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GENERAL BIOLOGY

Severe Industrial Pollution Increases the β-Diversity of Plant Communities

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The decrease in biota diversity caused by human activity is able to affect ecosystem functions on both local and global scales [1]. The main reasons for a present-day increase in the species extinction rate are the loss, fragmentation, and decreased quality of habitats [2]. Pollution is one of the factors resulting in the appearance of areas that are partially or completely unsuitable for a large number of species and, therefore, decrease their biodiversity. The pollution influence on the cenotic diversity is analyzed mainly via the use of a small number of sample plots (SPs); in this case, scientists operate only with α-diversity assessments [3]. The change in the β-diversity, another important parameter, reflecting the differentiation of the species composition, still remains almost unstudied. Several authors mentioned either the absence of any changes in the β-diversity (mesoscale), or its increase (microscale) with approaching the source of pollution [4]. There is indirect evidence of the increasing β-diversity on industrial barrens [5, 6], but there are no quantitative assessments.

It would be possible to assess the β-diversity using the mapping of vegetation growing on polluted territories. However, there is a fundamental problem related to the inevitable disparity between compared areas; as a result, direct diversity assessments can be significantly biased. This problem can be solved by the interpolation and extrapolation of the biodiversity [7]. However, this approach still has not been used for industrially polluted areas.

The purpose of this study was characterization of changes in the β-diversity of plant communities in the gradient of industrial pollution caused by point polluters. We also tested the hypothesis that the pollution causes convergence of plant communities; one can logically suppose that, due to a limited number of tolerant species, initially differing plant communities become more similar in the case of pollution [8]. We focused on the macroscale (kilometers) and mesoscale (hundred meters), since the growth of the β-diversity caused by human activities on a microscale (meters) is rather trivial and connected with a large number of empty samples [4].

The study was carried out in the vicinity of the Sredneural'skii copper-smelting plant located near the town of Revda (Sverdlovsk oblast) and operating since 1940. The studied area (45 × 40 km) surrounds the plant; in 1995–1998 we arranged 202 SPs (25 × 25 m) differing in their positions in the relief (eluvial, transient, and accumulative landscapes), soil types (gray forest soil, brown forest mountain soil, and sod–ashen–gray soil), and vegetation (birch forest, pine–birch forest, and pine and spruce forests of various associations). The choice of SPs was based on the following criteria: the absence of recent fires and strong anthropogenic impact not related to the pollution; the distances between the SPs and highways should exceed 100 m; the age of the overstorey layer edificators should exceed 80 years. For each SP, we determined the abundance of ground layer species using Droude's scale and collected three combined samples of the forest litter to determine the concentrations of mobile forms of Cu, Pb, and Cd. Based on the spatial interpolation (ARC/INFO) of the pollution level (of the excess over the background content averaged over chemical elements), the territory was divided into five zones: background (I), low (II), medium (III), high (IV), and very high (V) pollutions (the last zone included an industrial barren).

The β-diversity was evaluated using the following indices: (1) the ratio between the γ-diversity and α-diversity (the Whittaker index); (2) the average similarity between communities for all combinations (taking into account the abundance of species); and (3) the plateau attainment rate of accumulation curves, characterizing the growth of the species richness as the SP number increases. To obtain unbiased

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Values of the parameters studied in different polluted zones

Parameter	Pollution zone				
	I	II	III	IV	V
Number of sample plots	13	97	39	30	23
Area, km^2	44	1146	359	248	55
$D1$, km	21.0 (15–31)	18.5 (7–31)	16.0 (6–26)	11.0 (3–16)	3.0 (0.6–8)
$D2$, km	24.8 (0.9–49)	23.6 (0.3–52)	15.4 (1–37)	10.1 (0.7–22)	5.1 (0.4–16)
Cu concentration, μg/kg	68.6 (52–108)	167.2 (64–315)	451.6 (170–1015)	1555.1 (729–2549)	4398.9 (2467–9585)
α-Diversity	35.1 (21–50)	35.6 (13–62)	38.1 (20–54)	27.2 (10–57)	8.5 (0–22)
γ-Diversity:					
γ^1	117	176	152	125	74
γ^2	109 [99–124]	108 [99–121]	110 [97–123]	91 [79–104]	50 [36–60]
β-Diversity:					
β^1	3.3	4.9	4.0	4.6	8.7
β^2	3.1 [2.8–3.3]	3.0 [2.7–3.5]	2.9 [2.6–3.3]	3.4 [2.9–3.9]	5.9 [4.9–6.9]
CS	0.33 [0.30–0.36]	0.34 [0.28–0.42]	0.39 [0.31–0.48]	0.35 [0.27–0.43]	0.09 [0.05–0.14]
R	–0.52*	–0.42*	–0.29*	–0.36*	-0.02^{ns}
K_{mm}	3.5 ± 0.1	3.9 ± 0.2	3.5 ± 0.1	4.9 ± 0.2	12.8 ± 0.1
ST:					
disappearing	–	26 [14–37]	23 [13–34]	33 [22–48]	53 [37–71]
appearing	–	24 [15–33]	25 [14–37]	15 [7–25]	11 [5–18]

Note: The table contains averaged values; the minimum and maximum values are shown in round brackets, and the 95% confidence interval is shown in square brackets. $D1$ and $D2$ indicate the distance to the industrial plant and the distance between sample areas, respectively. γ^1 and γ^2 indicate the observed and interpolated γ-diversity, respectively; $\beta^1 = \gamma^1/\alpha$, $\beta^2 = \gamma^2/\alpha$. CS is a Czekanovski–Sjörensen index; R is a coefficient of linear correlation between CS and $D2$ (*, $p < 0.001$; ^{ns}, $p > 0.05$); K_{mm}, Michaelis–Menten constant (± error); ST, the number of species (the median) during the transition to the next zone.

estimators of the γ-diversity, we performed the interpolation of the accumulation curve obtained for 10 SPs; all calculations were carried out using an the EstimateS 7.5 software. In addition, we approximated accumulation curves for 20 SPs (13 SPs for zone I) using the Michaelis–Menten equation; the rate constant was interpreted as the number of SPs sufficient to reveal a half of all presented species; i.e., the higher the rate constant, the higher the β-diversity. Resampling was used to obtain unbiased estimates of the Whittaker index, the numbers of species that had disappeared and appeared, and the similarity index. For each zone, we randomly sampled 10 SPs without replacement; the number of replications was 1000. The calculations were carried out using the RSXL 4.0 software.

The adjacent impact zones differed in the average content of metals by a factor of two to three (table), and the concentration range within each zone was rather large, which evidences for an uneven distribution of toxicants. When going from zone I to zones II and III, the diversity remained unchanged; the number of disappeared species was equal to the number of newly appearing species. A significant decrease in the α- and β-diversities was observed only in zones IV and V, since the elimination of species was not compensated. At the same time, the α-diversity in these zones varied in a very wide range (0–57 species), which evidences for a high spatial unevenness of the species elimination process.

Regardless of the assessment method, the β-diversity increased by a factor of two to four as the pollution level increased. Some plant communities of zone V did not have any common species, though the distance between these communities was rather small. The correlation between the similarity index and the distance between plant communities within the same zone decreased to the degree of absolute absence in zone V as the pollution level increased; this fact confirms the mosaic character of vegetation transformation and evidences for an increase in the spatial isolation of local populations. Only two out of 23 SPs of zone V were lifeless, and these SPs did not influence significantly the β-diversity assessment: after their exclusion, the average similarity index was increased only to 0.11 (0.08–0.16). Therefore, the presence of empty samples in our case did not play any significant role as in a microscale increase in the β-diversity [4].

The increased β-diversity in the pollution gradient was determined by uneven elimination of species in the space; the rate of the decrease in the species richness was higher for the mesoscale compared to the macroscale. A similar tendency is observed in the case of comparison between the microscale and mesoscale [6, 9]. It is connected with the fact that an increase in the pollution level often causes a decrease in the density of local populations rather than elimination of species [6]. Even in the case of extremely heavy pollution, some individuals still continue to exist in habitat fragments where environmental conditions remain relatively favorable for some or another reason. The growth of the β-diversity caused by the increasing spatial heterogeneity of environmental conditions may also take place in other gradients, such as the altitudinal gradient [10].

Thus, the initial hypothesis about the convergence of plant communities in the pollution gradient has not been confirmed, since the decrease in the α-diversity of such communities is accompanied by divergence of their species composition. Our data indicate that the industrial pollution results in a sharp increase in the spatial isolation of local populations and causes an almost total loss of the vegetation continuity on a macroscale. This process may hasten the extinction of remaining species, occurring via either stochastic processes or the influence of other anthropogenic factors [2], which may result in continuing degradation of ecosystems located near industrial enterprises, even in the case of reduction of their discharges.

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