

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 и 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 KCSP, zonal ecosystems are completely destroyed: vegetation and soil humus are missing and an extensive technogenic wasteland is formed (Fig. 1).



Figure 1. Locations of sample plot establishing in the northeast and south direction from KCP

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 & Schwyzer, 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.

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	<i>D</i> , km	Species composition	<i>A</i>	<i>H</i>	<i>DBH</i>	<i>N</i>	<i>G</i>	<i>V</i>	<i>P_s</i>	<i>P_b</i>	<i>P_f</i>	<i>P_a</i>	<i>P_u</i>	<i>Z_s</i>	<i>Z_b</i>	<i>Z_f</i>	<i>Z_a</i>	<i>Z_u</i>
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
Buffer	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_i* and *Z_i* 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	<i>D</i> , km	Species composition	<i>A</i>	<i>H</i>	<i>D</i>	<i>N</i>	<i>G</i>	<i>V</i>	<i>Ps</i>	<i>Pb</i>	<i>Pf</i>	<i>Pa</i>	<i>Pu</i>	<i>Zs</i>	<i>Zb</i>	<i>Zf</i>	<i>Za</i>	<i>Zu</i>
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
Buffer	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	25.57	306	145.4	18.9	3.70	168.0	1.074	1.53	0.484	2.90	4.91	0.662

	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

Table 2 continued

Pollution zone	<i>D</i> , km	Species composition	<i>A</i>	<i>H</i>	<i>D</i>	<i>N</i>	<i>G</i>	<i>V</i>	<i>P_s</i>	<i>P_b</i>	<i>P_f</i>	<i>P_a</i>	<i>P_u</i>	<i>Z_s</i>	<i>Z_b</i>	<i>Z_f</i>	<i>Z_a</i>	<i>Z_u</i>
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, m² per ha; *V* is volume stock, m³ per ha; *P_i* and *Z_i* 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 3. Shares of the regenerations, brushes and grasses in the understory biomass and NPP in different pollution zones

Pollution zone	Biomass, %				NPP, %			
	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

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 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

$$\text{index2} = \frac{1}{k} * \sum \frac{X_{ij}}{X_{i\min}} \quad , (1)$$

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

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

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_{999}).

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 $t_{05} = 2$. 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

$$P_i = \exp [a_0 + a_1 \ln I + a_2(X \times \ln I)], \quad (3)$$

$$Z_i = \exp [a_0 + a_1 \ln I + a_2(X \times \ln I)]. \quad (4)$$

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 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 Fig. 2.

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

Equation characteristic	P_a	P_s	P_f	P_b	P_u	Z_a	Z_s	Z_f	Z_b	Z_u
a_0	5.4703	5.3530	1.5307	3.0375	0.8666	2.0606	1.1305	1.3444	-0.1412	0.4393
a_1	-0.1755	-0.1744	-0.2072	-0.1701	-0.6590	-0.1888	-0.2281	-0.1593	-0.1882	-0.8222
a_2	0.1026	0.1000	0.2932	0.1125	0.3514	0.0165	0.0733	-0.0575	0.1058	0.4650
$adjR^2$	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).

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.

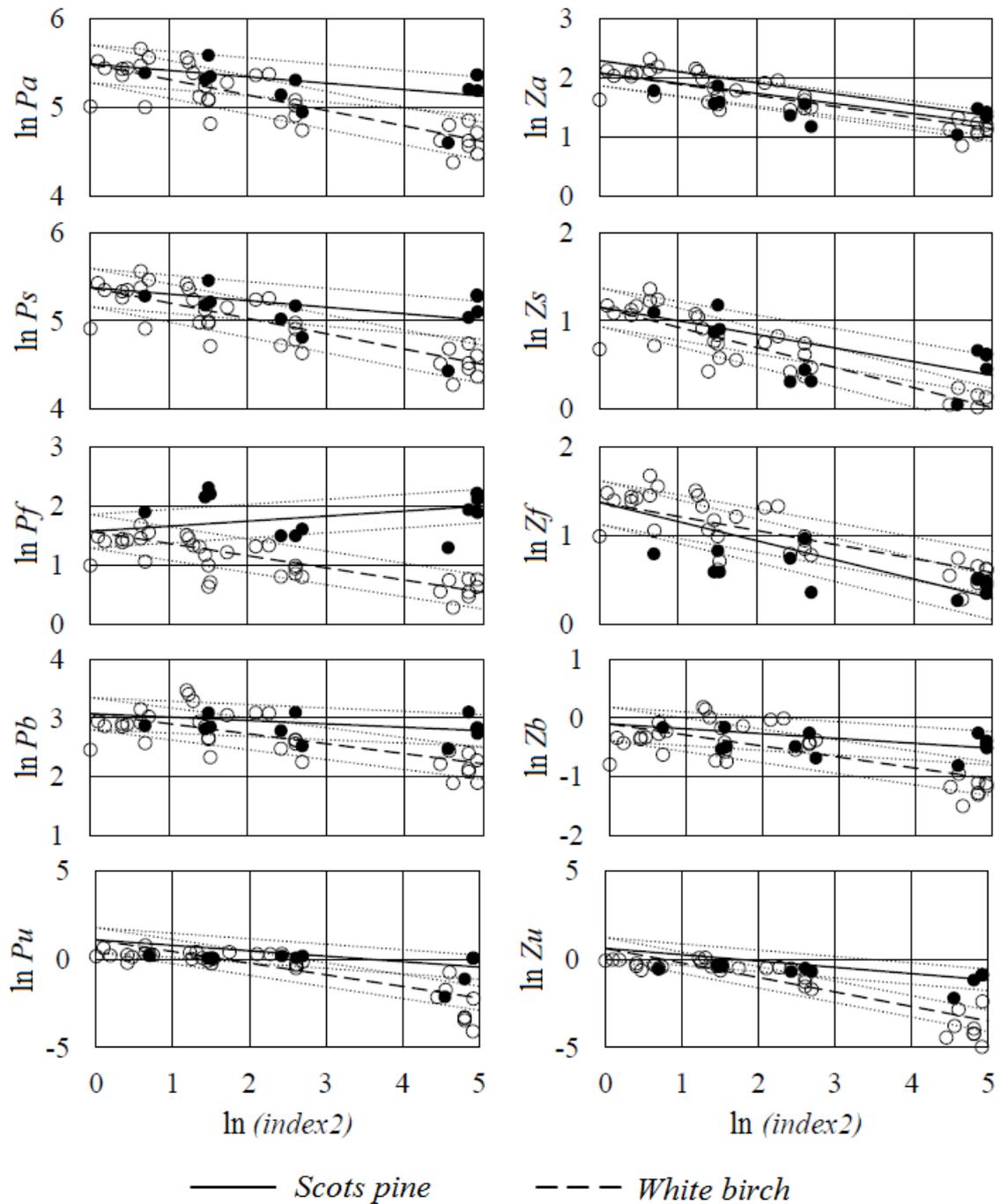


Figure 2. Linear log-log change trends of biomass (left) and annual NPP (right) of pine and birch stands in the pollution gradient at KCP. The dotted lines show the range of the standard error of the equations

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 influence of pollution from KCP on aboveground biomass and annual NPP of pine and birch trees in the gradient was no significant, their influence at a forest stand level is obvious.

However, there are differences concerning the traits of the studied dependencies. Judging by the structure of equations (3) and (4), shown in Table 5, and their graphical interpretation (Fig. 2), the obtained dependences of the stands production indices on the toxicity index are described by a simple allometric function, whereas their relation to the distance from the pollution source (D , km) was described by the equation

$$P_i \text{ and } Z_i = a_0 + a_1 (1/D)^2, \quad (5)$$

according to which, after the sharp increase in P_i and Z_i in the range of distances from 4 to 10 km, as they move away from the KCP, they gradually stabilize with the exit to the plateau.

Since in determining the biological productivity of stands in the sample plots, the main share of labor is spent on determining the dry matter content (DMC) in biomass components, we estimated dependences of DMC in biomass components upon determining factors that could be useful in studies of this nature at similar facilities. The equations for DMC are calculated:

- in stem components

$$S_w \text{ and } S_b = a_0 + a_1 I + a_2 X + a_3 h; \quad (6)$$

- and in foliage and branches

$$S_f \text{ and } S_{br} = a_0 + a_1 I + a_2 X, \quad (7)$$

where S_w , S_b , S_f and S_{br} are dry matter content in stem wood and bark, in foliage and branches, respectively, %; h – position of sawn disks along the stem, in shares of the stem height, i.e. 0.2, 0.5 and 0.8 H (numbering from bottom to top), where H is the stem height, m; I – index toxicity (Index2); X is a binary variable equal to 1 for pine and 0 for birch. All regression coefficients of the independent variables of the calculated equations (6) and (7) are significant at the probability level of 0.95 and above. The characteristic of equations (6) and (7) is given in Table 6.

Table 6. The characteristic of equations (6) and (7)

Equation characteristics	S_w	S_b	S_f	S_{br}
a_0	67.13	32.58	37.86	52.69
a_1	-0.024	-0.022	0.011	0.011
a_2	-4.39	19.35	9.26	-6.155

a_3	-18.31	6.93	-	-
$adjR^2$	0.636	0.797	0.835	0.638
SE	3.86	4.88	2.00	2.22

When judging by the characteristic of equations (6) and (7), the dry matter content in the stem wood decreases and in the bark increases from the bottom up; due to the increase in the toxicity index, DMC in the wood and bark decreases, and in the foliage and branches increases. At the same toxicity index, DMC in the stem wood and branches is more in birch, and in bark and foliage is more in pine.

For preliminary (approximate) calculations or in cases where it is not possible to determine the DMC in the biomass components by the thermal-weight method when evaluating it on sample plots in the stands of pine and birch, its average values can be used (Table 7).

Table 7. Average DMC (%) in pine and birch biomass components in the pollution gradient at KCP

Biomass component	Pine	Birch
Stem wood	52.5±0.60	57.1±0.44
Stem bark	54.1±0.70	35.4±0.22
Branches with their bark	47.0±0.23	53.1±0.21
Foliage	47.6±0.29	38.4±0.20

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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