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GENERAL BIOLOGY

Dynamics of Forest Vegetation after the Reduction of Industrial Emissions: Fast Recovery or Continued Degradation?

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The recent reduction of emissions from industrial enterprises to the atmosphere occurring in many countries motivates studies of natural ecosystem recovery. They are important both theoretically, with regard to resilience mechanisms, and practically, with regard to proper management of natural resources. However, the investigation of processes involved in the recovery faces a fundamental restriction, namely, incompleteness of information on the biota state prior to the emission reduction. For the sake of adequate comparison, this state should have been recorded at precisely the same sites, because otherwise the spatial variability of parameters, most notable in polluted areas [1], can be mistaken for their temporal change. Although natural recovery of degraded ecosystems attracts increasing attention [2–7], this condition is neglected in most studies with few exceptions [8].

There are two opposite viewpoints as to the rates of demutational successions after industrial load reduction. Some authors believe that ecosystems recover rapidly, and others, that the biota "by inertia" remains suppressed for long even after complete ceassation of emission. The inertial hypothesis was first formulated on the basis of simulations [9]. It is poorly supported by facts, and available information is ambiguous. In some cases, no recovery trends are noticed [8], but other observations demonstrate fast recovery, in particular, of radial tree increment [4] and the density of the ground layer (GL) [3, 10].

Here, we analyze the dynamics of plant communities after reduction of atmospheric pollution.

In 1989, we started the investigation of forest ecosystems exposed to long-term (since 1940) emission from a Middle Ural Copper Smelter [11]. Twenty-five permanent sample plots 25 × 25 m in size were established in fir–spruce forests of different ages with components of nemoral floristic complex vegetation in the impact (1 and 2 km west of the plant), buffer (4 and 7 km), and background (30 km) zones, five plots at each distance. The plots were located on flat hill slopes. The soils were sod-podzolic, heavy loamy, of medium thickness. At the start of the record, the mean ages of the upper layer trees were mostly within 60–80 years. The maximum tree heights and diameters (18–20 m and 18–23 cm, respectively) were found in the background zone, and the minimum (9–12 m and 9–14 cm), in the impact zone. Subsequent records of the stand states were done in the same plots in 1998 and 2008, and the records of GL, in 1999 and 2007. The stand parameters were assessed by total tree survey with measurement of heights and diameters. The aboveground biomassof GL was assessed by hay-harvest method in 10–15 squares (50 × 50 cm) with species identification, and species richness by taking geobotanical descriptions. The contents of soluble heavy metals (Cu, Zn, Cd, and Pb) in the upper soil layer A_1 were determined by extraction with 5% nitric acid in 1989, 1999, and 2012 (one, five, and five mixed samples per plot, respectively).

The emission from the plant was 141 thousand tons in 1989, 66 in 1999, 25 in 2005, and less than 5 per year after 2010. Copper emission decreased most significantly. In 2005, it was 58 times less than in 1989. The emission of other pollutants decreased by factors of 51 for HF, 35 for As, 7.8 for Zn, and 5.5 for SO_2. Thus, we possess information on the vegetation states at the time of large emission (1989), the beginning of its substantial decrease (1998–1999), and nearly complete ceassation (2007–2008).

Soil acidity did not change in 1989–1999. From 1999 to 2012, pH increased by 0.5–0.7, but in the impact and buffer zones it remained lower than in the background zone (Tables 1 and 2). The concentrations of all heavy metals (Zn and Cd not shown) increased in the periods 1989–1999 and 1999–2012. Only the Cu concentration slightly decreased in the impact zone (1 km) in the second period. The increase in the

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Table 1. Dynamics of forest ecosystem parameters in zones with various degrees of industrial load: mean ± error of the mean; test plots as statistical units; $n = 5$

Parameter	Year	Load zone (distance from the plant, km)				
		Background (30)	Buffer (7)	Buffer (4)	Impact (2)	Impact (1)
		Soil				
pH	1989	4.53 ± 0.12	4.33 ± 0.17	4.04 ± 0.08	4.29 ± 0.09	4.18 ± 0.13
	1999	4.42 ± 0.08	4.51 ± 0.19	4.01 ± 0.07	4.04 ± 0.04	3.87 ± 0.06
	2012	4.89 ± 0.06	5.03 ± 0.06	4.55 ± 0.03	4.63 ± 0.09	4.60 ± 0.12
Cu, ppm	1989	23.8 ± 2.2	169.0 ± 13.4	251.9 ± 29.9	883.3 ± 105.7	1567.8 ± 111.0
	1999	36.4 ± 3.8	339.4 ± 52.8	219.2 ± 23.8	520.6 ± 40.8	2038.2 ± 234.5
	2012	52.2 ± 21.4	424.1 ± 21.9	366.7 ± 114.3	1039.6 ± 146.9	1084.4 ± 131.7
Pb, ppm	1989	19.4 ± 1.3	46.9 ± 5.6	44.6 ± 9.1	128.0 ± 22.1	278.0 ± 33.4
	1999	30.1 ± 2.2	101.3 ± 16.6	47.9 ± 9.5	60.4 ± 6.4	288.4 ± 51.8
	2012	65.9 ± 23.5	215.0 ± 14.4	135.0 ± 45.3	317.1 ± 31.6	378.7 ± 46.4
		Tree layer				
Z	1989	409.2 ± 53.9	418.1 ± 44.0	313.1 ± 26.4	149.3 ± 22.1	63.0 ± 9.2
	1998	253.1 ± 29.4	321.2 ± 19.6	228.5 ± 25.1	139.6 ± 24.5	38.2 ± 6.8
	2008	438.9 ± 61.5	526.0 ± 32.3	394.5 ± 23.5	301.2 ± 14.9	74.2 ± 57.2
N	1989	2048 ± 251	2086 ± 108	1318 ± 148	1450 ± 125	822 ± 126
	1998	858 ± 86	1226 ± 49	701 ± 86	1094 ± 206	365 ± 60
	2008	1104 ± 117	1155 ± 69	1184 ± 262	1997 ± 133	464 ± 257
D	1989	7.8 ± 4.2	7.0 ± 1.2	16.5 ± 3.2	25.2 ± 2.3	26.8 ± 4.7
	1998	7.4 ± 2.9	12.4 ± 0.7	18.7 ± 4.9	7.8 ± 2.7	34.4 ± 4.2
	2008	22.3 ± 1.2	18.7 ± 5.7	4.1 ± 1.9	–	80.4 ± 8.2
		Ground layer (GL)				
S_1	1989	7.6 ± 1.2	3.9 ± 0.5	3.8 ± 0.4	0.6 ± 0.1	0.8 ± 0.1
	1999	11.4 ± 0.7	5.4 ± 0.4	4.9 ± 0.4	0.9 ± 0.3	1.7 ± 0.3
	2007	10.0 ± 0.3	4.9 ± 0.3	3.9 ± 0.2	0.9 ± 0.3	1.3 ± 0.2
S_2 (S_3)	1989	36.8 ± 2.4 (52)	32.2 ± 1.2 (42)	24.8 ± 1.8 (35)	9.2 ± 0.6 (18)	7.0 ± 1.4 (15)
	1999	53.2 ± 1.9 (72)	39.0 ± 1.8 (57)	31.4 ± 3.6 (56)	11.6 ± 1.6 (26)	6.4 ± 1.2 (15)
	2007	58.2 ± 0.9 (82)	44.0 ± 1.8 (71)	31.8 ± 3.2 (56)	14.0 ± 2.0 (30)	7.0 ± 0.6 (14)
M GL	1989	16.5 ± 3.0	7.3 ± 1.7	18.6 ± 4.8	6.7 ± 2.0	16.5 ± 7.8
	1999	30.2 ± 2.8	14.6 ± 0.3	14.3 ± 1.8	4.8 ± 2.2	15.7 ± 2.2
	2007	52.2 ± 6.9	17.9 ± 3.7	16.5 ± 1.9	2.9 ± 1.7	44.5 ± 21.1

Designations (here and in Table 2): Z, standing volume, m^3/ha; N, stand density, trees/ha; D, percentage of snags number in tree stand; S_1, number of species in 0.25 m^2 (mean of 10–15 replications for each test plot); S_2, number of species in 625 m^2; S_3, number of species in the whole load zone; M, biomass, g/m^2; –, no data.

contents of metals, in addition to precipitation from the atmosphere, was most likely to be related to their gradual leaching from the litter. The reduced acidity may be an additional factor fixing metals in soil. Thus, the technogenic geochemical anomaly formed by the late 1990s displayed no significant changes within the 20 years of observation. Quite the reverse, it became even more pronounced. This fact is in good agreement with the notion of very slow unloading of industrially polluted landscapes even after complete ceassation of emission owing to poor metal mobility [12].

In 1989–1999, the stand densities and volumes decreased by 20–40% in all plots (Tables 1 and 2), whereas the proportion of dead wood remained practically unchanged. This observation is indicative of an external factor common for the whole region and not associated with the decreased pollution. The common trend in all plots was an increase in species diversity of

Table 2. Two-way analysis of variance (with repeated measurements) of the differences among load zones and observation intervals. The obtained levels of significance for the F test are shown

Parameter	Observation interval and source of variability					
	interval I			interval II		
	zone	time	zone × time	zone	time	zone × time
pH	0.003	0.339	0.298	<0.001	⩽0.001	0.375
Cu	⩽0.001	0.004	0.033	⩽0.001	0.131	0.008
Pb	⩽0.001	0.028	0.059	<0.001	⩽0.001	0.011
Z	⩽0.001	0.001	0.774	<0.001	0.001	0.165
N	<0.001	⩽0.001	0.419	<0.001	0.031	0.115
D	<0.001	0.252	0.579	0.022	0.177	0.011
S_1	⩽0.001	0.001	0.595	⩽0.001	0.101	0.157
S_2	⩽0.001	0.002	0.062	⩽0.001	0.018	0.823
M (GL)	0.059	0.033	0.249	<0.001	0.115	0.427
M (graminoids)	0.069	<0.001	0.030	0.010	0.004	0.152
M (forbs)	<0.001	0.012	0.041	⩽0.001	0.072	<0.001
M (ferns)	<0.001	0.107	0.447	0.005	0.010	0.302
M (horsetails)	<0.001	0.123	0.829	<0.001	0.167	0.008

Observation periods: I, 1989–1999 (soil and GL) or 1989–1998 (tree stand); II, 1999–2012 (soil), 1999–2007 (GL), or 1998–2008 (tree stand).

GL on a microscale, tens of centimeters (parameter S_1 in Table 1). On a mesoscale (tens of meters, S_2) and a macroscale (hundreds of meters, S_3), the diversity increased in all plots except for that closest to the plant, mainly owing to plants typical of disturbed habitats (*Agrostis capillaris, Chrysosplenium alternifolium, Phegopteris connectilis*, etc.) The GL biomass increased substantially only at distances of 30 and 7 km from the plant due to *Calamagrostis obtusata* and forbs but decreased in other plots. Vegetation structures changed at the distances of 4, 2, and 1 km from the plant. The proportion of grasses increased, and that of horsetails decreased (figure).

The stand density and volume increased in the period from 1998 to 2008 in all plots, as before. The proportion of dead wood also increased, but not uniformly. The greatest increase, to 80%, was recorded in the impact zone. This indicates progressive degradation of the tree layer, which agrees with the literature data [6–8]. The species diversity of the GL remained unchanged on the small scale. On the medium scale, it increased only 30 and 7 km from the plant, but less than in the previous period. It stabilized in other plots. Changes in species composition in the background and buffer (7 km) zones, as before, were associated with the appearance of species characteristic of disturbed habitats (*Galeopsis bifida, Tussilago farfara, Chamaenerion angustifolium*, etc.) or meadow species (*Coccyganthe floscuculi, Succisa pratensis*, etc.) The impact zone, unlike other areas, showed no changes in species richness or community composition. Ground layer biomass noticeably increased only at distances of 30 and 1 km from the plant. In the background zone, this was mainly owing to ferns; and in the impact zone, solely owing to *Agrostis capillaris*. The biomass of horsetails decreased further.

It is tempting to relate the changes in GL in the first period to the emission decrease and regard them as a proof of fast recovery. However, this conclusion disagrees with the temporal variation of the GL state in both periods. It is more likely that GL changes follow changes in the stand, which, in turn, are caused by natural factors. It is known that a storm caused large treefalls in Sverdlovsk oblast in the middle of the first period (June 6, 1995). The storm merely brushed against the region of our study and thinned the stand. The explosion of GL diversity and biomass and trends in the changes in its composition and structure in the background and buffer zones (appearance or increase in the abundance of species typical of open and disturbed habitats) are in good agreement with the well-documented pattern of demutational processes following windfalls [13]. Two important inferences can be made: (1) Natural disturbances can exert greater effects on the behavior of pollution-affected forest communities than emission reduction; (2) data from short-term observations may be treacherous as a proof of fast ecosystem recovery after emission decrease, because they may be related to natural factors. Long-term observations are necessary to estimate the causes of the changes properly.

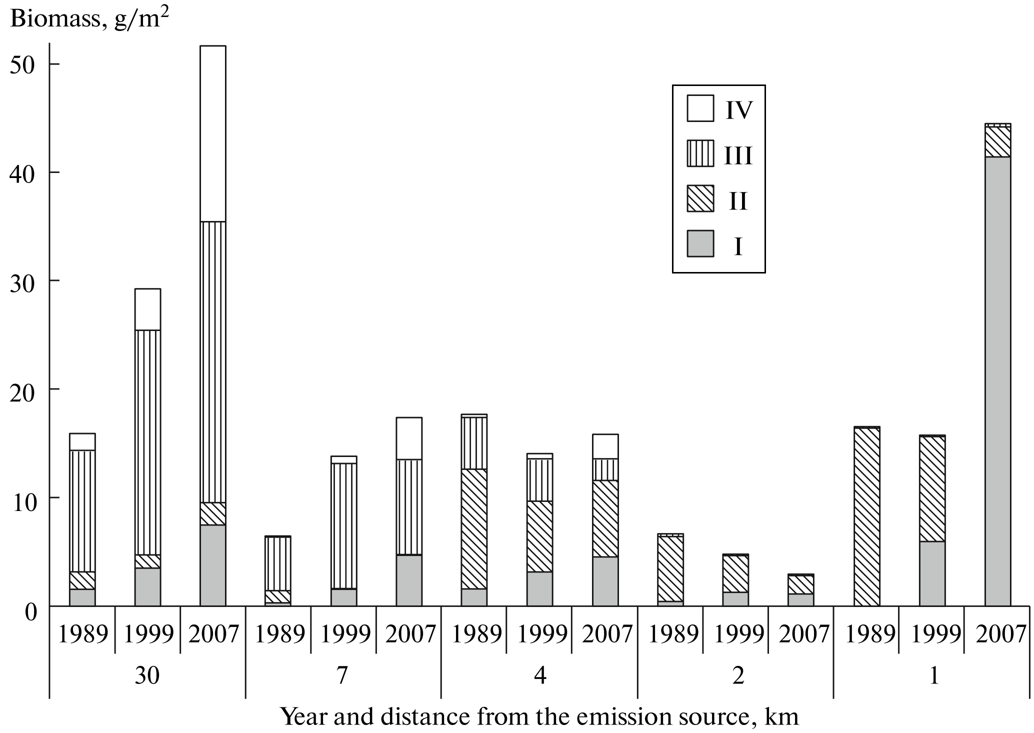

Fig. 1. Changes in the ground layer structure at various distances from the emission source: I, graminoids; II, horsetails; III, forbs; IV, ferns.

The absence of beneficiary trends in the vegetation state in highly polluted areas during the whole 20-year period indicates that, despite cessation of emissions, the toxic load in the impact zone still exceeds the critical level for most species. This may be considered an argument for the inertial hypothesis. In this case, slow purification of soil from metals is the main stability factor.

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