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Bird Population in Birch Forests of the Southern Urals Affected by Industrial Pollution: Report 2. Relationship with Habitat Variables

E. A. Belskii and E. A. Belskaya

Institute of Plant and Animal Ecology, Ural Branch, Russian Academy of Sciences, ul. 8 Marta 202, Yekaterinburg, 620144
e-mail: belskii@ipae.uran.ru

Abstract—The changes in habitat variables are analyzed according to the data of 2009 at ten sites along the gradient of pollution by emissions from the Karabash Copper Smelter (Chelyabinsk oblast): the pollution level, basic structural characteristics of phytocenosis, and abundance of leaf-eating invertebrates and epigeic invertebrates. The height of the top canopy, stand basal area, foliage cover of all forest layers, and biomass of epigeic invertebrates decrease as pollution grows. Foliar damage in birch (the indirect index of the abundance of phyllophages) changes only insignificantly. It seems impossible to differentiate the contribution of abiotic and biotic variables to the formation of the bird population in the study region because of close correlation between them. Pollution seems to affect the bird population indirectly through the changes in habitats.

Keywords: industrial pollution, Southern Urals, birds, vegetation, invertebrates

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This article is the second part of a study devoted to the responses of the bird population in birch forests of the Southern Urals to industrial pollution (near the Karabash Copper Smelter, KCS). The first part [1], which describes the responses of separate species and the bird community to the environmental pollution, presents the substantiation and goal of the investigations and describes the region of works. The classical task of ecotoxicology is to differentiate the direct and indirect effects of pollution on biota. The direct effect is related to the intake of toxicants into the environment; the indirect effect is related to the change in habitats, structure of phytocenoses, and their food supply. The estimate of the contribution of different environmental parameters to the responses of biotic components is a necessary stage to reveal the casual relationships of the anthropogenic ecosystem transformation. The relationship of the bird population with natural factors is intensively studied [2–4]. However, the role of habitat variables in the responses of bird communities to pollution has been investigated very weakly [5, 6]. The task of the second part of the study is to characterize habitats and estimate the contribution of habitat variables to the change in the structure of the bird population and the abundance of separate ecotoxicological groups along the gradient of pollution by emissions of the copper-smelting industry.

MATERIALS AND METHODS

Ten study sites were selected in the environs of the Karabash Copper Smelter (Southern Urals, Chelyabinsk oblast). In the northern direction, the sites are at distances of 5, 11, 18, and 32 km from the emission source; in the southern direction, they are 3, 9, 12, 26, and 27 km away. The site nearest to the plant is 1 km east. To make analysis more convenient, the sites were grouped according to the pollution zones: industrial barren (maximum pollution, up to 3 km from the plant), impact zone (strong pollution, up to 6 km), buffer zone (moderate pollution, 9–18 km), and background zone (pollution at the level of the regional background, more than 20 km from the plant).

In order to comprehensively characterize the habitat variables that affect birds, the pollution level, abundance of invertebrates (potential food supply in insect-eating birds) and basic phytocenotic indices were determined.

The pollution level at the sites was estimated by metal concentrations in leaves of the common birch *Betula pendula* Roth. Samples were taken from 9 to 12 June 2009, 1–2 weeks after complete leaf unfolding. Five trees with distances of no less than 20 m between them were selected randomly in each area. One branch was taken from each tree and 20–50 leaves were torn off from short shoots; after petioles were cut off, leaves were dried in a desiccator at $t = 60°C$. The sample for the analysis was about 100 mg of air-dry mass; the accuracy of weighting was 0.1 mg. The samples were digested in a mixture of 7 mL of HNO_3 + 1 mL of deionized H_2O in teflon vessels in a MWS-2 microwave digestion system of the Berghof Company (Germany). Metal concentrations (Cu, Pb, Cd, Zn, Fe, Ni) were determined by flame atomic absorption spectrometry using an AAS-6 vario spectrometer of the Analytik Jena Company (Germany). The analyses were performed at the laboratory of the Institute of Plant and Animal Ecology, Ural Branch, Russian Academy of Sciences, which is accredited in the system of analytical laboratories (certificate POCC.RU001.515630). Fifty samples were analyzed and 300 element concentrations were obtained.

To estimate the food supply in insect-eating birds, censuses of leaf-eating and epigeic invertebrates were performed. The abundance of leaf-eating insects was estimated based on foliar damage of the common birch in the same periods and in the same trees from which samples were taken for the chemical analysis. One branch with 100 (75–150) leaves was cut off from each tree at a height of 1.5–2 m. Branches were placed individually in a fabric package. Foliar damage was censused in the laboratory as soon as possible after the branches were cut off. Hole feeding (a mesophyll with ribs), window feeding (only a mesophyll), and mines were taken into account for this study. These damages are typical of Lepidoptera larvae, sawfly larvae, and Coleoptera larvae and imagoes. Leaves were related to the following classes according to the removed leaf area: less 1, 1–5, 6–25, 26–50, 51–75, 76–100%. The weighted mean percent (%) of foliar damage (including undamaged leaves) was estimated for each tree using the average values of the classes. Fifty trees were analyzed.

In order to count epigeic invertebrates, pitfall traps were installed in the center of each study site in three lines with five traps in each and a distance of 2.0–2.5 m between them. A distance between lines was 50–100 m. The diameter of a trap was 85 mm; a 3% solution of acetic acid was used as a fixer. The exposure was 5 days. Censuses were made from 5 to 10 June 2009; 750 trap days were processed. The samples of invertebrates were weighted at the laboratory (with an accuracy of 0.1 mg) after removing excess moisture using filter paper. Then the air-dry mass was estimated based on the proper data on the mass lost while drying by hard-cover and soft-cover invertebrates. Altogether 146 samples were processed. The mass of samples was used as an index of the abundance in epigeic invertebrates.

The structural characteristics of the phytocenosis were described in each point, where birds were censused. The stand basal area was determined using a relascop. The height of the top tree canopy was estimated as a mean of five highest trees at a radius of 50 m from a point using a Silva Clino Master height-meter. The formula of a stand per 10 trees, cover of the tree canopy, underwood and underbrush, and field layer were determined. Forty descriptions were made.

The significance of the differences between zones and sites was tested using the Kruskal–Wallis and Mann–Whitney *U*-tests. A tree ($n = 50$), trap (146), count point (40), and geobotanical description (40) served as registration units here. Before the statistical analysis, the initial data were transformed to conform to normality. Instead of the absolute values of metal concentrations and distances from the emission source, their decimal logarithms were used. Percentages (the proportion of the birch in the stand, cover of underbrush, underwood, and field layer, as well as the proportion of the leaf area removed by phyllophages) were subjected to arcsine square-root transformation. In order to reduce the number of variables, the principal component analysis was used. The dependence of the indices of the bird population on the distinguished principal components was studied using the forward stepwise regression. The mean for each site served as a registration unit here ($n = 10$).

RESULTS AND DISCUSSION

The size of anthropogenic load that is reflected by metal concentrations in birch leaves significantly grows as the emission source is approached (Table 1). The greatest increase in concentrations is demonstrated by Pb (the industrial barren/background zone ratio = 35.7) and Cu (11.8); the concentrations of Fe and Cd grow to a lesser extent (5.3 and 5.0, respectively). The content of Ni and Zn in the leaves increases least of all (1.6 and 1.4 times, respectively). The damage of birch leaves (the indirect index of the abundance of phyllophages) somewhat decreases in the industrial barren compared to other polluted zones, but the differences are insignificant. The abundance (biomass) of epigeic invertebrates abruptly decreases as pollution grows. The principal characteristics of the phytocenosis decline as the smelter is approached (see Table 1). The height of the top canopy, stand basal area, and cover of all forest layers decrease. The proportion of the birch in a stand somewhat grows in the impact zone and decreases in the barren one. Let us note that the buffer and background zones do not significantly differ from each other in the main indices which characterize the phytocenosis and invertebrates. Most visible effects of pollution appear only in the impact zone at a distance up to 6–8 km from the emission source.

We tried to relate the observed changes in the bird population with the environmental factors. Three groups of variables characterized the level of pollution at the study sites, phytocenosis, and abundance of invertebrates (the “food supply” in insect-eating birds). Many variables that describe the pollution and change of habitats correlated with each other (Table 2). The coefficients of correlation of habitat variables with abundance of invertebrates have a positive sign, and those of the same variables with the level of pollution have a negative sign.

Table 1. Characteristics of the study sites in the environs of the Karabash Copper Smelter (mean ± SE)

Indicator	Zone				n	H** ($df = 3$)	p
	Background	Buffer	Impact	Industrial barren			
Metals in birch leaves, mkg/g*							
Cu	4.4 ± 0.2^a	5.2 ± 0.2^a	11.4 ± 1.2^b	52.2 ± 6.5^b	50	32.6	<0.001
Zn	306.2 ± 23.5^{ab}	263.9 ± 29.9^a	325.2 ± 27.9^{ab}	443.7 ± 76.9^b	50	9.5	0.024
Cd	0.40 ± 0.05^a	0.39 ± 0.07^a	0.44 ± 0.04^a	2.00 ± 0.42^b	50	14.1	0.003
Pb	2.3 ± 0.5^a	4.4 ± 0.6^a	16.6 ± 2.3^b	82.4 ± 10.5^b	50	32.5	<0.001
Fe	87.2 ± 6.2^a	90.0 ± 3.1^a	173.6 ± 32.8^{ab}	457.8 ± 71.3^b	50	18.0	<0.001
Ni	13.7 ± 0.9^{ab}	13.1 ± 1.3^a	21.6 ± 2.9^{ab}	21.8 ± 2.5^b	50	12.2	0.007
Removed leaf area, %	3.0 ± 0.6^a	4.1 ± 0.8^a	3.4 ± 0.8^a	1.8 ± 0.8^a	50	3.1	0.373
Biomass of epigeic invertebrates, g*/day-trap	1.68 ± 0.14^a	1.66 ± 0.10^a	0.23 ± 0.02^b	0.008 ± 0.002^b	146	92.9	<0.001
Height of the top canopy, m	25.4 ± 1.0^a	23.5 ± 0.6^{ab}	15.9 ± 0.9^{bc}	3.4 ± 0.5^{c} ***	40	20.3	0.001
Stand basal area, m^2/ha	32.0 ± 1.7^a	28.1 ± 2.0^a	12.4 ± 1.3^b	0^b	40	26.6	<0.001
Proportion of the birch in a stand, %	80.0 ± 4.3^{ab}	79.7 ± 4.3^{ab}	93.8 ± 2.6^a	40^b ***	40	15.3	0.002
Cover, %							
underbrush and underwood	45.0 ± 5.3^a	37.5 ± 4.9^a	41.3 ± 7.6^a	0.8 ± 0.1^b	40	11.4	0.010
field layer	65.8 ± 3.1^a	65.0 ± 3.3^a	11.5 ± 3.8^b	5.3 ± 1.1^b	40	25.3	<0.001

Note: The values within a line that are designated with different letters differ significantly ($p < 0.05$) from each other (the Mann–Whitney U-test); *The air-dry mass; **The Kruskal–Wallis test; ***for the trees remaining at the site.

The close correlation between the variables does not enable analysis of relationship of bird characteristics with separate habitat and pollution variables. In order to reduce the number of variables in the analysis, we applied the principal component (PC) analysis using the rotation maximizing the variance. As a result, 14 variables were reduced to three components that explained 85.1% of the total variance (Table 3). The distance from the plant, concentrations of Cu, Pb, and Fe in leaves, height of the stand and stand basal area, and cover of the field layer correlate most closely with the first PC (the absolute values of factor loadings >0.900). The second PC is mainly determined by the proportion of the birch in the stand and concentration of Cd in leaves. The third PC is mainly related to the feeding activity of phyllophages. Consequently, the first PC, which explains 64% of the total variance, is determined by both pollution and properties of habitats. The coefficients of correlation of pollution and habitat variables with PCs differ in a sign because of negative relations between these variables.

Subsequently, the dependence of the indices of the bird population on the values of three principal components was determined using multiple regression. The first PC only affects the bird population significantly ($p < 0.05$) (Table 4). Since the habitat variables entered the first PC with the minus sign, the negative partial correlation means that the density and diversity of the bird community grow with increase in the height of the stand and stand basal area; cover of the underwood, underbrush, and field layer; and abundance of epigeic invertebrates. The same indices of the bird population grow as the proportion of the birch in the stand (the second PC) decreases, i.e., as the diversity of the tree layer increases.

The first PC only provides a significant contribution to the variation in the density of birds nesting at the top canopy and in holes, explaining 89 and 55% of their variance, respectively (see Table 4). The density of birds nesting at the lower forest layer and on the ground is not significantly affected by the distinguished PCs.

Insectivorous and granivorous birds were only used in the analysis according to trophic groups, since the abundance of the remaining species was low. A significant relationship with the distinguished PCs was only shown for insectivorous species. The first PC explained 57% of the variation in the density of the group (see Table 4).

The concentrations of Cu and Zn we measured in birch leaves proved to be lower than the values presented in the article of M.V. Kozlov et al. [7] for the sites that were near ours. These differences may be primarily related to different sampling periods. To perform the analysis, we gathered leaves in early June 2009, soon after the complete leaf unfolding. Our colleagues performed the collection in late July 2003. Leaf metal concentrations increase during the veg-

Table 2. Linear correlation coefficients (above the diagonal) and levels of significance (below the diagonal) for the characteristics of pollution and habitats

N	Indicator	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Distance from the plant, log	–	**–0.92**	–0.41	**–0.67**	**–0.93**	**–0.83**	–0.63	**0.92**	**0.95**	0.23	0.61	**0.88**	0.25	0.69
	Metal concentrations in birch leaves, log														
2	Cu	<0.05	–	0.51	**0.81**	**0.92**	**0.94**	0.58	**–0.98**	**–0.89**	–0.46	**–0.72**	**–0.86**	–0.46	–0.71
3	Zn	ns**	ns	–	**0.83**	0.29	0.37	0.14	–0.39	–0.52	–0.24	–0.21	–0.39	–0.22	–0.29
4	Cd	<0.05	<0.05	<0.05	–	0.55	**0.68**	0.34	**–0.71**	**–0.74**	**–0.64**	–0.54	–0.55	–0.26	–0.31
5	Pb	<0.05	<0.05	ns	ns	–	**0.88**	0.58	**–0.95**	**–0.85**	–0.19	**–0.74**	**–0.89**	–0.44	**–0.84**
6	Fe	<0.05	<0.05	ns	<0.05	<0.05	–	**0.68**	**–0.91**	**–0.79**	–0.49	**–0.66**	**–0.82**	–0.53	**–0.70**
7	Ni	ns	ns	ns	ns	ns	<0.05	–	–0.63	**–0.74**	–0.12	–0.21	**–0.77**	–0.24	–0.46
8	Height of a stand	<0.05	<0.05	ns	<0.05	<0.05	<0.05	ns	–	**0.91**	0.38	**0.74**	**0.90**	0.43	**0.74**
9	Stand basal area	<0.05	<0.05	ns	<0.05	<0.05	<0.05	<0.05	<0.05	–	0.23	0.52	**0.92**	0.20	0.62
10	Proportion of the birch*	ns	ns	ns	<0.05	ns	ns	ns	ns	ns	–	0.48	0.04	0.22	–0.14
	Cover:														
11	underbrush and underwood	ns	<0.05	ns	ns	<0.05	<0.05	ns	<0.05	ns	ns	–	0.45	0.32	0.48
12	field layer	<0.05	<0.05	ns	ns	<0.05	<0.05	<0.05	<0.05	<0.05	ns	ns	–	0.37	**0.81**
13	Removed leaf area*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	–	**0.69**
14	Biomass of epigeic invertebrates	<0.05	<0.05	ns	ns	<0.05	<0.05	ns	<0.05	ns	ns	ns	<0.05	<0.05	–

Note: The coefficients that are significant at $p < 0.05$ are bolded; * Transformed using the formula $y = 2\arcsin(\sqrt{p})$; ns indicates that the correlation coefficients are insignificant.

Table 3. Factor loadings of different variables

Variable	Principal components		
	1	2	3
Distance from the plant, log	**–0.933**	0.090	0.194
Metal concentrations in birch leaves, log:			
Cu	**0.986**	0.106	0.034
Zn	**0.504**	0.458	–0.305
Cd	**0.763**	**0.586**	–0.178
Pb	**0.944**	–0.210	0.094
Fe	**0.940**	0.036	0.143
Ni	**0.668**	–0.306	–0.291
Height of a stand	**–0.979**	0.018	–0.032
Stand basal area	**–0.924**	0.037	0.360
Proportion of the birch*	–0.369	**–0.785**	–0.260
Cover*:			
underbrush and underwood	**–0.697**	–0.223	–0.366
field layer	**–0.912**	0.322	0.193
Removed leaf area*	–0.482	0.123	**–0.688**
Biomass of epigeic invertebrates	**–0.768**	0.484	–0.264
Proportion of the total variance	0.642	0.124	0.085

Note: The values that exceed 0.5 in absolute magnitude are bolded; * Transformed using the formula $y = 2\arcsin(\sqrt{p})$.

Table 4. Direction of a relationship (sign) and proportion of the variance of the indices, which is explained by separate principal components after taking the remaining PCs into account (the partial correlation square, R^2)

Indicator	Principal components		
	1	2	3
Total density of the bird population	(–) 0.575 **	(+) 0.053	(+) 0.005
Average number of species in counts	(–) 0.774 **	(+) 0.128	(+) 0.022
Total number of species	(–) 0.834 ***	(+) 0.047	(+) 0.001
Density of birds nesting in different vegetation layers:			
Top canopy	(–) 0.890 ***	(–) 0.006	(–) 0.001
Holes	(–) 0.548 *	(+) 0.157	(+) 0.024
Lower layer	(–) 0.341	(–) 0.009	(–) 0.001
Ground	(–) 0.180	(+) 0.053	(+) 0.002
Density of the bird population for the trophic groups:			
Insect-eating birds	(–) 0.566 *	(+) 0.031	(+) 0.027
Grain-eating birds	(–) 0.099	(+) 0.120	(–) 0.175

Note: The values are significant at $*p < 0.05$; $**p < 0.01$; $***p < 0.001$.

etation season as a result of dust precipitation on leaf surface. Consequently, our data characterize metal concentrations in plant tissues to a greater extent as compared to the data of colleagues which reflect largely the level of precipitation. The decrease in the amount of emissions from the KCS also partially explains the differences of our data and the published ones. In 2008, the total emissions from the KCS decreased by a factor of 10 compared to the early 2000s [7].

Our data on the state of forest ecosystems in the environs of the KCS agree with results of the previous studies [7–12]. As the emission source is approached, the height of the stand and stand basal area, foliage cover, and species diversity of plants at the lower forest layers decrease. Meanwhile, the field layer is affected more than the stand. The cover of field layer in the impact zone is by a factor of almost 6 smaller than the background one, and the cover of the tree canopy is twice as low (35.6 and 70%). The degradation of forest ecosystems peaks in the immediate proximity of the plant (see the description of the study area). This industrial barren extends to a distance of up to 4 km east of the plant. Despite the extreme pollution, its effect is local. The changes in the phytocenotic characteristics of birch forests in the region under investigation are registered at a radius of less than 10 km from the plant [8]. Consequently, the principal structural characteristics of the phytocenosis that can affect the bird population already correspond to the background ones in the buffer zone.

The abundance of invertebrates in tree crowns and on the surface of soil can be considered to be the characteristics of the food supply in insect-eating birds. The birch foliar damage in the industrial barren tends to be lower than in the remaining zones, but there are no significant differences between zones. An analogous result was obtained by M.V. Kozlov et al. for the *Betula pendula* and *Alnus incana* (L.) Moench in the environs of Karabash in 2007, as well as in other regions and for other tree species [7]. The population of epigeic invertebrates in the environs of the KCS is not known by us to have been studied earlier. The earlier performed research on soil mesofauna showed a decrease in the absolute density and biomass of all groups at a distance of up to 10 km from the emission source. As the smelter is approached, the proportion of saprophages (primarily, earthworms) in the mesofauna decreases and the proportion of predators (ants) grows [9, 11]. The decrease in the abundance of soil invertebrates (decomposers and predators) in polluted areas and absence of response in phytophages is typical of most impact regions [12]. Moreover, some phytophages irrupt in number in polluted territories owing to the disappearance of natural enemies [13, 14]. However, taking into account the thinning of a stand and decrease in the size of trees in polluted zones, the reduction in the abundance of phytophages per unit area of the phytocenosis should also be expected. Consequently, the food supply in the birds that search for invertebrates on the ground and in a forest litter, as well as, apparently, in the insect-eating species of the tree layer, decreases along the pollution gradient near the KCS.

Earlier [1] we have observed emissions from the KCS to affect the bird population at a local level (at a radius of 6–8 km). The same territory also limits the changes in most characteristics of the phytocenosis and abundance of invertebrates under study.

The attempt to link the observed changes in the bird population with habitat variables has not given an unambiguous result because of high correlation between the indices of pollution and most structural characteristics of the phytocenosis. The greatest contribution to the variation in the abundance and species diversity of the bird population provides the first PC, with which the characteristics of pollution, the stand, and the field layer correlate most closely. The contribution of other PCs is insignificant.

Therefore, it does not seem possible to strictly differentiate the contribution of the abiotic and biotic variables to the formation of the bird population in the study region. Nevertheless, relying upon the conclusions of other authors [5, 6] and our own research in the Middle Urals, we think that the characteristics of the phytocenosis are of primary importance for birds. Most birds in the taiga zone are migrants, and the bird population in local territories is formed every spring anew based on the species-specific requirements for habitats. The role of biotopic preferences in choosing nesting territories is illustrated by the species in which the population density grows in the impact zones: the wheatear and redstart, Emberizidae, Motacillidae, etc. [15–18]. Meanwhile, the levels of toxicants in natural food objects are not high enough to cause large-scale acute intoxication and affect the territorial distribution of birds. The toxic effect manifests itself later, during nesting in adult individuals and their offspring [19–22].

Under the natural conditions, the density of the population and species diversity in forest birds depend on the structural complexity of a phytocenosis [23–25], composition of vegetation [26], and food supply [27]. The environmental pollution that causes the degradation of forest vegetation and simplifies the structure of a phytocenosis impairs the habitat conditions for typical forest species. Therefore, it is not amazing that the area of the anthropogenic transformation of the bird population coincides with the area of the degradation of forest ecosystems. The pollution of a territory declines not only the protective properties of a forest phytocenosis because of simplification of its vertical structure, but also the feeding conditions for insect-eating birds that gather food in a forest litter; on the ground; and, apparently, in tree crowns.

CONCLUSIONS

The changes in most structural characteristics of the phytocenosis and indices of the abundance of invertebrates and the bird population are limited by the local territory (6–8 km from the plant). The degradation of the ecosystem reaches the most extreme degree in the epicenter of degradation. It does not seem possible to differentiate the contribution of abiotic (pollution) and biotic variables (the characteristics of the phytocenosis and abundance of invertebrates) to the formation of the bird population in the region under investigation owing to the fact that they are closely correlated. Pollution is likely to affect the bird population indirectly through the change in habitats, their protective properties, and food supply. There is a need for subsequent studies in this field, inclusively, in other regions.

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