupriyanov et al., 2010; Josu et al., 2012; Glazyrina et al., 2016; Lukina et al., 2017), including copper ore (Zheleva et al., 2012; Avensio et al., 2013).

The Ural is a historically developed industrial region, one of the most powerful in Russia. The mining industry has been intensively developing since the beginning of the 20th century. The region is characterized by the presence of large areas of old industrial dumps, where for many decades the natural restoration of soil and vegetation took place. Therefore, the Urals are an excellent research site for research spontaneous revegetation of industrial dumps (Makhnev et al., 2002; Glazyrina et al., 2016; Lukina et al., 2017; Chibrik et al., 2018), and studying the structure and properties of technogenic soils (Makhonina, 2003). However, many questions about the restoration and transformation of vegetation and soil on industrial dumps, especially metallurgical slags, have remained little studied. Single studies about assess the soils and vegetation geochemical transformation in the copper industry dumps (Pasynkova, 1997) are found.

Some studies state that old copper smelting slags are often more dangerous for the environment than modern production wastes, since they were placed uncontrollably, in direct contact with the soil, surface water and groundwater. Old copper smelting slags also contain more potentially toxic elements than modern slags exposed to more technological and advanced smelting processes (Piatak et al., 2004; Vítková et al., 2010; Kierczak et al., 2013).

In connection with the above researches of the chemical composition of technogenic soil and plants in one of the oldest copper slag dumps in the Urals are great interest. The our research purpose was to study of the elements distribution in soil and plants growing spontaneously on the old Polevsky copper smelter dump. Similar studies for this facility have not been conducted.

2. Materials and methods

Polevskoy copper smelter is one of the oldest copper smelters and iron smelters in the Urals. It was located on the Dumna mountain on the bank of the Polevaya river, a tributary of the Chusovaya river, 52 kilometers southwest of Yekaterinburg (Fig. 1). The coordinates of the study area are 56°26′22″N, 60°11′22″E. The climate is temper-
ate continental. Snow cover is established in November and lasts until April. The depth of soil freezing is 1.25 m. The prevailing winds are westerly and southwesterly. The study area belongs to the Middle Ural taiga region (according to the list of forest growing zones and forest regions of the Russian Federation), and to the border of forest growing district identified according to the classification of B.P. Kolesnikov (Kolesnikov et al., 1973): the south taiga forest district of the Trans-Ural hilly foothill province. In the area of the Polevskoy town the primary forests were not preserved, clear cutting was carried out. Derived mixed forests grow.

Polevskoy copper smelter was founded in 1724 and worked until 1930. The oxidation zone of skarn deposit was processed as ore. The technology of producing copper is a mine smelting method. The dump as a result of the activity of Polevskoy copper smelter was formed and has survived to the present day as a steep hill, which is a continuation of the northwestern slope of Dumnaya mountain. A mixed forest with a predominance of birch grows on top of the mountain.

The research object is the Polevskoy copper smelter dump, on which technogenic soil and plants spontaneously growing were formed. The dump is about two hundred years old. According to the classification of V.V. Tarchevsky (1970) the research object refers to bulk medium height (about 10 meters) dumps of the processing industry.

The copper smelting slag of the studied dump is represented by angular black fragments of various sizes with a porous inhomogeneous structure. Oxidation processes are characteristic of the slags; brown iron hydroxides develop along cleavage planes and the upper porous part. The composition of the copper smelting slag includes: man-made silicate glass, pyroxene, magnetite and minerals related to ferrites (Makarov et al., 2018).

We laid the sample plot on a relatively flat terrassoid section of the foot of the northwestern steep slope of the copper smelting dump. The technogenic soil profile was 10-15 cm and looked like a layer of mostly fine-grained material, which covers coarse-grained crushed stone of the slag. The soil has ensured the development of mixed grass vegetation. The plant roots develop within the dense moss cover and together form a litter.

Soil blocks (20 x 20 cm) together with growing plants on a transect of 4-5 m were selected at equal intervals for the our research purpose. The transect was laid along the foot of the dump on a relatively flat section. The main environmental gradients (altitude, humidity, lighting) are the same. The composite sample included four plots 20 x 20 cm. Soil was collected up to the parent rock (slag). The thickness of the soil profile was 10-15 cm. Plant stems with leaves were cut at the root. The material of the composite sample was divided into natural fractions (soil, plants) and according to the size of copper slag fragments, then air-dried and weighed (Table 1).

Each fraction of the composite sample was analysed in the chemical laboratory of the Zavaritsky Institute of Geology and Geochemistry of the Ural Branch of the Russian Academy of Sciences. The microelements composition of the samples was determined by inductively coupled plasma mass-spectrometry using Elan-9000 ICP mass-spectrometer. The sample preparation was performed by acid decomposition, followed by autoclave mineralization in the microwave oven. The obtained element concentrations agree with available reference values to a tolerance of about 15%.

3. Results and discussion

Man-made ecosystems are very different from natural ones primarily by the lack of a developed soil profile, morphological parameters and properties of the substrate, the structure and productivity of the plant community, and the circulation of matter and energy (Makhonina, 2003; Sibirin et al., 2012).

The investigated technogenic soil of the old Polevskoy copper smelter dump mainly consist of slag particles less than 1 mm. The abundance of fine soil at the dump base may indicate that subsidence of the fine fraction to the

| Fractions of the sample       | Composition of the sample               | Fraction mass |
|-------------------------------|----------------------------------------|---------------|
| Stone                         | Slag particles over 5 mm                | 32.63%        |
| Gravel                        | Slag particles 1–5 mm                   | 21.98%        |
| Fine soil                     | Slag particles smaller than 1 mm        | 37.55%        |
| Litter (plant roots and moss) | -                                      | 1.43%         |
| Plant stems and leaves        | -                                      | 6.41%         |
deeper horizons of slag rubble, partial flushing, and accumulation at the foot of the dump slope occurred.

The results of the elemental analysis of the investigated composite sample are presented in Table 2. The chemical composition of the large fraction of the soil sample (slag particles over 5 mm) should be taken as the average composition of the soil-forming slag. Mainly all the chemical elements (except Al, V, Cr, Mn, Se, Mn) show signs of accumulation already at the first stage of the stone disintegration – in gravel. The most elements content in gravel is noticeably higher than in stone of slag. The maximum accumulation of all elements occurs in the fine soil (slag particles less than 1 mm). We explain the abnormally high content of elements by the fact that the part of the dissolved slag components were washed down along the the slope and sorbed by fine soil from the solution at the foot of the dump slope. The content of deposited Pb, Cd and Bi is especially high, their content in the fine soil is 700-1000 times higher than in stone of slag. The smallest differences in the elements concentrations contained in stone and fine soil of old copper slag dump were found for Zn, Sb, As, Cu, Hg, B and Ca; they concentrations are 100-200 times larger in the fine soil than in the stone.

We used the maximum permissible concentration of total forms of elements (MPC) and concentration coefficient relative to the MPC (Table 3) for ecotoxicological assessment of technogenic soil. Concentration coefficient relative to the MPC is equal to the ratio of the element content in the soil to its maximum permissible concentrations. Maximum permissible concentrations of dangerous chemical elements are regulated in Russia by state documents for

Table 2. The distribution of chemical elements (total, mg/kg) by fractions of the composite sample of the old copper slag dump (Middle Ural, Russia)

| Element | Stone   | Gravel  | Fine soil | Litter (plant roots, moss) | Plant stems, leaves |
|---------|---------|---------|-----------|---------------------------|-------------------|
| B       | 7.19    | 10.0    | 1,031     | 24.3                      | 6.33              |
| Mg      | 8,347   | 12,159  | 351,666   | 9,838                     | 674               |
| Al      | 11,271  | 10,619  | 765,271   | 26,779                    | 853               |
| P       | 1,840   | 2,215   | 78,628    | 1,691                     | 656               |
| K       | 2,167   | 3,661   | 197,295   | 5,060                     | 3,632             |
| Ca      | 3,158   | 5,989   | 568,731   | 15,688                    | 4,620             |
| V       | 116     | 84.1    | 2210      | 44.4                      | 1.19              |
| Cr      | 830     | 754     | 11,145    | 187                       | 3.33              |
| Mn      | 6,038   | 5,178   | 101,630   | 1,924                     | 55.0              |
| Co      | 46.4    | 66.3    | 2,282     | 33.6                      | 0.984             |
| Ni      | 220     | 507     | 19,035    | 233                       | 4.79              |
| Cu      | 201     | 243     | 21,391    | 497                       | 18.0              |
| Zn      | 37.6    | 78.0    | 9,137     | 163                       | 53.8              |
| As      | 9.62    | 14.0    | 999       | 11.6                      | 0.555             |
| Se      | 20.0    | -       | 984       | 49.9                      | 206               |
| Mo      | 2.03    | 1.86    | 67.1      | 1.47                      | 0.394             |
| Cd      | 0.062   | 0.217   | 56.1      | 1.43                      | 0.393             |
| Sb      | 1.08    | 1.79    | 170       | 2.66                      | 0.178             |
| Hg      | 1.05    | 1.37    | 118       | 2.14                      | 0.396             |
| Pb      | 13.4    | 103     | 14,623    | 140                       | 13.0              |
| Bi      | 0.038   | 0.104   | 27.4      | 0.449                     | 0.089             |
Elements distribution in soil and plants of an old copper slag dump in the Middle Urals, Russia

The concentrations of As, Mn, Cu, Ni exceeded the maximum permissible concentration of elements in all mineral fractions of technogenic soil (stone, gravel, fine soil). The most significant excess concentrations for heavy metals were in the fine soil. Concentrations of As, Pb, Cu, Ni were 499, 457, 389, 224 times of the maximum permissible concentration (Table 3), respectively.

Plants absorb almost all chemical elements from the environment. Some elements are necessary for metabolic processes, however, in high concentrations they become toxic for plants, other elements, such as Pb, Cd, are toxic even in low concentrations (Baker, 1981). The mechanisms of plant resistance are manifested in different directions: some species are able to accumulate high concentrations of heavy metals, but are tolerant to them; others plants seek to reduce their intake by maximizing the use of barrier functions. The first barrier level is the roots, where the largest amount of heavy metals is retained, the next is the stems and leaves, and finally, the last barrier is the organs and parts of plants responsible for reproductive functions (most often seeds and fruits, as well as root and tuber crops) (Ilyin & Syso, 2001).

For the studied soil litter (mosses and plant roots), most elements (B, Al, K, Ca, Cu, Zn, Se, Cd, Sb, Hg, Pb, Bi) are in concentrations higher than in stone of slag dump, but lower than in fine soil. Probably, the upper threshold of accumulation of these elements in the plant roots and mosses is reached. Despite the abundance of available forms of metals, their further entry into the plants does not occur. Another group of elements (V, Cr, Mn, Co, Mo) is found in mosses and plant roots in lower concentrations relative to the stone of slag dump, which reflects their lower accumulation threshold. Perhaps the explanation of the identified features in the elements distribution is simplified. The elements migration from soil to plants is a complex and multifactorial process. Analysis of scientific articles showed that a significant positive correlation exists between the metal concentration in soils and some plant species, however for other plant species, for example such as *Silene paradoxa*, does not exist (Pignattelli et al., 2012).

Aboveground parts of plants have a lower accumulation threshold for all components compared to the litter. However, the content of such chalcophilic elements as Se, Zn, Cd and Bi in plant stems and leaves exceeds that in the stone of the old copper slag dump. The peculiarity of the aboveground parts of plants is the accumulation of selenium.

Potassium and calcium are important elements for vegetation, their concentrations in the plant stems are commensurate with the content of K and Ca in the stone of slag dump. However, the concentrations of Mg and P in the

Table 3. The ecological assessment of technogenic soil using the element concentration coefficient relative to the maximum permissible concentration

| Element | Maximum permissible concentrations, mg/kg | Concentration coefficient relative to the maximum permissible concentration |
|---------|------------------------------------------|---------------------------------------------------------------|
|         | Stone | Gravel | Fine soil | Stone | Gravel | Fine soil | Stone | Gravel | Fine soil |
| V       | 150.0 | 0.770  | 0.560  | 14.7  |
| Mn      | 1,500 | 4.03   | 3.45   | 67.8  |
| V+Mn    | 100+1,000 | 5.59 | 4.78   | 94.4  |
| As      | 2.0   | 4.81   | 6.99   | 499   |
| Sb      | 4.5   | 0.239  | 0.399  | 37.9  |
| Hg      | 2.1   | 0.501  | 0.652  | 56.5  |
| Pb      | 32.0  | 0.420  | 3.23   | 457   |
| Pb+Hg   | 20.0+1.0 | 0.690 | 4.99   | 702   |
| Cu*     | 55    | 3.65   | 4.42   | 389   |
| Zn*     | 100   | 0.376  | 0.780  | 91.4  |
| Ni*     | 85    | 2.59   | 5.97   | 224   |

* – The approximate values are given in the earlier government document on the regulation of the content of elements in the soil.
plant stems are significantly less than in slag, despite the recognized high biophilicity.

We calculated the biological absorption coefficients to assess the degree of accumulation of heavy metals by plants. Biological absorption coefficient is the ratio of the content of an element in a plant to the total content of this element in the soil (in our case – fine soil of slag). Visual series of accumulation were compiled. For different parts of the plant sample, an increase in the biological absorption coefficients is as follows:

1. Plant roots and moss:
   \[
   \text{Pb–As–Ni–Co–Sb–Bi–Cr–Zn–Hg–Mn–V–(Mo, P)–Cu–B–Cd–K–(Ca, Mg–Al–Se)
   \]
   The biological absorption coefficients are greatest for selenium (0.051), aluminum (0.035), calcium (0.028) and magnesium (0.028).

2. Plant stems and leaves:
   \[
   \text{Ni–Cr–Bi–Co–(V, Mn–As–Cu–Pb–(Sb, Al)–Mg–Hg–(Mo, Zn, B)–Cd–(Ca, P)–K–Se)
   \]
   The highest biological absorption coefficients in plant stems and leaves was found for selenium (0.21), potassium (0.018), calcium (0.08) and phosphorus (0.08).

4. Conclusion

For two hundred years, the technogenic soil with a capacity of 10-15 cm was formed on the old copper slag dump. Fine soil is more than a third of the mass of technogenic soil and is a sorption geochemical barrier. Fine soil accumulates the elements mobilized from slag. The concentration of most elements in the fine soil by 1-2 orders of magnitude higher than the concentration in the stone of slag. Pb, Cd, Bi are especially effectively retained in the fine soil: their content is 700-1000 times higher than in slag stone. Concentrations of As, Pb, Cu, Ni were 499, 457, 389, 224 times of the maximum permissible concentration.

The plants growing spontaneously on an old copper slag dump has an upper threshold of accumulation in the conditions of a large stock of elements migrating from slag. Litter (plant roots and moss) deposit almost the entire range of elements of copper smelting slag. The biological absorption coefficients (from fine soil) are greatest for selenium (0.051) and aluminum (0.035). The plant stems and leaves in comparison with the litter have a lower concentration of all elements, but they show the stronger ability to accumulate selenium (biological absorption coefficient is 0.21).

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Biomass structure of *Pinus sylvestris* and *Betula pendula* forest ecosystems in pollution gradient near copper plant on the Southern Ural

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**Abstract.** In the gradient of pollution from the Karabash copper smelter in the Southern Urals (55° 29’ N, 60° 13’ E) in predominantly pure Scots pine and white birch stands, 12 and 34 sample plots are established, respectively, on which 42 and 56 model trees are taken, respectively, by stem diameter. The pollution gradient is expressed by the toxicity index suggested with a relative index of the content in the litter of three “technogenic” metals Cu, Pb and Fe. Regression analysis of the dependence of biomass and NPP of trees and stands from toxicity index is performed. There is a log-log-linear pattern of reduction of biomass and annual NPP of spruce-fir forest stands with increasing toxicity index in the direction to the source of pollution, but for the biomass of trees in the same gradient no consistent pattern is detected. The dry matter content (DMC) in all biomass components depends on the toxicity index and species at a statistically significant level: due to the increase in the toxicity index, it decreases in wood and bark, and increases in foliage and branches. At the same toxicity index, DMC in the branches and stem wood more in birch, but in the bark and foliage – in pine. In the wood and bark of a stem, this index is also related to the position in a stem: in the wood it decreases, and in the bark it increases in the direction from the bottom up.

**Key words:** Scots pine, white birch, air pollution, copper smelter, model trees, sample plots, toxicity index, regression analysis.

1. Introduction

An integral indicator reflecting the natural and anthropogenic impact on forest ecosystems is their biological productivity. Assessment of biological productivity, or carbon-depositing capacity of forests is now reaching the global level, and its increase is one of the main factors of climate stabilization, but “our understanding of changes in terrestrial biomass remains rudimentary” (Houghton et al., 2009).

This uncertainty is increasingly exacerbated by an air pollution factor. It is found that even a slight decrease in the biological productivity of forests under the influence of pollution has substantial negative impact on carbon-depositing function of forest cover (Savva & Berlinger, 2010), which reduces the “assimilation” resource forest cover and the opportunity to obtain benefits to the market of environmental services (Kozhukhova, 2001).

It is necessary to study the influence of atmospheric pollution on changes in the structure of biomass and net
primary production (NPP) of forest ecosystems in gradients of industrial pollution. The lack of such information is one of the most important reasons that make it difficult to build an overall picture of the transformation of biota under the influence of industrial pollution (Zvereva & Kozlov, 2012).

The vast expanses of the background environment of the Urals, combined with the presence of large long-term sources of air pollution, provide a unique opportunity to engage in experimental work with entire ecosystems at the level of territorial complexes. In the Urals one of the most intensive sources of toxic emissions is the copper production, in particular, the Karabash copper plant – KCP, Chelyabinsk region in Southern Urals (55° 29’ N, 60° 13’ E). Because of the strong anthropogenic pollution on the territories plant nearest to KCP, zonal ecosystems are completely destroyed: vegetation and soil humus are missing and an extensive technogenic wasteland is formed (Fig. 1).

Many publications describe vegetation reactions to technogenic pollution at the KCP polygon (Chernenkova et al., 1989; Stepanov et al., 1992; Chernenkova, 2002; Kozlov et al., 2009; Koroteeva et al., 2011; Kuyantseva et al., 2011). It was found that radial growth of pine is reduced by 2 times on the gradient of pollution at distances from 1 to 18 km in southern direction of the KCP, while there is a violation of the growth correlation with climatic factors (Kucherov & Muldashev, 2003). The radial growth also decreases as the sources of pollution are approached in white birch in the Central Urals (Makhnev et al., 1990), in Latvian Scots pine (Liepa et al., 1986) and in Siberian fir in Central Siberia (Pavlov, 2006).

As a result of studying the influence of atmospheric emissions of KCP on the apical growth, length and state of needles, the number of resin passages on the cross-section of needles of Scots pine, it was found that the apical growth depends on the amount of gross emissions of KCP. The most sensitive to air emission of KCP are the needle length in Scotch pine (Agikov, 2012), and the area of the leaf blade in white birch (Kuyantseva et al., 2011). The integral index of heavy metal content increases most significantly in leaves and to a lesser extent in bark and wood as birch trees approach the KCP (Koroteeva et al., 2015).

It is stated the increase of crown defoliation in Scots pine stands up to 50% as they approach the Krasnouralsky copper smelter (Vlasenko et al., 2001), the 4-5-fold increase of tree crown transparency as they approach pollution sources in different regions (Sidaravicius, 1987; Yarmishko, 1990; Brassel & Schwyzzer, 1992; Nizametdinov, 2009), but, at the same time, the density of needles on tree shoots is increasing (Augustaitis, 1989; Yarmishko, 1997; Zarubina, 2011). These two opposite trends overlap, and as a result, as we approach the source of pollution, there is no significant decrease in the biomass of trees, as was shown by the example of spruce and fir in the pollution gradient in the Central Urals (Usoltsev et al., 2011, 2012). However, at the stand level, all researchers of biomass structure of different species in pollution gradients came to an unambiguous conclusion about biomass decrease as it approaches the source of pollution (Lukina & Nikonov, 1991; Stepanov et al., 1992; Yusupov et al., 1997; Chernenkova, 2002; Martynyuk, 2011; Usoltsev et al., 2012).

The purpose of this study is to establish patterns of changes in the structure of biomass and NPP of trees and stands of Scots pine and white birch in connection with an increase in the toxicity index in the pollution gradient at the Karabash copper smelter in the Southern Urals.

2. Objects and methods

The Karabash copper plant (KCP) has been operating since 1910. The main emission ingredients are sulfur dioxide
(91% by weight among gaseous pollutants) and dust particles with adsorbed toxic elements (Cu, Pb, Zn, Cd, Fe, Ni, etc.). The volume of emissions for the entire period of plant operation amounted to more than 15 million tons (Usoltsev et al., 2012).

The studies were carried out in two pollution gradients in predominantly pure birch and pine stands northeast of the KCP, and in birch stands also south of the plant (Fig. 1). 12 and 34 sample plots are established, in Scots pine (Table 1) and white birch (Table 2) stands respectively. The methods of work on the sample plots were described earlier (Usoltsev et al., 2011, 2012).

A total of 42 sample trees for pine and 56 ones for birch were taken. The number of disks sawn from the stems to determine the qualitative indices of wood and bark is following: 126 for pine and 168 for birch; the number of definitions of qualitative indices of the crown at the samples of foliage and branches (crown skeleton): 102 pine and 56 birch. To determine the biomass and NPP of regenerations and brushes, 169 and 515 sample trees of pine and birch are taken, respectively. Shares of the regenerations, brushes and grasses in the understory biomass and NPP in different pollution zones are shown in Table 3.

To estimate the stability of ecosystems, to predict their response to pollutants, to find the maximum permissible loads, it is necessary to build “dose – effect” relationships (Stepanov, 1988; Armand et al., 1991; Vorobeychik & Khantemirova, 1994; Mikhailova & Vorobeychik, 1995). It was revealed that the content of heavy metals in the humus layer of the soil changes in the pollution gradient at the KCP as it is removed from it, and this relationship has a nonlinear character (Koroteeva et al., 2015). Therefore, as an indicator of the “dose” we have adopted the toxicity index (index2), calculated from the concentration of mobile forms of the three most “man-made” metals (Cu, Pb and Fe) deposited in the forest litter, i.e. those metals that have the highest exceedances above the minimum level at the three dirtiest sites and the lowest

### Table 1. Tree species composition* and taxation characteristics and harvest data** of stand aboveground biomass on 12 sample plots established in predominantly pure pine stands in the pollution gradient at the KCP

| Pollution zone | D, km | Species composition | A | H | DBH | N | G | V | Ps | Pb | Pf | Pa | Pu | Zs | Zb | Zf | Za | Zu |
|----------------|------|---------------------|---|---|-----|---|---|---|----|----|----|----|----|----|----|----|----|----|
| Impact         | 4.2  | 7Ps3Bp              | 80| 20.6| 26.9| 392|15.97|179|84.1|11.9|3.65|99.6|0.12|1.05|0.446|1.30|2.82|0.112|
|                | 5.5  | 9Ps1Bp              | 80|19.9 |31.1| 422|27.97|323|154.2|22.2|6.97|182.2|0.33|1.94|0.774|1.66|4.4 |0.312|
|                | 5.8  | 10Ps                | 80|21.2 |31.1| 504|34.46|485|199.0|16.9|9.21|214.9|1.08|1.84|0.64 |1.41|3.96|0.418|
|                | 6.6  | 8Ps1Bp1Pt           | 80|19.8 |28.4| 440|26.33|368|164.3|15.4|6.63|179.7|1.08|1.57|0.602|1.61|3.83|0.418|
|                | 7.3  | 10Ps                | 80|20.4 |27.6| 640|35.74|468|196.0|17.0|8.31|214.8|1.08|1.86|0.675|1.54|4.15|0.418|
|                | 8.3  | 8Ps1Bp1Ls          | 80|19.5 |23.8| 560|25.64|275|123.0|12.5|5.00|140.9|1.21|1.37|0.507|1.43|3.25|0.503|
|                | 8.8  | 7Ps3Bp              | 80|18.6 |27.8| 437|24.6 |322|151.5|16.2|4.46|171.2|1.21|1.36|0.618|2.10|3.91|0.503|
|                | 9.5  | 7Ps3Bp              | 80|18.6 |28.4| 434|27.23|401|175.8|22.1|4.46|202.7|1.10|1.56|0.774|2.63|4.75|0.610|
|                | 13.3 | 10Ps                | 80|20.4 |27.6| 549|30.64|373|177.3|16.7|8.63|203.5|1.08|2.39|0.59 |1.80|4.79|0.726|
|                | 13.8 | 10Ps                | 80|20.6 |27.7| 591|32.48|386|183.9|17.3|9.10|211.1|1.08|2.47|0.613|1.80|4.91|0.726|
|                | 14.5 | 9Ps1Bp              | 70|19.5 |25.3| 989|43.69|512|234.3|21.9|10.1|268.0|1.08|3.25|0.853|2.29|6.49|0.726|
| Background     | 32.0 | 8Ps2Bp              | 80|20.3 |28.5| 600|35.0 |492|196.7|17.6|6.70|219.8|1.25|2.98|0.85 |2.21|5.97|0.573|

*Species designations: Ps – Pinus sylvestris L., Bp – Betula pendula Roth., Pt – Populus tremula L., Ls – Larix sibirica L.

**Stand designations: D is distance from pollution source, km; A is stand age, yrs; H and DBH are mean height and mean diameter at breast height correspondingly, in m and cm; N is tree number per ha; G is basal area, m² per ha; V is volume stock, m³ per ha; P and Z are biomass and annual NPP, t per ha; i is the index of biomass component: stem with bark (s), branches (b), foliage (f), aboveground (a), and understory (u).
Table 2. Tree species composition* and taxation characteristics and harvest data** of stand aboveground biomass on 34 sample plots established in predominantly pure birch stands in the pollution gradient at the KCP

| Pollution zone | D, km | Species composition | A | H | D | N | G | V | Ps | Pb | Pf | Pa | Pu | Zs | Zb | Zf | Za | Zu |
|----------------|-------|---------------------|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|
| Impact         |       |                     |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |
| 3.5            | 10Bp  | 69                  | 19.0 | 15.1 | 832 | 14.9 | 152 | 71.8 | 6.65 | 1.32 | 79.7 | 0.481 | 0.810 | 0.224 | 1.32 | 2.35 | 0.059 |
| 3.5            | 10Bp  | 69                  | 18.2 | 14.0 | 1168 | 17.9 | 197 | 91.2 | 9.21 | 1.73 | 102.1 | 0.119 | 1.05  | 0.310 | 1.73 | 3.09 | 0.012 |
| 3.5            | 10Bp  | 70                  | 21.2 | 18.5 | 768  | 20.7 | 236 | 108.1 | 11.5 | 2.10 | 121.7 | 0.178 | 1.27  | 0.387 | 2.10 | 3.76 | 0.023 |
| 3.8            | 10Bp  | 50                  | 14.2 | 15.3 | 1072 | 19.4 | 193 | 91.7 | 8.41 | 1.72 | 101.9 | 0.038 | 1.02  | 0.280 | 1.66 | 2.96 | 0.02  |
| 3.8            | 10Bp  | 69                  | 18.4 | 14.3 | 960  | 24.9 | 266 | 114.8 | 11.0 | 2.14 | 128.0 | 0.036 | 1.17  | 0.332 | 1.92 | 3.43 | 0.0147 |
| 3.8            | 10Bp  | 70                  | 20.4 | 17.3 | 752  | 17.7 | 183 | 86.4 | 8.06 | 1.59 | 96.0  | 0.032 | 0.970 | 0.271 | 1.59 | 2.83 | 0.015 |
| 3.8            | 10Bp  | 70                  | 21.9 | 19.7 | 736  | 22.5 | 260 | 99.9 | 9.77 | 1.87 | 111.5 | 0.017 | 1.14  | 0.329 | 1.87 | 3.34 | 0.007 |
| 4.8            | 9Bp1Ps| 45                  | 13.7 | 14.1 | 1178 | 17.6 | 158 | 78.9 | 6.68 | 2.13 | 87.7  | 0.109 | 0.934 | 0.314 | 1.85 | 3.09 | 0.093 |
| 8.5            | 10Bp  | 40                  | 15.0 | 14.9 | 1239 | 21.76 | 208 | 103.0 | 9.50 | 2.22 | 114.8 | 0.885 | 1.60 | 0.685 | 2.18 | 4.46 | 0.183 |
| 9.1            | 10Bp  | 45                  | 15.1 | 15.1 | 1217 | 21.55 | 214 | 112.0 | 11.9 | 2.23 | 126.1 | 1.375 | 1.52  | 0.582 | 2.21 | 4.31 | 0.592 |
| 9.2            | 6Bp4Pt| 71                  | 21.9 | 18.7 | 832  | 22.9 | 262 | 119.7 | 13.0 | 2.34 | 135.1 | 0.721 | 1.45  | 0.641 | 2.34 | 4.43 | 0.353 |
| 9.1            | 10Bp  | 63                  | 20.2 | 16.0 | 1152 | 23.2 | 309 | 135.5 | 13.7 | 2.57 | 151.8 | 0.610 | 1.85  | 0.657 | 2.57 | 5.08 | 0.282 |
| 9.2            | 10Bp  | 69                  | 21.4 | 18.0 | 960  | 34.1 | 369 | 144.7 | 13.9 | 2.69 | 161.3 | 0.777 | 2.10  | 0.652 | 2.69 | 5.45 | 0.215 |
| 10.6           | 9Bp1Pt| 66                  | 21.6 | 16.8 | 1536 | 34.0 | 417 | 188.7 | 21.9 | 3.73 | 214.3 | 1.338 | 2.13  | 0.969 | 3.73 | 6.82 | 0.608 |
| 10.6           | 7Bp3Pt| 78                  | 25.3 | 21.5 | 768  | 27.8 | 382 | 172.7 | 21.1 | 3.37 | 197.2 | 1.511 | 1.74  | 0.871 | 3.37 | 5.99 | 0.614 |
| 10.6           | 8Bp2Ps| 62                  | 20.7 | 15.7 | 1802 | 43.2 | 423 | 191.4 | 21.8 | 3.80 | 216.9 | 1.352 | 2.28  | 0.991 | 3.80 | 7.07 | 0.637 |
| 12.3           | 9Bp1Pt| 72                  | 23.3 | 21.0 | 960  | 33.5 | 453 | 168.2 | 17.4 | 3.23 | 188.8 | 0.920 | 2.15  | 0.841 | 3.23 | 6.22 | 0.683 |
| 12.3           | 9Bp1Pt| 57                  | 19.5 | 15.0 | 1408 | 24.8 | 271 | 111.3 | 10.3 | 2.03 | 123.6 | 1.041 | 1.78  | 0.475 | 2.03 | 4.29 | 0.675 |
| 12.3           | 10Bp  | 63                  | 21.1 | 17.1 | 1264 | 29.2 | 367 | 144.4 | 14.0 | 2.70 | 161.1 | 0.797 | 2.09  | 0.659 | 2.70 | 5.45 | 0.532 |
| 13.1           | 10Bp  | 50                  | 19.5 | 21.5 | 740  | 26.6 | 337 | 147.0 | 14.3 | 1.88 | 163.2 | 1.068 | 2.31  | 0.566 | 1.85 | 4.72 | 0.711 |
| 17.5           | 7Bp2Ps1Pt | 50            | 17.8 | 21.0 | 796  | 25.5 | 306 | 145.4 | 18.9 | 3.70 | 168.0 | 1.074 | 1.53  | 0.484 | 2.90 | 4.91 | 0.662 |
Table 2 continued

| Pollution zone | $D$, km | Species composition | $A$ | $H$ | $D$ | $N$ | $G$ | $V$ | $Ps$ | $Pb$ | $Pf$ | $Pa$ | $Pu$ | $Zs$ | $Zb$ | $Zf$ | $Zu$ | $Zu$ |
|----------------|--------|---------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| **Buffer**     |        |                     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| 18.5           | 10Bp   | 69                  | 24.9| 22.0| 912  | 34.8| 457 | 212.9| 30.0| 4.28 | 247.2| 1.033| 2.83 | 1.16 | 4.28 | 8.27 | 0.860|
| 18.5           | 10Bp   | 71                  | 25.6| 23.2| 720  | 30.5| 405 | 188.5| 26.8| 3.79 | 219.1| 1.534| 2.49 | 1.01 | 3.79 | 7.29 | 1.101|
| 18.5           | 10Bp   | 72                  | 25.8| 23.5| 848  | 36.7| 483 | 224.7| 32.1| 4.53 | 261.3| 1.464| 2.93 | 1.20 | 4.53 | 8.65 | 1.074|
| **Background** |        |                     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| 25.7           | 10Bp   | 68                  | 23.6| 19.0| 1168 | 33.1| 527 | 209.8| 18.0| 4.16 | 232.0| 1.141| 3.21 | 0.719| 4.16 | 8.09 | 0.544|
| 25.8           | 10Bp   | 74                  | 27.3| 22.8| 752  | 30.7| 482 | 207.0| 18.3| 4.22 | 229.6| 1.295| 3.07 | 0.720| 4.22 | 8.01 | 0.790|
| 28.7           | 9Bp1Ps | 71                  | 25.5| 20.9| 912  | 31.3| 495 | 210.2| 17.5| 4.05 | 231.7| 1.248| 2.97 | 0.652| 4.05 | 7.68 | 0.977|
| 28.7           | 9Bp1Ls | 72                  | 26.1| 21.5| 960  | 34.8| 535 | 227.4| 19.0| 4.41 | 250.9| 1.906| 3.23 | 0.713| 4.41 | 8.36 | 0.985|
| 28.7           | 8Bp2Pt | 68                  | 23.8| 21.2| 832  | 24.0| 318 | 135.9| 11.7| 2.70 | 150.3| 1.190| 1.97 | 0.453| 2.70 | 5.13 | 0.934|
| 31.0           | 10Bp   | 40                  | 16  | 17.9| 856  | 22.18|297 | 135.9| 13.1| 2.88 | 149.1| 1.288| 2.05 | 0.537| 2.88 | 5.45 | 0.611|
| 31.7           | 10Bp   | 72                  | 25.6| 21.1| 912  | 31.9| 505 | 215.9| 18.5| 4.28 | 238.6| 1.404| 3.40 | 0.764| 4.28 | 8.44 | 0.728|
| 31.7           | 10Bp   | 72                  | 25.8| 21.3| 992  | 35.2| 552 | 236.2| 20.5| 4.74 | 261.4| 1.281| 3.45 | 0.799| 4.74 | 8.99 | 0.659|
| 31.7           | 10Bp   | 72                  | 25.6| 21.0| 1136 | 39.4| 603 | 259.9| 23.3| 5.37 | 288.6| 2.227| 3.89 | 0.928| 5.37 | 10.19| 0.723|

*Species designations: $Ps$ – *Pinus sylvestris* L., $Bp$ – *Betula pendula* Roth., $Pt$ – *Populus tremula* L., $Ls$ – *Larix sibirica* L.

** Stand designations: $D$ is distance from pollution source, km; $A$ is stand age, yrs; $H$ and DBH are mean height and mean diameter at breast height correspondingly, in m and cm; $N$ is tree number per ha; $G$ is basal area, m$^2$ per ha; $V$ is volume stock, m$^3$ per ha; $Pi$ and $Zi$ are biomass and annual NPP, t per ha; $i$ is the index of biomass component: stem with bark ($s$), branches ($b$), foliage ($f$), aboveground ($a$), and understory ($u$).
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exceedances at the three sites furthest from the emission source. In contrast to sulfur, they are stronger adsorbed by depositing environments, and they are easier to measure on polygons of a large area (Mikhailova & Vorobeichik, 1995).

In this case, index2 is calculated for concentrations of mobile forms of Cu, Pb and Fe in forest litter according to the following formula

$$\text{index2} = \frac{1}{k} \sum \frac{X_{ij}}{X_{\text{min}}}$$  \hspace{1cm} (1)

where, \(k\) is a number of elements (in our case – three); \(X_{ij}\) is concentration of \(i\)-th element on \(j\)-th site; \(X_{\text{min}}\) is minimum concentration of \(i\)-th element on all sites.

### 3. Results and discussion

To assess the impact of pollution on the structure of tree biomass, the allometric equations are calculated, having the form

$$p_i = \exp [a_0 + a_1 \ln(\text{DBH}) + a_2(X) + a_3 \ln(I)],$$  \hspace{1cm} (2)

where \(p_i\) is biomass of \(i\)-th component, kg; DBH is stem diameter at breast height, cm; \(I\) is toxicity index (index2); \(X\) – binary variable, equal 1 for pine and 0 for birch. The calculation of (2) for aboveground biomass, stems, foliage and branches, showed the following coefficients of determination, correspondingly: 0.981, 0.972, 0.861 and 0.951. The significance level according to the Student’s criterion for the constant \(a_2\) was 10.6, 9.9, 12.1 and 18.1 respectively. This means that the difference of allometric dependences of biomass components upon DBH in pine and birch is highly reliable (at the level of probability \(P_{\text{sig}}\)).

But for the constant \(a_3\), the significance level was 1.1, 0.9, 1.1 and 0.4 respectively, which is significantly less than the critical value \(t_{0.05} = 2\). This means that the biomass structure of equal-sized trees of both species remains unchanged throughout the pollution gradient. As it was mentioned above, this phenomenon may be explained with joining two contrary trends, i.e. firstly, increasing foliage density on twigs and, secondly, increasing crown transparency when approaching pollution source. Thus, these two contrary trends overlap and the total trend is absent.

This also means that ignoring of previously obtained experimental data of tree biomass and seeking new experimental data to calculate “modern” allometric equations, supposedly more appropriate to the changed environmental conditions (Xing et al., 2005), is completely unfounded.

Similar equations are calculated for the annual growth of tree biomass. The obtained equations for each sample plot are further used to calculate biomass and NPP per 1 ha, which are then analyzed in relation to the toxicity index.

A standard regression analysis procedure was used to approximate “dose – effect” relationships. The dependencies were analyzed

$$P_i = \exp [a_0 + a_1 \ln(I) + a_2(X \times \ln(I))],$$  \hspace{1cm} (3)

$$Z_i = \exp [a_0 + a_1 \ln(I) + a_2(X \times \ln(I))].$$  \hspace{1cm} (4)

Designations in (3) and (4) see in Table 1. All regression coefficients of the independent variables of the calculated equations are significant at the probability level

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### Table 3. Shares of the regenerations, brushes and grasses in the understory biomass and NPP in different pollution zones

| Pollination zone | Regeneration | Brush | Grass | Total | Regeneration | Brush | Grass | Total |
|------------------|--------------|-------|-------|-------|--------------|-------|-------|-------|
| Pine stands      |              |       |       |       |              |       |       |       |
| Impact           | 4            | 2     | 94    | 100   | 0.5          | 0.2   | 99.3  | 100   |
| Buffer           | 22           | 34    | 44    | 100   | 4            | 6     | 90    | 100   |
| Background       | 16           | 43    | 41    | 100   | 3            | 7     | 90    | 100   |
| Birch stands     |              |       |       |       |              |       |       |       |
| Impact           | 32           | 48    | 20    | 100   | 15           | 22    | 63    | 100   |
| Buffer           | 20           | 34    | 46    | 100   | 4            | 6     | 90    | 100   |
| Background       | 19           | 24    | 57    | 100   | 3            | 3     | 94    | 100   |
of 0.95 and above. When calculating equations (3) and (4), the taxation characteristics of pine and birch stands were consistently included as additional independent variables. However, in most cases their influence on biomass and NPP of forest stands in the pollution gradient was not statistically reliable. The characteristics of the final equations is given in Table 4 and their graphical interpretation in Figure 2.

If no significant impact on the aboveground biomass and its annual NPP of pine and birch in the gradient of pollution from KCP was revealed at a tree level, at a stand level such an impact was significant. This means that the change in biological productivity of stands in the pollution gradient is influenced not by the structure of biomass and NPP of their constituent trees, but by the taxation structure of stands.

A previously published paper (Usoltsev et al., 2012) the dependence of biomass and NPP of trees and stands was investigated in the same pollution gradient on the KCP, but the pollution index was the distance from the source of pollution. The first output was like this: if an

Table 4. Characteristic of equations (3) and (4) for pine and birch stands in the pollution gradient near the KCP

| Equation characteristic | Pa  | Ps  | Pf  | Pb  | Pu  | Za  | Zs  | Zf  | Zb  | Zu  |
|-------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| a0                     | 5.4703 | 5.3530 | 1.5307 | 3.0375 | 0.8666 | 2.0606 | 1.1305 | 1.3444 | -0.1412 | 0.4393 |
| a1                     | -0.1755 | -0.1744 | -0.2072 | -0.1701 | -0.6590 | -0.1888 | -0.2281 | -0.1593 | -0.1882 | -0.8222 |
| a2                     | 0.1026 | 0.1000 | 0.2932 | 0.1125 | 0.3514 | 0.0165 | 0.0733 | -0.0575 | 0.1058 | 0.4650 |
| adjR2                  | 0.594 | 0.587 | 0.697 | 0.465 | 0.671 | 0.672 | 0.708 | 0.621 | 0.483 | 0.804 |
| SE                     | 1.24 | 1.24 | 1.33 | 1.31 | 1.98 | 1.24 | 1.25 | 1.28 | 1.33 | 1.83 |

Designations of symbols: \( P_i \) and \( Z_i \) are biomass and annual NPP, t per ha; \( i \) is the index of biomass component: aboveground (\( a \)), stem with bark (\( s \)), foliage (\( f \)), branches (\( b \)), and understory (\( u \)).
Figure 2. Linear log-log change trends of biomass (left) and annual NPP (right) of pine and birch stands in the pollution gradient at KCP. The dotted lines show the range of the standard error of the equations.
evaluating it on sample plots in the stands of pine and birch, its average values can be used (Table 7).

4. Conclusion

Thus, it is not revealed any statistically significant patterns of change in biomass and annual NPP of trees in the gradient of the index of toxicity, but at the stand level, a linear log-log pattern of declining biomass and annual NPP of forest stands with increasing index of toxicity in the direction to the source of pollution have been established, and most of the components reduce in birch more pronounced than in pine. The exception is the ratio of these trends in pine and birch related to biomass and NPP foliage.

Neither the age of a tree nor its size contribute significantly to the explanation of the variability of DMC in biomass components. But DMC of all the components of biomass depends upon the value of the toxicity index and species on a statistically significant level: due to the increase in the toxicity index, DMC in wood and bark decreases, and in foliage and branches increases. At the same toxicity index DMC in the stem wood and branches above birch, and in the bark and foliage above pine. In the stem wood and bark, this indicator is also related to the position in a stem: in the wood it decreases, and in the bark it increases in the direction from the bottom up.

The use of the toxicity index in the pollution gradient enables a comparative analysis of pollution situations at different sites and some physiologically determined interpretations of the revealed trends.

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