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Grassland Land Snail Communities after Reduction of Emissions from a Copper Smelter

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Abstract—The species structure of land snail communities inhabiting the meadow herb layer has been studied in the periods of relatively high emissions from the Middle Ural Copper Smelter (2006–2008) and after their almost complete reduction (2015–2017). No snails were found in the impact zone during these periods. In the background and buffer zones, their species richness during the second period decreased by a factor of two, and their abundance, by a factor of up to three, which was due to weather fluctuations (drought in 2016). The impact of drought was more distinct in the buffer zone, but two species (*Discus ruderatus* and *Vitrina pellucida*) appeared there and increased in abundance during the second period. The processes of recovery in land snail communities may be explained by normalization of soil pH and calcium content and also by an increase in the proportion of graminoids in the herb layer, which provided for stabilization of microclimatic conditions.

Keywords: land snails, grassland ecosystems, industrial pollution, heavy metals, soil pH, calcium, emission reduction, recovery, Middle Ural Copper Smelter

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Industrial emissions, including those containing heavy metals, are currently decreasing in many regions due to production cutbacks or renovation of industries [1]. This should initiate the processes of recovery in the ecosystems of impact regions, at least in the long term. Studies on grassland ecosystems in the vicinities of shutdown industrial facilities have revealed the recovery of both plant communities [2, 3] and invertebrate communities of the herb layer [2]. However, we are not aware of studies on the recovery of species structure in the taxocenes of invertebrates.

Invertebrates inhabiting the herb layer are traditionally regarded as an individual stratum of the fauna closely associated with this layer and characterized by high abundance and species richness [4]. Mollusks (land snails) are a component of this stratum. They may be classified as stratochortophiles, i.e., invertebrates with stratified mobility that are closely associated with herbaceous vegetation but periodically migrate to the upper soil horizons [5]. The latter is important, since these horizons accumulate the greatest amounts of pollutants [6].

The choice of land snails as the object of study is made in view of their specific features that suggest the possibility of recovery of their communities within a short time after emission reduction. First, land snails are relatively tolerant of heavy metals, as they can accumulate them in considerable amounts without any apparent harm to themselves [7–11]. A critical factor for mollusks is a sufficient supply of available calcium [12–14]. Heavy metals can create a deficiency of calcium for land snails [15, 16], but its bioavailability is limited primarily by soil acidity [12, 13]. Normalization of soil pH in the upper horizons after cessation of emissions [17] relieves this limitation, which may initiate the recovery of land snail communities.

Second, land snails are sensitive to the vertical structure of herb layer [14, 18, 19]. Forb meadows in the vicinities of industrial plants often transform into grass meadows [20, 21], and the greater the proportion of grasses, the simpler the general architecture of herb layer and the more contrasting the microclimate, which is unfavorable for snails [18, 22]. In addition, light intensity in the thinned grass stand of polluted areas in increased, which is another adverse factor [14]. According to our data, the proportion of forbs increases in the buffer zone, which may also serve as a driver of land snail community recovery.

Emissions from the Middle Ural Copper Smelter (MUCS) were gradually reduced since the early 1990s and almost ceased after 2010 [17]. This provided a basis for evaluating patterns in the recovery of ecosystems. Studies on invertebrate communities of the herb layer were performed both in the period of high emissions [21] and during their reduction [23]. Mollusks as a component of soil macrofauna were studied with respect to their distribution in polluted areas [24–26] and dependence on certain structural features of herb layer [27].

The purpose of this study was to evaluate changes in grassland land snail communities after reduction of emissions from a copper smelter and to test the hypothesis that this reduction provides conditions for relatively rapid recovery of communities.

MATERIAL AND METHODS

The study was performed in the vicinity of MUCS, in the outskirts of Revda, Sverdlovsk oblast. Emissions from the MUCS (primarily SO_2 and heavy metals contained in dust) amounted to 225000 t per year in 1980, decreased to 148000 t in 1990 and 63000 t in 1990, and were reduced to only 3000 t after an overhaul of the smelter in 2010. Between 1980 and 2012, the total amount of pollutants emitted to the atmosphere decreased 75-fold. Annual SO_2 emissions were reduced by a factor of 116 (from 201000 to 1700 t per year); dust emissions, by a factor of 44 (from 21000 to 500 t), with the amount of Cu decreasing 5500-fold (from 4400 to 0.8 t); of As, 1571-fold (from 900 to 0.6 t); of Pb, 16-fold (from 1000 to 70 t); and of Zn, 15-fold (from 1800 to 100 t between 1989 and 2012). The composition and dynamics of emissions were described in detail previously [17, 28].

Permanent sampling plots 50 × 50 m were established in the impact (strongly polluted), buffer (moderately polluted) and background (conditionally clean) zones at respective distances of 1, 4, and 30 km west of the smelter, against the prevailing wind direction. In each zone, there were three plots with a distance of 100–300 m between them. They were located in depressed topographic areas occupied by secondary upland meadows in glades (about 5000 m^2) formed after forest clearcutting approximately 70 years ago. The floristic composition of the meadows changed considerably along the pollution gradient, with more sensitive forbs being replaced by pollution-tolerant grasses. Thus, the meadows in the background zone were of forb type; in the buffer zone, of forb–grass type; and in the impact zone, of grass type, with absolute dominance of *Agrostis capillaris* L. The composition of vegetation in these meadows was described in detail previously [23]. Neither hay harvesting nor livestock grazing took place in any of the plots.

Mollusks inhabiting the herb layer were collected using a biocenometer (base area 0.25 m^2) with a portable battery-powered vacuum sampler [29]. Each sample was taken by placing this device on the ground to collect all invertebrates and herbaceous plants within its area, cutting the plants at the ground surface. The sampling procedure and design of the biocenometer were described in detail previously [23, 29].

The study was performed during two periods, 2006–2008 and 2015–2017, in the same permanent plots. Three rounds of censuses were conducted each year in the second halves of summer months (round 1 in June, round 2 in July and round 3 in August), with ten samples per plot being taken during each round. Thus, the material collected over 6 years (18 census rounds) amounted to 1620 samples of invertebrates and plants, 270 samples per year. Land snails collected during the first and second periods (1095 and 462 ind., respectively) were identified to species level (in some cases, to genus level). In plant samples, the air-dry weights of the total phytomass and two its fractions—graminoids (grasses, sedges, and rushes) and forbs—were measured with an accuracy of 0.1 g.

Descriptive statistics (means and standard errors) were calculated for data analysis. The dependence of species richness and abundance of land snails on different factors (pollution zone and the period, year, and round of census) was evaluated using generalized linear models for quasi-Poisson distribution; multiple comparisons were made using Tukey's test. The SPEI R package v. 1.7 was used to calculate standardized precipitation—evapotranspiration index (SPEI) on the basis of monthly average temperature and precipitation values recorded at the Revda weather station over the period from 1977 to 2018. The dendrogram of dissimilarity in species structure between pollution zones in different years was plotted in pvclust R package v. 2.2-0 by UPGMA method based on the Bray-Curtus index, taking into account the abundance of species. Reliability of clustering was assessed by a bootstrap method. All calculations were made in the R environment [30].

RESULTS

Weather conditions differed considerably between study years. According to SPEI values, these conditions in 2006, 2007, 2008, and 2017 were close to long-term average; the summer of 2015 was excessively moist, while that of 2016 was very dry (Fig. 1). The proportion of graminoids in the buffer zone decreased in the second period, compared to the first ($p < 0.001$), and their ratio to forbs approached that in the background zone. This ratio in the impact zone was similar in both periods ($p = 0.997$; Table 1). These differences should be taken into account when interpreting the results concerning land snail communities.

No land snails were found in the impact zone either in the first or in the second period. In other zones, their species richness and abundance decreased in the second period, compared to the first, by factors of 2.1 and 2.4, respectively, in the background zone ($p <$ 0.001) and by factors of 2.0 and 3.4 in the buffer zone ($p < 0.001$). This decreasing trend manifested itself equally in both zones (Table 2). However, data analysis by years showed the significance of the interaction "zone × year": both species richness and abundance

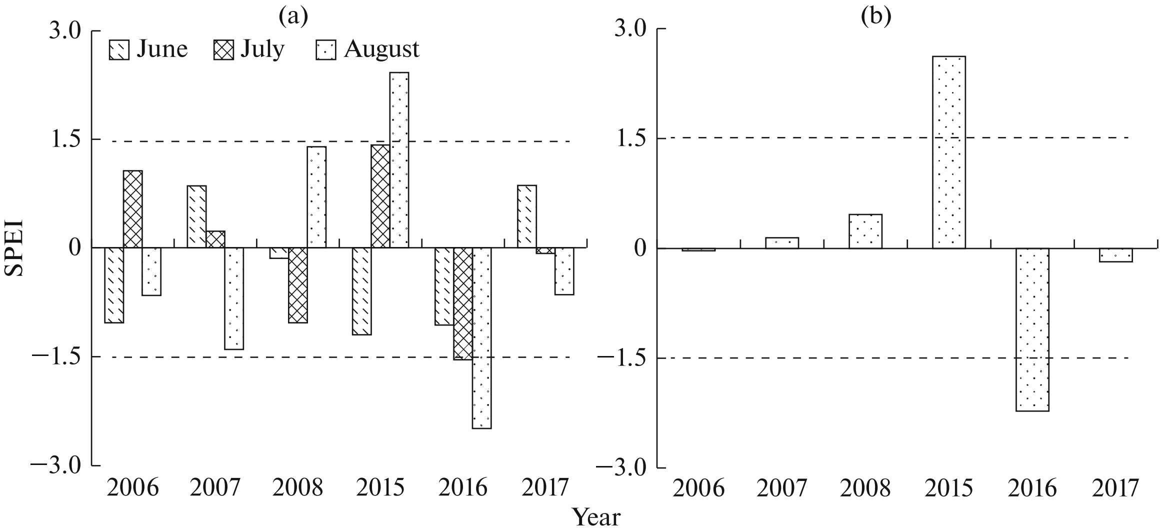

Fig. 1. SPEI values calculated (a) for each summer month and (b) over 4 months (May–August) of different years. Values above 1.5 and below −1.5 indicate excessive moisture and drought, respectively.

of snails in the background and buffer zones changed differently over the study years. The interaction "zone × census round" proved to have a significant effect on their abundance but not on species richness.

The species richness (Fig. 2) and abundance of snails (Fig. 3) in both zones were the highest in 2006 and 2007 but decreased in 2008 to the level of 2015, and the lowest values of both parameters were recorded in 2016 and 2017.

The tendency toward decrease in the species richness and abundance of snails during the first and third rounds of 2016 census was more distinct in the buffer than in the background zone (Figs. 2, 3). The decrease in abundance during the second period was recorded for all species except two (Table 3). The abundance of *Discus ruderatus* (Hartmann, 1821) in the buffer zone increased eightfold in 2015, compared to 2008; then it decreased significantly in 2016 but increased again in 2017. The other species, *Vitrina pellucida* (O.F. Müller, 1774), was first recorded in the buffer zone in 2015. It successfully survived the 2016 drought, and increased in abundance in 2017. Thus, the abundance of both these species in the moderately polluted buffer zone proved to increase during the second study period, which is in accordance with the expected dynamics of community recovery.

The species structure of land snail communities was found to differ considerably between pollution zones (Fig. 4), while differences between years were minor, despite contrasting weather conditions. It is noteworthy that similarity in species structure was revealed between the land snail communities of the background zone in 2006 and of the buffer zone in 2015–2017, which allowed them to be pooled into a single cluster.

DISCUSSION

The observed decrease in the species richness and abundance of land snails in the second period is contrary to expected. Since the pattern of changes in the background zone was the same as in the buffer zone, they cannot be attributed to the impact of pollution. The most probable explanation is that fluctuations of weather conditions have exerted a negative effect on land snail communities in the entire study region. A known fact is that land snails strongly depend on moisture conditions in the upper soil horizons [22, 31], which in upland meadows is primarily determined by the ratio between the amount of precipitation and evapotranspiration rate. The period from early May to late August 2015 was excessively moist relative to the climatic norm, whereas the summer of 2016 was abnormally dry (Fig. 1). Since land snails generally prefer high-moisture conditions [18, 22], excessive precipitation in 2015 could not have an appreciable negative effect on them. Apparently, the 2016 drought was the weather fluctuation that caused an abrupt drop in the abundance of snails. The possibility of such an effect of drought is confirmed by the results of an experiment in which land snails successfully survived long-term exposure at high temperatures under adequate moisture conditions, whereas their mortality but showed an increase in mortality up to 100% when moisture supply was insufficient [32]. The low values of species richness and abundance in 2017 probably reflect early stages in the process of community recovery after the "weather disaster" in the previous year.

When discussing the question of recovery after technogenic impact, it is important to note that a significant drop of abundance in the second period was observed not for all snail species. Two of them, *Discus ruderatus* (Hart-

Table 1. Parameters of meadow herb phytomass in zones with different pollution levels in different periods and years

Period/year	Zone	Total phytomass, g/m^2	Graminoid phytomass, g/m^2	Proportion of graminoids, %
I	Background	264.7 ± 13.6	74.5 ± 8.6	27.8 ± 2.5
	Buffer	280.6 ± 14.7	126.3 ± 11.3	44.1 ± 2.6
	Impact	166.3 ± 9.1	165.2 ± 9.3	99.2 ± 0.3
II	Background	209.7 ± 9.0	59.4 ± 3.6	28.8 ± 1.7
	Buffer	251.8 ± 13.4	60.3 ± 6.1	25.2 ± 2.6
	Impact	104.6 ± 4.8	100.9 ± 4.3	96.8 ± 0.9
2006	Background	337.5 ± 20.4	95.9 ± 17.1	28.3 ± 4.6
	Buffer	378.0 ± 13.5	190.0 ± 16.5	50.4 ± 4.1
	Impact	221.0 ± 12.0	220.7 ± 12.0	99.9 ± 0.1
2007	Background	235.8 ± 8.8	42.3 ± 3.4	18.0 ± 1.5
	Buffer	248.4 ± 7.8	83.1 ± 9.0	33.1 ± 3.1
	Impact	150.2 ± 4.8	150.0 ± 4.8	99.8 ± 0.1
2008	Background	220.7 ± 16.5	85.3 ± 13.4	37.2 ± 3.7
	Buffer	215.5 ± 8.2	105.9 ± 9.5	48.7 ± 3.5
	Impact	127.8 ± 7.4	125.0 ± 7.6	97.8 ± 0.7
2015	Background	214.9 ± 15.0	72.3 ± 3.4	34.8 ± 2.6
	Buffer	265.9 ± 22.0	95.1 ± 8.9	36.3 ± 3.0
	Impact	115.1 ± 7.4	106.0 ± 5.8	92.7 ± 2.0
2016	Background	194.5 ± 9.5	50.6 ± 5.6	26.8 ± 3.2
	Buffer	239.2 ± 25.3	45.0 ± 4.4	23.3 ± 5.0
	Impact	113.8 ± 4.9	112.6 ± 4.7	99.0 ± 0.4
2017	Background	219.8 ± 19.3	55.4 ± 6.8	24.7 ± 1.9
	Buffer	250.4 ± 21.3	40.7 ± 5.6	15.9 ± 1.4
	Impact	85.0 ± 7.9	84.0 ± 7.9	98.8 ± 0.4

Mean values with standard errors are shown. Statistical units: for years, sampling plot × census round ($n = 9$); for periods: sampling plot × year × census round ($n = 27$).

Table 2. Results of generalized linear model for the dependence of land snail species richness and abundance on pollution zone, study period, year, and census round

Source of variation	df	df$_{\text{error}}$	Number of species		Abundance	
			F	p	F	p
Zone	1	8	5.3	0.050	2.3	0.168
Period	1	8	13.7	0.006	8.5	0.019
Zone × period	1	8	11.3	0.010	2.4	0.159
Zone	1	72	34.0	<0.001	11.1	0.001
Year	5	72	24.5	<0.001	25.7	<0.001
Census round	2	72	10.0	<0.001	8.6	<0.001
Zone × year	5	72	2.7	0.026	2.6	0.031
Zone × census round	2	72	1.3	0.291	4.2	0.019
Year × census round	10	72	4.3	<0.001	3.4	0.001

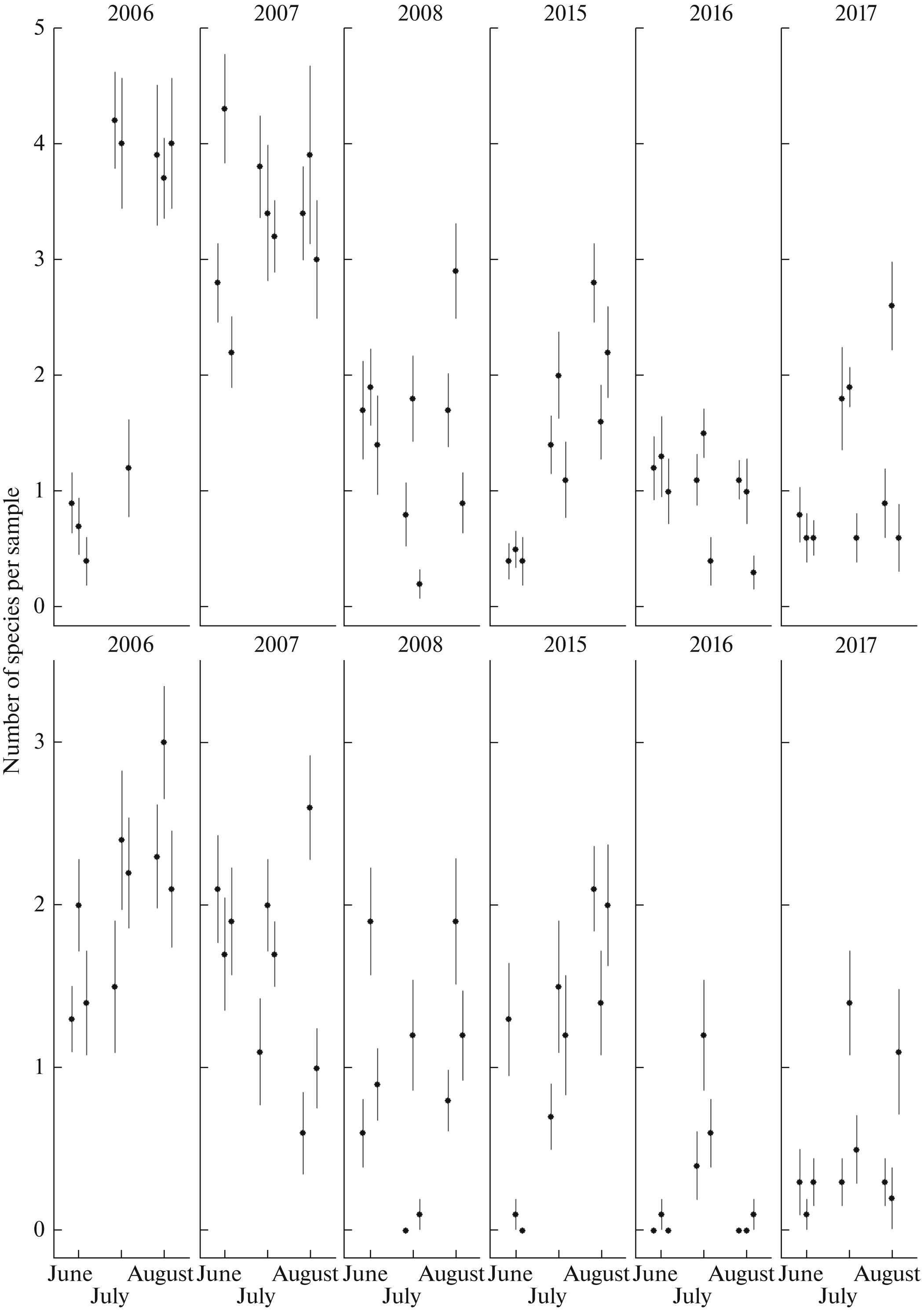

Fig. 2. Land snail species richness in (a) background and (b) buffer zones. Data are presented as arithmetic means with standard errors for each plot in each year and census tour, with each sample used as a statistical unit ($n = 10$).

mann, 1821) and *Vitrina pellucida* (O. F. Müller, 1774), showed an increase in abundance in the moderately polluted buffer zone, in accordance with the expected dynamics of community recovery. These species are eurybionts and can live in a broad spectrum of habitats with different conditions [33], although *V. pellucida*

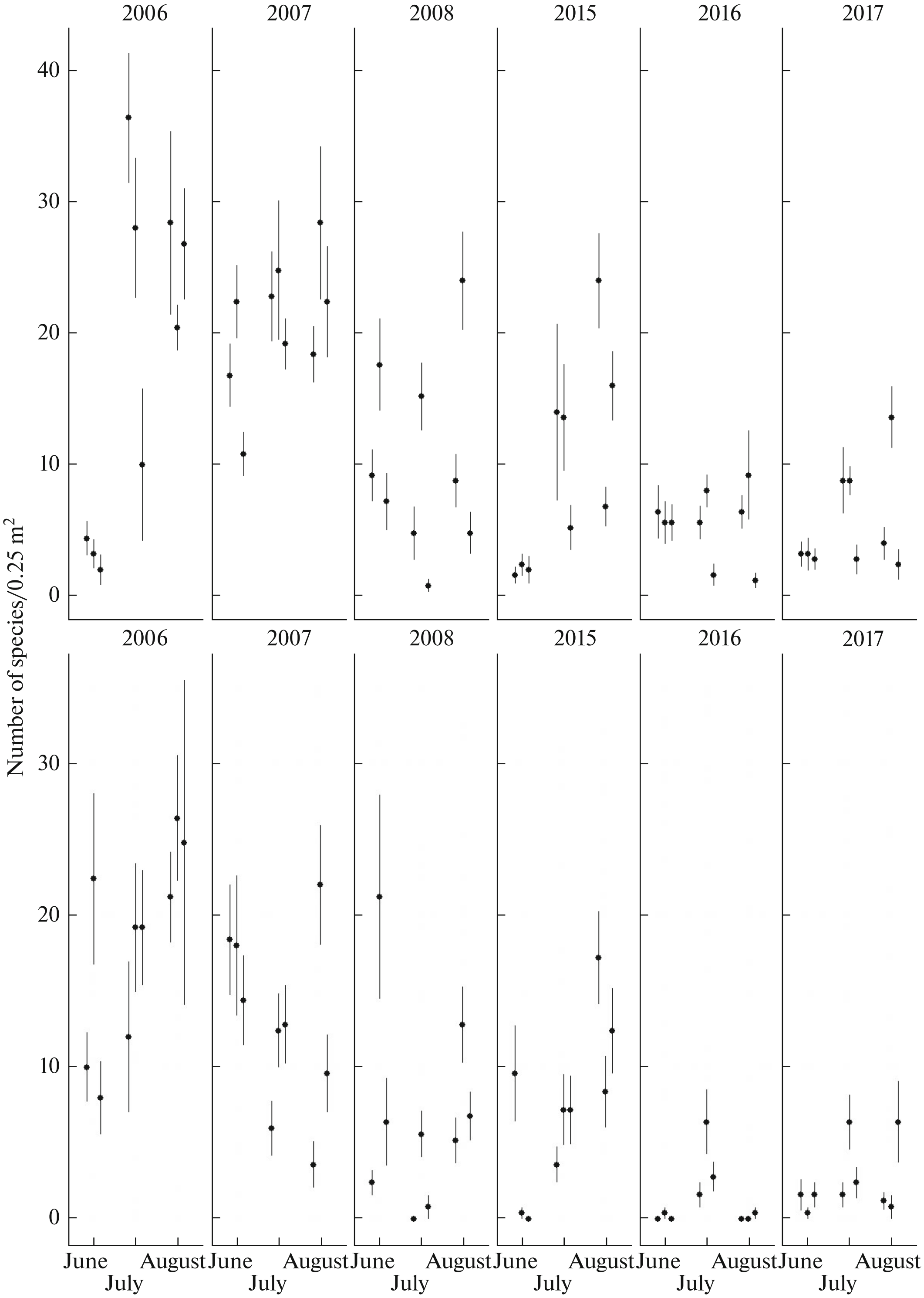

Fig. 3. Land snail abundance in (a) background and (b) buffer zones. Data are presented as arithmetic means with standard errors for each plot in each year and census tour, with each sample used as a statistical unit (n = 10).

prefers biotopes with relatively high moisture level [22]. Apparently, it is relative "unpretentiousness" that allowed these species to find conditions suitable for them in the buffer zone, where such conditions appeared due to the aforementioned reparative changes in the structure of herb layer.

Table 3. Abundance of land snails (ind./m^2) in the herb layer of background (Bg) and buffer (Bf) zones in different years

Species	Zone	Year					
		2006	2007	2008	2015	2016	2017
Arion subfuscus	Bg	0.27 ± 0.11	0.13 ± 0.09	–	0.36 ± 0.15	–	–
	Bf	1.07 ± 0.24	0.40 ± 0.11	0.31 ± 0.10	0.98 ± 0.36	0.13 ± 0.09	0.27 ± 0.09
Deroceras agreste	Bg	4.62 ± 1.60	1.02 ± 0.34	0.36 ± 0.25	3.11 ± 1.16	–	0.89 ± 0.27
	Bf	5.51 ± 0.99	0.71 ± 0.25	0.62 ± 0.27	4.09 ± 1.05	0.36 ± 0.29	0.53 ± 0.19
Deroceras reticulatum	Bg	0.04 ± 0.04	–	–	–	–	–
	Bf	0.04 ± 0.04	–	–	0.04 ± 0.04	–	–
Discus ruderatus	Bg	–	–	0.04 ± 0.04	0.04 ± 0.04	–	–
	Bf	0.09 ± 0.08	–	0.04 ± 0.04	0.31 ± 0.10	0.04 ± 0.04	0.22 ± 0.14
Euconulus fulva	Bg	1.47 ± 0.35	0.76 ± 0.28	0.31 ± 0.15	0.09 ± 0.06	0.04 ± 0.04	0.18 ± 0.09
	Bf	3.02 ± 0.57	3.42 ± 0.58	1.51 ± 0.67	0.58 ± 0.23	0.09 ± 0.06	0.09 ± 0.06
Euomphalia strigella	Bg	0.18 ± 0.07	0.18 ± 0.09	0.09 ± 0.06	–	–	0.04 ± 0.04
	Bf	–	–	–	–	–	–
Fruticicola fruticum	Bg	1.38 ± 0.29	4.04 ± 1.27	5.64 ± 1.71	4.22 ± 1.09	3.73 ± 0.64	2.04 ± 0.41
	Bf	–	–	–	–	–	–
Perpolita hammonis	Bg	3.69 ± 0.99	2.36 ± 0.36	0.62 ± 0.14	0.40 ± 0.22	0.04 ± 0.04	0.36 ± 0.21
	Bf	6.40 ± 1.26	5.96 ± 1.04	2.40 ± 0.56	0.18 ± 0.07	0.31 ± 0.16	0.09 ± 0.08
Punctum pygmaeum	Bg	0.09 ± 0.06	0.84 ± 0.18	0.09 ± 0.06	–	0.04 ± 0.04	0.09 ± 0.08
	Bf	–	–	–	–	–	–
Succinea putris	Bg	1.29 ± 0.46	1.96 ± 0.28	0.93 ± 0.20	0.18 ± 0.09	1.07 ± 0.21	0.58 ± 0.19
	Bf	–	–	–	–	–	–
Vallonia costata	Bg	–	0.04 ± 0.04	–	–	–	–
	Bf	–	–	–	–	–	–
Vitrina pellucida	Bg	0.09 ± 0.06	0.22 ± 0.11	0.04 ± 0.04	0.04 ± 0.04	–	0.13 ± 0.09
	Bf	–	–	–	0.44 ± 0.33	0.04 ± 0.04	0.40 ± 0.21
Zonitoides nitidus	Bg	–	–	–	–	–	–
	Bf	1.96 ± 1.09	2.27 ± 1.13	1.87 ± 1.05	0.13 ± 0.09	0.04 ± 0.04	0.04 ± 0.04
Carychium sp.	Bg	–	0.09 ± 0.06	0.09 ± 0.06	–	–	–
	Bf	–	–	–	–	–	–
Cochlicopa sp.	Bg	2.93 ± 0.74	2.0 ± 0.33	0.58 ± 0.16	0.67 ± 0.22	0.09 ± 0.06	0.36 ± 0.17
	Bf	–	0.22 ± 0.17	0.04 ± 0.04	0.58 ± 0.25	0.09 ± 0.06	0.80 ± 0.29
Columella sp.	Bg	1.02 ± 0.47	1.82 ± 0.40	0.44 ± 0.20	0.22 ± 0.09	0.40 ± 0.20	0.84 ± 0.21
	Bf	0.04 ± 0.04	–	–	–	–	0.04 ± 0.04
Vertigo sp.	Bg	0.67 ± 0.17	4.76 ± 0.99	1.02 ± 0.31	0.18 ± 0.17	0.09 ± 0.06	–
	Bf	–	0.04 ± 0.04	–	–	–	–
Overall abundance	Bg	17.7 ± 4.1	20.2 ± 1.7	10.3 ± 2.3	9.5 ± 2.4	5.5 ± 0.8	5.5 ± 1.2
	Bf	18.1 ± 2.1	13.0 ± 1.9	6.8 ± 2.1	7.3 ± 1.7	1.11 ± 0.59	2.49 ± 0.72
Total number of species	Bg	10.2 ± 2.1	13.3 ± 0.8	5.9 ± 1.0	5.5 ± 1.1	4.0 ± 0.5	4.6 ± 0.9
	Bf	8.1 ± 0.7	6.5 ± 0.8	3.8 ± 0.9	4.6 ± 0.9	1.07 ± 0.51	2.0 ± 0.56

Mean values with standard errors are shown. Statistical unit: census round × sampling plot, $n = 9$; (–) the species is absent.

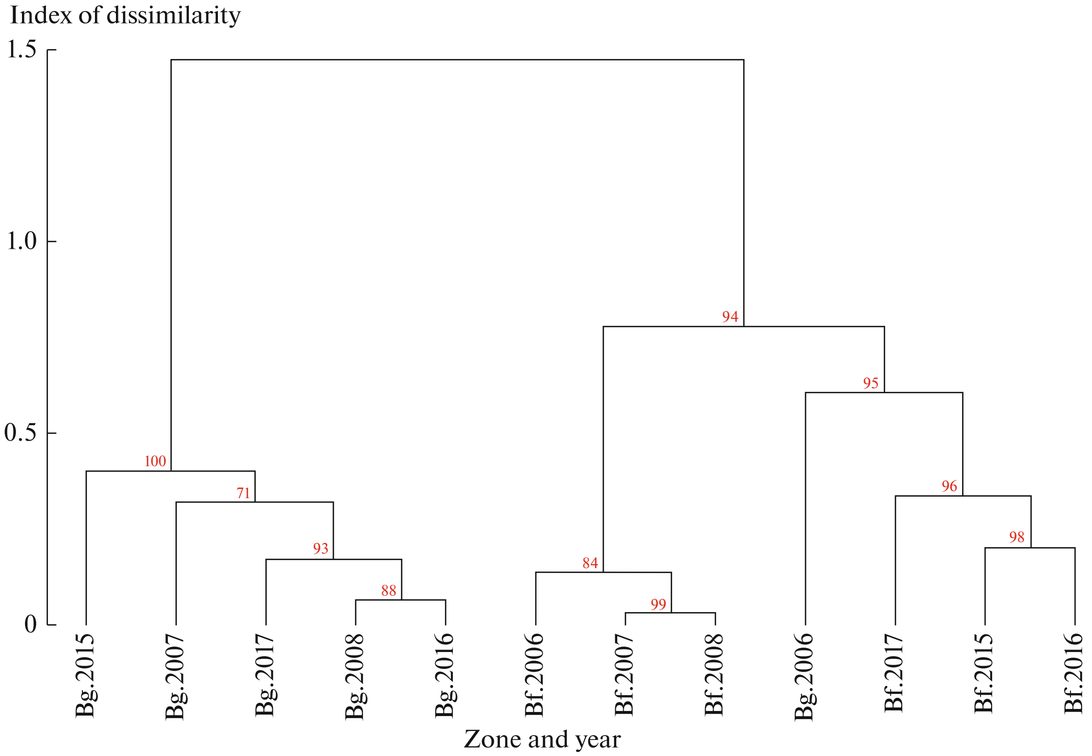

Fig. 4. Dendrogram of dissimilarity in species structure between land snail communities of background (Bg) and buffer (Bf) zones in different years. Figures at notes are approximately unbiased (AU) test values. Clusters with AU ≥ 95% are considered statistically significant.

It is telling that the decrease in snail species richness and abundance recorded during the first and third round of 2016 census was more distinct in the buffer than in the background zone (Figs. 2, 3). Species richness—a fairly conservative parameter of community— in the background zone remained relatively stable during both study periods, while abundance (a less conservative parameter) in both zones was higher in the second period. It may well be that the impact of drought on snail community in the background zone was largely attenuated by vegetation, where forbs obviously prevailed over graminoids. The low proportion of the latter (plants with a linear vertical structure, weakly branching stems, and narrow leaf blades) accounts for a more complex architecture of the herb layer, which, in turn, contributes to the formation of stable microclimate. The proportion of graminoids in the buffer zone is decreased as well (Table 1), indicating a distinct tendency toward recovery, but vegetation is still in a depressed state and less efficiently compensates strong weather fluctuations. Temperature and humidity in the herb layer should vary more strongly, which is unfavorable for many groups of invertebrates [34], and light intensity is increased, which has a negative effect on mollusks [14]. As shown in our previous study, the abundance of land snails is inversely correlated with the phytomass of graminoids and directly correlated with the phytomass of forbs [27]. A distinct correlation with the vertical structure of herb layer has been revealed for land snails in general [14, 18, 19] and, in particular, for *V. pellucida* [22], one of the two species whose abundance in the buffer zone increased in the second study period. It should be noted, however, that the abundance of both these species was relatively low, and our conclusion is preliminary and needs proof in the course of subsequent monitoring.

The results presented above may create an impression that the land snail community of the herb layer responds primarily to the influence of climatic factors, while industrial pollution is of secondary significance. However, land snails were absent in the impact zone either in the first or in the second study period. When only the two other zones are considered, differences in the species structure of snail community between them are still more pronounced than those between years, despite contrasting weather conditions (see Fig. 4). On the other hand, there are certain signs of recovery over time: in the second period, the structure of snail community in the buffer zone shows similarity to that in the background zone.

Mollusks inhabiting the herb layer are in permanent contact with the upper soil horizons [5, 18] and, hence, with heavy metals accumulated there [6]. Heavy metals are among the main components of emissions from metal industries, and land snails can accumulate considerable amounts of Cu, Pb, Cd, and Zn without any serious consequences [8, 10]. The rates of feeding, growth, and development decrease in some cases, but no increase in mortality has been observed [9, 11, 35, 36], except in some experiments where snails were fed on hyperaccumulator plants with very high Ni content [37, 38].

The fact of elimination of land snails near the MUCS contradicts the data on their heavy metal tolerance. Snails were not recorded in the soil fauna of the impact zone in the period from 1990 to 2012; single individuals appeared there only in 2014 [25], whereas snails in the meadow vegetation are still absent. Soil mollusks in the area exposed to emissions from the Severonikel smelters were found only in the background and buffer (slightly polluted) zones [39]. They have been repeatedly recorded near metal industries [7, 11, 40], but only in cases where metal pollution was not accompanied by soil acidification. Apparently, the direct toxicity of metals does not play the main role, and more complex mechanisms are responsible for this situation (e.g., the combined influence of different factors).

Metabolic barrier to heavy metals is especially effective against Pb: its content in tissues is always significantly lower than in food [9, 34]. Experimental data show that snails fed Pb-enriched diet have lower soft tissue concentrations of Ca and Mg, which are probably expended in an effort to excrete Pb [16]. This leads to reduced Ca supply at early developmental stages, which affects the mineral composition of eggs [15] and shell formation in juveniles, reducing shell weight [16].Thus, the toxic effect of heavy metals appears to be based on creating Ca deficiency.

Availability of Ca is an important ecological factor that has influence on qualitative and quantitative features of mollusk communities [12–14]. Soil Ca content depends on soil pH [13], which decreases from 5.1–6.0 to 3.5–3.8 in areas exposed to industrial emissions [17]. After the reduction of emissions from the MUCS, pH of the upper soil horizons in polluted areas approached the background level already in 2012; soil Ca^{2+} concentration in the buffer zone was also close to the background level, while that in the impact zone was twice lower [17]. Therefore Ca deficiency is no longer a limiting factor for snails in the buffer zone but remains so in the impact zone.

CONCLUSIONS

A comparative analysis of the species structure of grassland land snail communities between the periods of relatively high emissions (2006–2008) and after their almost complete reduction (2015–2017) did not confirm the initial hypothesis that this reduction provides conditions for relatively rapid recovery of communities. The species richness and abundance of snails in the background and buffer zones decreased significantly from the first to the second period, which is due to weather fluctuations. Recovery after emission reduction is probable for only two species that appeared and increased in abundance in the moderately polluted buffer zone. The impact zone is still uninhabited by snails. The processes of recovery in their communities appear to be initiated due to normalization of soil pH and Ca content and also by changes in the relative proportions of graminoids and forbs in the buffer zone, which approach these proportions in the background zone.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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