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Response of the Avifauna to Technogenic Environmental Pollution in the Southern Taiga Zone of the Middle Urals

E. A. Bel'skii and A. G. Lyakhov

Institute of Plant and Animal Ecology, Ural Division, Russian Academy of Sciences, ul. Vos'mogo Marta 202, Yekaterinburg, 620144 Russia

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Abstract—The results of original studies and published data are used for evaluating the main responses of the avifauna of boreal forests to the combined effect of sulfur dioxide and heavy metals. It is shown that environmental pollution results in the reduction of species richness, biomass, and stability of the nesting bird fauna. In degraded areas, the structure of the bird community changes: (1) typical forest species are replaced by the species of open habitats, and (2) the proportion of species nesting in the upper tree layer decreases, whereas that of ground-nesting species increases.

Key words: avifauna, southern taiga, technogenic pollution.

Bird communities are formed in close dependence on environmental conditions. The species composition, general and relative abundance, and structure of the avifauna in a certain area reflect its geographic location, environmental conditions (climatic, phytocenotic, etc.), and the type and magnitude of anthropogenic impact (Ravkin, 1984). Hence, the parameters of bird populations and communities can be used in environmental monitoring (Koskimies, 1989). In monitoring the ecological state of a certain area, it is necessary to take into account specific features of both environmental factors (natural and anthropogenic) and the avifauna as a tool for monitoring. This circumstance gives emphasis to the importance of regional studies on the responses of bird populations to ecological factors. Moreover, the analysis of corresponding information makes it possible to reveal general trends in the adaptation of bird populations and communities to adverse environmental factors.

Published data on the responses of birds to chemical environmental pollution in the Middle Urals are insufficient. Among the sources of hazardous pollutants, a special role belongs to the nonferrous metal industries and, in particular, to the copper-smelting plants where primary (top-and-bottom) smelting is performed. The toxicity of discharge from these plants is accounted for by the combined effect of sulfur dioxide, heavy metals, and, in some cases, fluorine compounds (Vorobeichik *et al.*, 1994). The purpose of this work was to study the structural transformation of forest bird communities in the southern Middle Urals (the southern taiga subzone) along a gradient of technogenic environmental pollution.

STUDY REGION AND METHODS

Studies were performed in the vicinity of the Middle Ural Copper-Smelting Plant (Revda, Sverdlovsk oblast) from 1991 to 1993 and from 1999 to 2001. Zones differing in toxic load were delimited by analyzing the samples of snow and soils and the state of phytocenoses (Vorobeichik *et al.*, 1994). The toxic load was estimated from the concentrations of heavy metals in the litter, which were measured in weakly acidic extracts (5% HNO_3). The impact zone (heavy pollution) extended westward from the plant (the direction we chose) for 3 km. The contents of acid-soluble forms of copper and lead in the litter averaged 5497.6 ± 166.6 and 1562.2 ± 48.0 μg/g dry weight, respectively (n = 47). In the buffer zone (moderate pollution, up to 15 km from the plant), these contents were 1000.4 ± 170.7 and 404.3 ± 44.2 μg/g (n = 32). In the background area, the routes were laid 16 and 20 km away from the plant, and the contents of copper and lead in the litter averaged 53.8 ± 2.2 and 63.9 ± 1.9 μg/g, respectively (n = 32).

Censuses of nesting birds were taken in the forest biotopes of two types prevailing in the study area, namely, in a conditionally primary dark coniferous forest (middle-aged fir–spruce forest with linden and a small admixture of pine, birch, and aspen) and a secondary small-leaved forest (middle-aged aspen–birch forests with a small admixture of conifers). In the impact zone, tree stands in both forest types had a relatively low density and contained a significant proportion of dead trees. The relative density of such trees in the coniferous forest ranged from 27 to 44% (Vorobeichik *et al.*, 1994). The recreational load on all forest areas in the nesting period was minimum.

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Table 1. The length of census routes (km) in the zones differing in toxic load in different years. Figures in parentheses show the number of censuses

Year	Dark coniferous forest			Small-leaved forest		
	Zone					
	background	buffer	impact	background	buffer	impact
1991	–	6.0 (2)	5.6 (3)	–	–	1.8 (1)
1992	3.9 (2)	6.4 (2)	3.0 (2)	–	–	–
1993	–	16.2 (6)	5.4 (3)	–	–	–
1999	8.5 (4)	15.1 (7)	8.9 (3)	10.0 (3)	4.7 (4)	14.6 (3)
2000	11.1 (4)	7.3 (4)	12.0 (4)	13.2 (4)	4.4 (4)	19.7 (4)
2001	11.1 (4)	7.3 (4)	12.0 (4)	13.2 (4)	4.3 (4)	18.5 (4)
Total	34.6	58.3	46.9	36.4	13.4	54.6

Table 1 shows the length of census routes and their distribution by years, forest types, and pollution zones. Censuses were taken between May 15 to June 23, mostly between June 1 and 18, and were repeated upon completing the first cycle of censuses on all plots (i.e., after seven to ten days). This work was performed by A.G. Lyakhov in 1991–1993 and by A.G. Lyakhov and E.A. Bel'skii in 1999–2001.

The censuses were taken in the early morning along the routes with a variable observation zone: its width for each species depended on the average distance allowing its detection (Naumov, 1965; Shchegolev, 1977). Records were made of singing males and the birds making calls or detected visually. Each territorial (singing) male was regarded as a nesting pair. As the males do not all sing simultaneously, the number of territorial pairs was calculated using the activity coefficient. Its value was determined during repeated censuses taken along a permanent route from April 30 to June 23, 1999, at ten-day intervals. The total nesting density was calculated without taking into account red crossbills (*Loxia curvirostra*), as these birds in June ceased to reproduce and began to migrate in small flocks. The distribution of nesting species over the vegetation layers was estimated from the percentage of a certain species group in the total density of nesting birds (minus cuckoos).

The vegetation layers favored for nesting are classified according to Zakharov (1998), and bird species are named according to Stepanyan (1975, 1978).

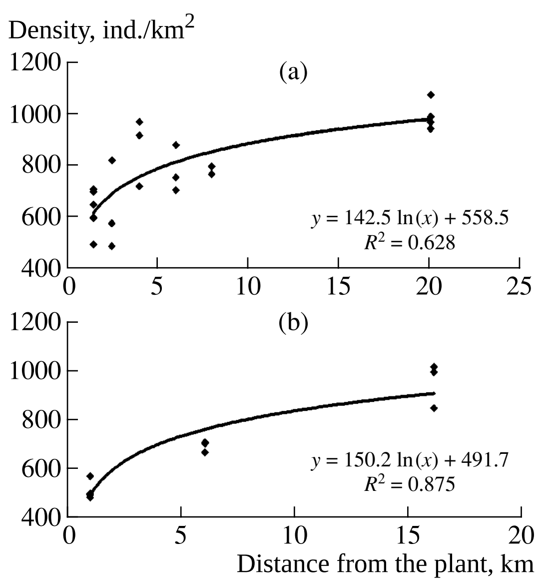

Fig. 1. Total bird density in (a) dark coniferous and (b) small-leaved forests as a function of distance from the plant.

RESULTS

Table 2 shows the basic parameters of the local avifauna averaged over the entire period of studies. In both biotopes, the increasing toxic load resulted in a decrease in the total number of bird species recorded during this period and in the average number of species recorded per year: these numbers in the background and impact zones differed by a factor of 1.1–1.3 in the coniferous forest and by a factor of 1.3–1.4 in the small-leaved forest. On the whole, 79 species (excluding field and water birds) were recorded in the study region during the nesting period: 74 species in the background area, 67 species in the buffer zone, and 59 species in the impact zone.

The dependence of total bird population density on distance from the plant was similar in both forest types (Fig. 1). This parameter decreased with an increase in the toxic load: in the buffer zone, it averaged 81.5% of the control value in the coniferous forest and 72.4% in the small-leaved forest; in the impact zone, the respective values were 61.8 and 53.5%. Changes in the biomass of the avifauna along the pollution gradient had a similar pattern (see Table 2). This parameter was signif-

Table 2. Bird population density (ind./km^2) in the toxic load gradient (average data for 1991–1993 and 1999–2001). The species with a density of less than 1 ind./km^2 in all areas are not shown but have been taken into account in calculating the total density and number of species

Species	Dark coniferous forest			Small-leaved forest		
	Zone					
	background	buffer	impact	background	buffer	impact
Fringilla coelebs	151.6	105.9	84.3	155.9	147.3	57.9
Phylloscopus trochiloides	102.9	96.5	50.0	69.0	90.7	20.4
Erithacus rubecula	96.3	76.1	52.1	69.4	86.3	25.5
Regulus regulus	52.3	25.5	3.8	0	0	0
Parus montanus	47.3	52.0	26.1	27.5	34.5	4.5
Turdus philomelos	45.8	14.8	6.5	20.3	15.6	0.9
Parus ater	42.2	40.1	13.8	20.8	16.5	3.4
Phylloscopus collybita	40.2	40.0	27.3	16.1	36.4	16.2
Anthus hodgsoni	37.4	15.4	6.5	24.4	23.9	4.7
Pyrrhula pyrrhula	35.9	29.3	7.7	10.4	14.7	8.1
Phoenicurus phoenicurus	35.1	27.3	53.9	18.1	15.6	30.5
Carpodacus erythrinus	34.3	36.5	26.8	27.9	15.5	16.0
Ficedula hypoleuca	34.2	29.9	22.5	73.3	49.0	0.6
Anthus trivialis	29.9	20.9	45.6	75.0	10.2	90.7
Turdus iliacus	29.1	2.5	0	56.0	12.9	0
Sylvia curruca	24.3	32.2	29.6	2.0	9.9	13.9
Spinus spinus	21.7	26.4	8.9	5.3	7.5	9.9
Sylvia borin	17.2	11.1	10.6	52.2	22.9	13.6
Parus major	16.1	4.1	4.0	5.5	2.3	0
Phylloscopus trochilus	13.5	20.8	34.5	41.8	19.8	24.1
Prunella modularis	13.1	29.1	16.5	3.9	15.7	7.2
Acrocephalus dumetorum	13.0	5.7	2.8	27.3	0	14.8
Sylvia atricapilla	8.8	9.8	4.1	16.4	18.9	0
Locustella fluviatilis	7.9	0.6	0	3.1	0	0
Sylvia communis	7.2	6.4	10.6	0.7	0	31.3
Tetrastes bonasia	6.4	7.5	3.0	0.5	1.8	0
Dendrocopos major	6.2	2.8	1.4	10.8	1.4	0.5
Zoothera dauma	4.2	2.2	0	0.8	0	0
Carduelis carduelis	3.1	0	3.1	1.7	0	0
Tringa ochropus	2.7	0.1	0.3	0.9	0	0
Fringilla montifringilla	2.2	12.1	6.7	28.4	3.4	8.7
Ficedula parva	1.9	5.1	0	3.1	2.0	0
Streptopelia turtur	1.6	0.1	1.2	0	0	0
Aegithalos caudatus	1.5	0	0	1.9	0	0
Turdus pilaris	1.5	0.3	1.0	25.1	0	0
Dryocopus martius	1.4	0.8	0.2	0.3	0	0
Turdus merula	1.3	0.5	0	2.3	0	0
Cuculus saturatus	1.3	0.9	0.4	0.2	0.6	0.2
Emberiza citrinella	1.3	2.2	28.9	0	0	51.8
Garrulus glandarius	1.2	2.2	0	0	7.2	0
Corvus cornix	0.9	3.1	3.9	0.4	0	1.5

Table 2. (Contd.)

Species	Dark coniferous forest			Small-leaved forest		
	Zone					
	background	buffer	impact	background	buffer	impact
Buteo buteo	0.8	0.8	0.05	0.3	0.9	0
Sitta europaea	0.6	0.8	0.7	2.6	0	0
Corvus corax	0.5	0.4	1.3	0	0.6	1.4
Columba palumbus	0.4	4.6	0	0	2.6	0
Scolopax rusticola	0.3	2.8	0	0.3	0.0	0
Hippolais icterina	0	0.4	0	28.2	1.5	0
Phylloscopus sibilatrix	0	0	0	12.9	0	0
Muscicapa striata	0	0	5.0	2.9	0	1.4
Turdus viscivorus	0	0.8	1.0	2.5	2.1	0.3
Motacilla cinerea	0	0	1.8	2.1	0	0.8
Emberiza rustica	0	2.1	0	0.8	0	0
Pica pica	0	1.4	3.2	0.7	0	7.0
Motacilla alba	0	0	4.8	0	0	26.9
Oenanthe oenanthe	0	0	1.1	0	0	0
Luscinia calliope	0	0	0	0	0	9.7
Motacilla flava	0	0	0	0	0	2.3
Lanius collurio	0	0	0	0	0	2.1
Total density, ind./km^2	999.3 ± 28.9	814.1 ± 32.6**	617.6 ± 34.3***	953.4 ± 53.2	690.5 ± 13.5**	510.3 ± 23.6**
Total number of species recorded throughout the study period	49	51	45	51	34	39
Average number of species recorded per year	35.5 ± 1.3	32.2 ± 1.7	27.2 ± 1.2**	38.0 ± 0.6	22.7 ± 1.8**	27.0 ± 4.5
Biomass, kg/km^2	25.8 ± 2.7	23.7 ± 3.2	16.1 ± 1.0**	23.5 ± 2.1	17.1 ± 2.0	13.5 ± 1.0*

Note: Differences from the background value are significant at * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$.

icantly lower in the impact zone than in the control (background) area.

Bird species responded differently to the technogenic influence. In the heavily polluted (impact) zone, many species became much less abundant than in the control area (by a factor of more than 10) or even disappeared. This concerns *Buteo buteo, Scolopax rusticola, Tringa ochropus, Garrulus glandarius, Locustella fluviatilis, Hippolais icterina, Regulus regulus, Ficedula parva* and *F. hypoleuca* (in the small-leaved forest), *Turdus iliacus, T. philomelos, T. merula, Zoothera dauma*, and *Emberiza rustica* (Table 2). The abundance of *Phylloscopus trochiloides, Parus ater, Anthus hodgsoni, Sylvia borin, Pyrrhula pyrrhula, Parus major, Acrocephalus dumetorum, Tetrastes bonasia, Dendrocopos major, Dryocopus martius*, and several other species decreased by more than 50%. Conversely, *Anthus trivialis, Corvus cornix, Pica pica, Sylvia communis, S. curruca, Phoenicurus phoenicurus*, and *Emberiza citrinella* populated the polluted area more densely. Some species—*Motacilla alba, M. flava, Hippolais caligata*, and *Oenanthe oenanthe*—were recorded only in the impact zone. These birds are not characteristic of undisturbed forest habitats.

DISCUSSION

To reveal general trends in the structural transformation of bird communities under conditions of chemical environmental pollution, we compared our results with published data on other regions of the European boreal forest zone. We chose the areas exposed to the same type of pollution (the combined effect of sulfur dioxide and heavy metals): (1) mountain dark coniferous forests of Central Europe (Flousek, 1989; Lemberk, 1989; *Šťastny and Bejček*, 1983) and (2) forests in the vicinity of Severonikel Combined Works, the northern taiga subzone of the Kola Peninsula (Gilyazov and Kataev, 1990; Gilyazov, 1993). The available data on heavy metal contents in the forest litter around the Severonikel Combined Works (*Vliyanie promyshlennogo…*, 1990) allowed us to compare the levels of toxic load on forests in the Kola Peninsula and in the region of our studies. The toxic load (in relative units) was estimated from the excess concentrations of main pollutants in the litter (compared to the background concentrations) averaged in each pollution zone. Two main pollutants per region were considered: copper and nickel in the Kola Peninsula and copper and lead in the Middle Urals.

Basic trends in the technogenic dynamics of the avifauna are similar in all these regions. Under the maximum load, the total number of bird species, compared to the local norm, decreases by a factor of 1.3 in the southern taiga and mountain forests of Central Europe and by a factor of 2.9 in the northern taiga. Figure 2a shows the number of bird species in boreal coniferous forests as a function of toxic load. The density of nesting bird populations in these forests decreases with an increase in the toxic load (Fig. 2b). A similar decrease (by a factor of 1.6–1.7) is observed in the southern taiga and mountain forests of Central Europe (Flousek, 1989). As in the case with the total number of species, the most drastic decrease—by a factor of 7.7—has been observed in the northern taiga (Gilyazov and Kataev, 1990; Gilyazov, 1993).

In the northern taiga forests of the Kola Peninsula, the toxic effects of technogenic pollutants are more conspicuous than in other regions. Two factors may be responsible for this situation. The first is that these forests are under a heavier toxic load (127 rel. units near the Severonikel Combined Works, compared to 63 rel. units near the Middle Ural Copper-Smelting Plant), and the second is that the northern ecosystems existing under extreme climatic conditions are known to be especially vulnerable to the anthropogenic impact. Thus, the immediate vicinities of the Severonikel Combined Works have been transformed into a technogenic desert, and primary pine forests in this area have been totally destroyed (*Vliyanie promyshlennogo…*, 1990; Gilyazov and Kataev, 1990).

The change of phytocenotic conditions along the pollution gradient largely determines the parameters of avifauna. Under a moderate technogenic impact on the primary taiga forests, some trees die off and fall down, so that gaps appear in the continuous tree stand. This gives rise to a mosaic pattern of habitats and creates conditions for the enrichment of bird communities with the species of open biotopes (buntings, wagtails, etc.) and, therefore, for an increase in species diversity (as follows from Table 2, the total number of bird species in the dark coniferous forest was greater in the buffer zone than in the control area). Under heavy pollution, the trees die off en masse. Due to the thinning of the tree stand, typical forest species gradually lose their prevalence in the community. In the southern taiga avifauna, the proportion of these species decreases from 71.1% (of the total bird density) in the control area to 54.7% near the plant in the dark coniferous forest and from 66.4 to 33.2%, respectively, in the small-leaved forest. In the northern taiga, this proportion decreases from 66.7% in the control to 37.5% near the source of emissions (Gilyazov and Kataev, 1990; Gilyazov, 1993).

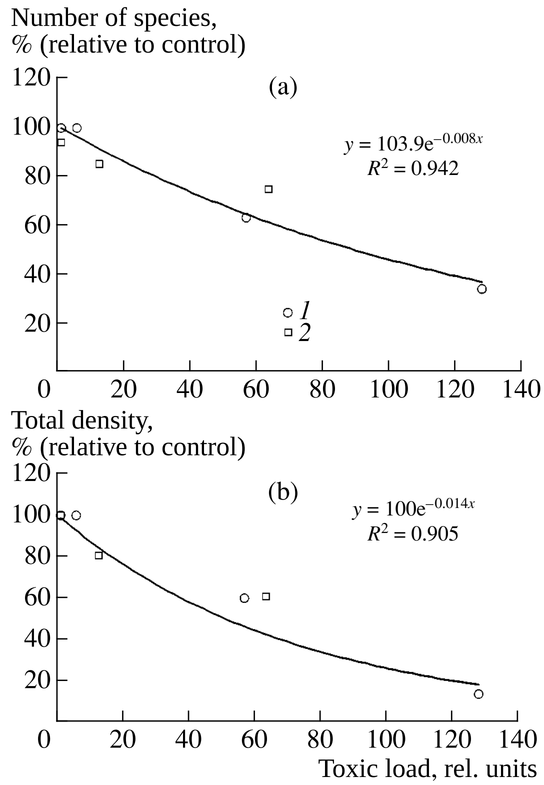

Fig. 2. Dependence of (a) the number of bird species and (b) total population density on pollution level in boreal forest ecosystems of (*1*) the Kola Peninsula and (*2*) the Middle Urals (pooled data).

The typical forest species that become much less abundant in the impact areas are as follows: kinglets, thrushes, *P. ater, Troglodytes troglodytes,* and *Fringilla coelebs* in the mountains of Central Europe (Flousek, 1989; *Šťastny and Bejček*, 1983); thrushes (*T. iliacus, T. philomelos,* and *T. pilaris*), *F. hypoleuca, P. pyrrhula, Spinus spinus*, and *A. hodgsoni* in the southern taiga; and *T. iliacus, T. philomelos, P. phoenicurus, F. hypoleuca,* and *Parus cinctus* in the northern taiga (Gilyazov and Kataev, 1990; Gilyazov, 1993). A general trend in all taiga subzones is that large forest species—grouse, owls, some diurnal birds of prey, and pigeons—decrease in numbers or even disappear as the toxic load increases.

The factors responsible for this situation include the absence of nesting sites (for hole-nesting birds); anxiety heightened by proximity to the sources of emissions, which are usually located within the city limits

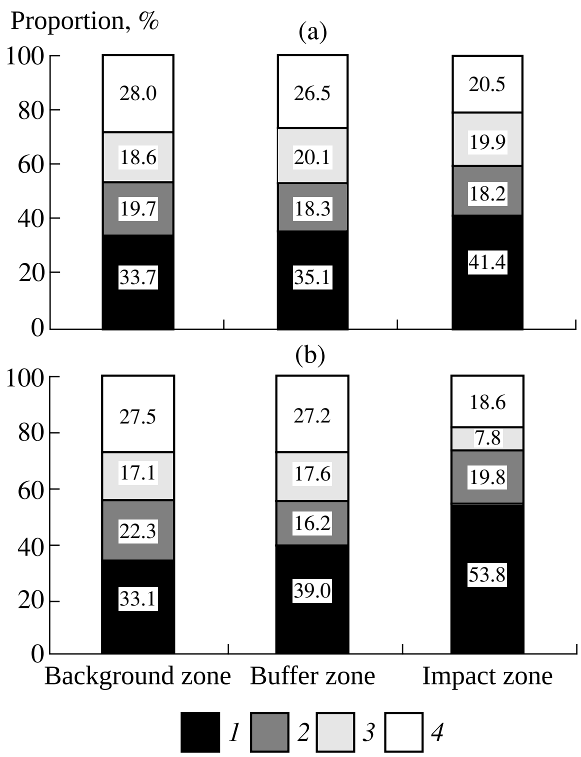

Fig. 3. Distribution of nesting birds by layers (proportions of the total density, %) in the zones differing in toxic load in (a) dark coniferous and (b) small-leaved forests: (*1*) ground, (*2*) lower vegetation layer, (*3*) tree hollows, and (*4*) upper tree layer.

(for grouse); and the depletion of food resources for specialized species. The density of owls and diurnal birds of prey becomes lower due to a decrease in the numbers of murine rodents along the gradient of technogenic load (Gilyazov and Kataev, 1990; Luk'yanova *et al.*, 1994). The density of thrushes, which largely feed on earthworms, decreases along with a decrease in the abundance of soil mesofauna (Vorobeichik *et al.*, 1994). Population decline in *S. spinus, Parus montanus*, and *P. ater* is probably explained by a reduced seed yield in conifers exposed to increasing pollution, because their seeds play an important role in the diet of these birds. In the northern taiga, however, another stenophagous bird—*Carduelis flammea*—is fairly abundant in the impact areas, as seed production in birch (the main food plant of this species) remains sufficiently high (Gilyazov and Kataev, 1990).

The dependence of abundance on pollution is weak in ecologically flexible species nesting mainly in shrubs, undergrowth, or on the ground, such as *Prunella modularis, Erithacus rubecula, Carpodacus erythinus*, and, in the southern taiga, *Phylloscopus collybita* and *P. trochilus*. Of the species nesting in the tree layer, the increasing technogenic load is favorable only for synanthropic corvine birds.

An increasing habitat openness is favorable for the species building nests in holes in the ground or on its surface. In the northern taiga, for example, the proportion of species characteristic of open (forest–tundra and tundra) habitats increases from 18% in the control area to 50% in the technogenic desert (Gilyazov and Kataev, 1990). In the areas located closer to the sources of emissions, the abundance of species belonging to this group increases. In the southern taiga, these are *M. alba, A. trivialis, P. phoenicurus*, and *E. citrinella*; in the mountain forests of Central Europe, *A. trivialis, A. pratensis, A. spinoletta; Saxicola rubetra, Phoenicurus ochruros*, and *Turdus torquatus* (Flousek, 1989); and in the northern taiga, *A. pratensis, O. oenanthe*, and *Emberiza pusilla* (Gilyazov and Kataev, 1990; Gilyazov, 1993). However, this increase is insufficient for counterbalancing population decline in the typical forest species, and, hence, the total density of birds in the impact zones decreases.

Along the gradient of technogenic load, changes occur in the structure of bird community, i.e., in its species composition and species abundance ratio. In dark coniferous forests of the southern taiga (Table 2) and the mountains of Central Europe, *F. coelebs* ranks first among dominants (the species making up no less than 5% of the bird community) at any stage of phytocenosis degradation. The composition of other dominants is more illustrative. In nonpolluted southern taiga regions of the Urals, this group consists of typical forest species: *P. trochiloides* (10.3% of the total bird density), *E. rubecula* (9.6%), and *R. regulus* (5.2%). In the impact zone, it includes the species of open and brushland biotopes, such as *A. trivialis* (7.4%) and *P. trochilus* (5.6%), whereas the proportions of *P. trochiloides* and *E. rubecula* decrease to 8.1 and 8.4%, respectively. *Phoenicurus phoenicurus* is a typical forest species, but its proportion in the bird community increases in the impact zone to 8.7%, compared to 3.5% in the control area. This is explained by the fact that these birds prefer open forest sites with a suppressed herbaceous–dwarf shrub layer (Burskii, 1987; Simkin, 1990; Preobrazhenskaya, 1998).

The change of dominants in the gradient of toxic load also occurs in small-leaved forests of the Middle Urals: in the impact zone, *A. trivialis* replaces *F. coelebs*. Other dominants—*F. hypoleuca, O. trochiloides, T. iliacus*, and *S. borin*—are replaced by *E. citrinella, S. communis, P. phoenicurus*, and *M. alba*; the proportion of *E. rubecula* decreases. In the mountain dark coniferous forests of Central Europe, *S. atricapilla* and *R. regulus* dominate in weakly disturbed forest habitats but are replaced by *E. rubecula, A. trivialis*, and *P. modularis* in heavily polluted areas (Flousek, 1989). In the northern taiga, *C. flammea* and *Anthus campestris* become dominant in the impact zone, replacing *Fringilla montifringilla*, and *O. oenanthe* is also included in the group of dominant species (Gilyazov, 1993).

Moreover, the structural transformation of the bird community manifests itself in a different distribution of birds with respect to the vegetation layers used for nesting. As the toxic load increases, the proportion of species nesting in the upper tree layer and tree hollows decreases, whereas that of ground-nesting species increases (Fig. 3). This is obviously explained by degradation of the tree layer and the resulting reduction in the number of nesting sites for dendrophilous species.

Interannual variation in the composition of the bird community proved to increase in technogenically disturbed areas. In the dark coniferous forest, for example, the proportion of species regularly recorded every year changed from 53.1 ± 7.3% in the background area to 33.3 ± 6.6% in the buffer zone and to 26.7 ± 6.6% in the impact zone ($p < 0.05$). This is evidence that the bird community loses its stability under the effect of increasing toxic load.

Thus, technogenic pollution leads to structural changes in the bird community, including the reduction of species diversity, total density and biomass, and stability of the nesting bird population. Industrial pollutants exert their effect on the avifauna indirectly, through changes they cause in phytocenoses (including their protective properties and food resources). The density of typical forest species, such as grouse, owls, some diurnal birds of prey, pigeons, thrushes, some tits, and finches, decreases under heavy pollution, whereas that of the species characteristic of open and brushland biotopes increases. This concerns wagtails, wheatear, buntings, some warblers, and redstarts. A heavy toxic load results in a different distribution of nesting birds over the vegetation layers: the proportion of species nesting in the upper tree layer and tree hollows decreases.

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