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The Response of the Invertebrate Communities of Steppe and Floodplain Meadows to Emissions from the Karabash Copper Smelter

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Abstract—Based on the materials of 2014, the response of invertebrate communities in floodplain and steppe meadows to emissions from the Karabash copper smelter was assessed (the main pollutants are SO_2 and heavy metals). Near the smelter, in the phytocenoses of meadows of both types, the phytomass of herbage decreases (2–7 times) and the proportion of graminoids increases (from 36–45 to 53–85%). The abundance of invertebrates in the meadows of both types varies similarly: the total abundance decreases (by a factor of 1.4–2.9), while the abundance of all trophic and most large taxonomic groups does not change. The taxonomic structure of invertebrates in floodplain meadows changed only in the impact zone, while in steppe meadows, already in the buffer zone. This result partially confirms the hypothesis put forward that in the communities of floodplain meadows, the reaction to pollution is less pronounced than in steppe meadows.

Keywords: herbivores, predators, cicadas, spiders, Diptera, phytomass, technogenic pollution, heavy metals, sulfur dioxide

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INTRODUCTION

The communities of invertebrates in the grass layer is characterized by high abundance and taxonomic richness, also due to the presence of elements of most other terrestrial layers in it. The close relationship with herbaceous vegetation, which is characteristic of representatives of the layer at least at certain stages of the life cycle [1], makes it possible to sensitively respond even to weak stresses. This allows us to consider the grass layer population as an indicator of the state of invertebrate communities as a whole.

The response of natural communities of invertebrate grass stands to technogenic pollution has been studied extremely fragmentarily. Most of the work on this topic was carried out by us in the area of operation of the Middle Ural Copper Smelter (MUCS) in the Middle Urals [2–4], other studies, including foreign ones, are sporadic and are devoted to the accumulation of metals [5] or other types of pollution sources [6]. The communities of grass layer invertebrates near other large point sources, including the Karabash Copper Smelter (KCS), whose environs were recognized as an ecological disaster zone in 1996, has not been studied at all [7].

Primary meadows of two types are widely represented in the zone of action of the KCS, differing in the regime of moisture and the structure of phytocenoses caused by this: floodplain (in lowlands) and steppe (on elevated relief elements). The humidification regime is likely to be able to significantly modify the response of invertebrate communities to pollution. It is known that in arid ecosystems, it is the availability of water that is the main limiting factor in the growth and development of plants [8, 9] and an important factor for invertebrate communities [10, 11]. In steppe areas with a sparse herbage architecture, the moisture regime can be even more important than the composition and structure of the herbaceous layer [12]. Consequently, insufficient moisture can act as an additional stressor that enhances the effect of pollutants on both plants and invertebrates [13, 14].

Floodplain meadows, ecosystems with a high level of moisture, exhibit certain specifics under conditions of technogenic pollution. The accumulation and distribution of heavy metals in river floodplains is associated with the leaching regime, in which pollutants aggregate with finely dispersed organic sediment and are actively transported along the channel [15]. However, information about the further impact of pollutants on floodplain ecosystems is contradictory. On the one hand, it is floodplain meadows that can act as "traps" for toxicants transported along the channel, in which toxic sediments accumulate and accrue [15]. On the other hand, a high content of organics in the sediment can reduce the bioavailability of heavy metals [16]; in addition, in the presence of free ions (for example, when water bodies are acidified by emissions from copper smelting), metals are more actively sorbed by organic material [15]. Indeed, in most cases, high concentrations of metals in floodplain meadows do not affect the structural and functional parameters of plant communities and different groups of invertebrates [17, 18].

Objective—To study the response of the population of invertebrates to technogenic pollution of two types of primary meadows differing in the moisture regime. The following tasks have been set: (1) to investigate the state of the habitat of invertebrates (by analyzing the change in the phytomass of the main fractions of the grass stand of the considered meadows); (2) to study the change in the abundance of invertebrates (general, main trophic, and largest taxonomic groups); (3) to conduct a primary analysis of changes in the taxonomic structure of communities (at the level of abundance of all represented families). We are testing the hypothesis that in communities of floodplain meadows, the reaction to pollution is less pronounced than in steppe meadows.

MATERIALS AND METHODS

The study was performed in the area of the Karabash Copper Smelter (KCS, ZAO Karabashmed), located in the city of Karabash (South Ural, Chelyabinsk region) and being one of the largest sources of industrial pollution in Russia. The factory was launched in 1907, in 1989 production was stopped, and in 1998 resumed simultaneously with the start of modernization. The total mass of emissions into the atmosphere of KCS for the period 1907–2004 amounted to 14.3 million tons; at the peak of production in 1970–1980, emissions reached 210000–290000 tons/year. The main component of emissions is sulfur dioxide, among heavy metals Zn, Pb, Cu, and As prevail. To date, the level of emissions has been reduced to 5000 tons/year.

The KCS is located in the forested, least elevated (300–600 m a.s.l.) part of the low mountains of the Southern Urals, in the subzone of preforest-steppe pine–birch forests. The climate is temperate continental with an average January temperature of −12.5°C, July +19.4°C, and an average annual rainfall of 540 mm. In 2014, an average of 512 mm of precipitation fell, including 63 mm in June, 160.5 mm in July, and 17 mm in August; the average temperature in June was +16.4°C, in July +14.4°C, and in August +17.6°C.

The key sites are located in two directions from the KCS: northeast (NE) and south (S) on primary meadows 5000–20000 m^2 in size, formed in the floodplains of small rivers (Sak-Elga, Tyelga, and Bolshaya Talovka) and on elevated element reliefs (southern slope, up to 600 m a.s.l.). The sites are divided into three zones of pollution: impact (heavy pollution, 6 km NE and 4 km S from the KCS), buffer (light pollution, 14 km S), and background (pollution at the level of regional background, 30 km S). The choice of the NE direction is due to the absence of steppe areas in the impact zone to the south of the smelter. The boundaries of pollution zones were established on the basis of geobotanical descriptions and the determination of the content of heavy metals in the forest litter [19, 20]. The floristic composition of the meadow vegetation of all pollution zones is dominated by graminoids, grasses and sedges. The floodplain meadows of the background and buffer zones are dominated by *Carex caespitosa* L., in the impact zone it is replaced by *Deschampsia cespitosa* (L.) P. Beauv. In steppe meadows in all zones, *Stipa pennata* L dominates, in the impact zone, the dominants also include *Echinops ruthenicus* Rochel. In the steppe meadows of the impact zone, the vegetation is considerably sparse, and there are devegetated areas. All floodplain meadow areas were partially mowed at the end of June; the round of counts in August was confined to the unmowed part of the meadows. There was no grazing anywhere.

Grassland invertebrates were collected using a modified Konakov–Onisimova biocenometer (base area 0.25 m^2) and a portable vacuum suction sampler with an autonomous power source. Each sample is the result of a single installation of a biocenometer, followed by the collection of all invertebrates that have fallen into it with a vacuum suction sampler and cutting off all herbaceous plants at the soil level. The study was conducted in 2014 in two rounds of counts, timed to coincide with the second half of June (1st round) and August (2nd round). Sampling plots 25 × 25 m in size, three in each type of meadow, were located at a distance of about 100 m from each other and removed from the forest boundary. The design of the biocenometer [21], as well as the methodology and procedure for collecting samples [2], were described in detail earlier.

The sample size was 10 samples per sampling plot per round of registration. Thus, a total of 360 material samples were collected (10 samples × 3 sampling plots × 2 types of meadows × 3 zones of pollution × 2 rounds of counts) and more than 23,400 specimens of invertebrates. For plants, with an accuracy of 0.1 g, the total air-dry weight and the weight of two fractions, graminoids (cereals, sedges, and rushes) and herbs, were measured.

Under laboratory conditions, taxonomic affiliation (up to the level of families) and trophic specialization of invertebrates were established. In total, six trophic groups were considered: sucking herbivores, chewing herbivores, sucking predators, chewing predators, hemophages, and others (see Table S1).

All data processing was performed in the R software environment [22]. Within each type of meadow in each zone of pollution, the mean and standard error were calculated (2 rounds × 3 sampling plots; $n = 6$) for the total phytomass and its fractions, total abundance, abundance of the main trophic and largest taxonomic groups (Table 1), as well as the abundance of

Table 1. Abundance of invertebrates (ind./m^2) and plant phytomass (g/m^2) in the grass layer of the studied meadows

Trophic group/ Phytomass fraction	Pollution zone and meadow type					
	background		buffer		impact	
	steppe	floodplain	steppe	floodplain	steppe	floodplain
Invertebrates						
Total abundance	154.0 ± 17.12^a	293.47 ± 24.56^b	191.27 ± 24.16^a	203.13 ± 15.16^a	65.07 ± 6.36^a	215.33 ± 25.16^b
Sucking herbivores:	100.27 ± 16.20^a	177.73 ± 25.76^a	106.73 ± 15.12^a	125.93 ± 10.80^a	49.0 ± 5.92^a	150.47 ± 23.56^b
Cicadinea	44.60 ± 8.68^a	119.60 ± 22.40^b	71.20 ± 9.20^a	69.07 ± 6.40^a	34.13 ± 6.68^a	100.27 ± 21.88^b
Heteroptera phytophaga	11.40 ± 0.60^a	7.53 ± 1.60^a	5.73 ± 0.96^a	3.67 ± 1.36^a	3.0 ± 0.68^a	6.93 ± 3.28^a
Diptera Brachycera	39.33 ± 8.64^a	42.60 ± 4.36^a	24.20 ± 7.72^a	37.07 ± 5.92^a	7.53 ± 0.72^a	31.60 ± 3.80^b
Chewing herbivores :	13.0 ± 2.64^a	29.40 ± 2.04^a	32.80 ± 7.16^a	28.53 ± 1.52^a	3.73 ± 1.40^a	26.07 ± 6.16^a
Coleoptera phytophaga	1.40 ± 0.32^a	1.0 ± 0.24^a	1.07 ± 0.20^a	0.53 ± 0.20^a	0.27 ± 0.08^a	0.33 ± 0.12^a
Diptera Nematocera	9.47 ± 2.32^a	22.40 ± 1.84^a	28.33 ± 6.68^a	24.73 ± 2.36^a	3.13 ± 1.36^a	24.20 ± 6.20^b
Gastropoda	–	4.20 ± 1.0	–	2.40 ± 1.04	–	–
Sucking predators:	6.33 ± 1.60^a	26.20 ± 3.88^a	19.60 ± 3.92^a	16.13 ± 3.0^a	4.07 ± 0.92^a	17.80 ± 1.40^a
Heteroptera zoophaga	1.80 ± 0.84^a	4.07 ± 1.0^a	1.27 ± 0.32^a	0.47 ± 0.12^a	1.27 ± 0.28^a	0.20 ± 0.12^a
Aranei	4.53 ± 1.04^a	22.07 ± 3.60^b	18.33 ± 3.72^a	15.67 ± 3.0^a	2.47 ± 0.64^a	17.60 ± 1.48^b
Chewing predators:	1.27 ± 0.24^a	1.33 ± 0.60^a	1.60 ± 0.48^a	0.20 ± 0.12^a	0.40 ± 0.24^a	0.47 ± 0.20^a
Coleoptera zoophaga	1.13 ± 0.20^a	0.73 ± 0.36^a	1.40 ± 0.36^a	0.20 ± 0.12^a	0.33 ± 0.24^a	0.47 ± 0.20^a
Opiliones	–	0.20 ± 0.12	–	–	–	–
hemophagus	12.13 ± 6.32^a	35.30 ± 14.3^b	11.0 ± 3.20^a	19.27 ± 4.20^a	0.27 ± 0.08^a	9.47 ± 2.04^a
Other groups	21.0 ± 4.04^a	23.50 ± 3.40^a	19.53 ± 4.88^a	13.07 ± 0.48^a	7.60 ± 0.56^a	11.07 ± 1.16^a
Herbaceous plants						
Total phytomass	60.81 ± 6.83^a	94.75 ± 5.83^b	58.33 ± 7.06^a	96.55 ± 9.95^b	37.79 ± 4.64^a	87.76 ± 24.53^b
Graminoids	22.52 ± 3.20^a	55.26 ± 11.95^b	21.27 ± 3.53^a	59.44 ± 12.83^b	18.65 ± 3.34^a	81.76 ± 25.57^b
Herbs	38.28 ± 4.13^a	39.49 ± 7.39^a	37.07 ± 4.43^a	37.11 ± 4.86^a	19.13 ± 2.29^a	6.0 ± 2.33^b
Share of graminoids, %	37.23 ± 3.18^a	45.27 ± 8.25^b	35.81 ± 3.36^a	45.28 ± 8.0^b	53.37 ± 4.39^a	85.04 ± 4.61^b

The accounting unit is the sampling plot. The mean ± standard error for a sample of 3 sampling plots × 2 rounds of surveys is given (n = 6). A dash means absence of group. Letter superscripts are the results of multiple comparisons; identical letters mean no differences between steppe and floodplain meadows for the group under consideration within the pollution zone.

all identified families (see Table S1). For the total phytomass and total abundance of invertebrates, an analysis was made of the influence of the factors "pollution zone," "meadow type," and "count round" based on generalized linear models (glm) in the car package [23]. For each pair of factors "pollution zone" and "meadow type," an analysis of the effect on phytomass (total and fractions) and abundance (total, trophic, and large taxonomic groups) was performed based on generalized linear models with mixed effects (glmer): fixed factors – zone of pollution and type of meadow, random factor – sampling plot; the LMERConvenienceFunctions package [24] was used. Based on the results, multiple comparisons were implemented using the Tukey test in the multcomp package [25]. For phytomass (total and fractions) and abundance (total, trophic, and large taxonomic groups), the size of the effect of technogenic pollution in the buffer and impact zones relative to the background was calculated. The natural logarithm of the ratio of responses is used in the version of the unbiased estimate proposed for small samples and values close to zero (LRR$^\Delta$) in the SingleCaseES package [26].

The standardized drought index (SPEI) was calculated in the SPEI package [27] for a set of values of mean monthly air temperature and total monthly precipitation from January 1936 to December 2015 according to the weather station in Chelyabinsk (WMO ID 28630, [28]), the results are visualized in the ggplot2 package [29]. The SPEI is designed to take into account the ratio of precipitation and potential evapotranspiration in any area on a global scale; the index values can be substantially refined using data

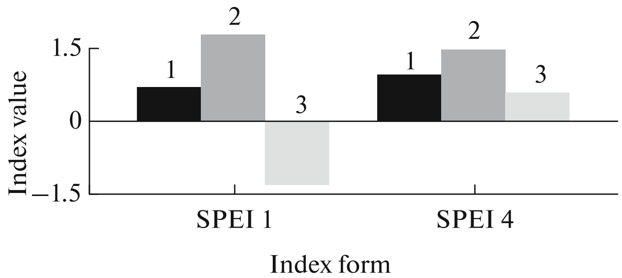

Fig. 1. SPEI index in 2014: SPEI 1 - calculated for each of the summer months: (*1*) June, (*2*) July, (*3*) August; SPEI 4 — total for four months (specified and three previous). SPEI values above 1.5 correspond to excessive moisture, below 1.5, to drought.

from local meteorological observations over a fairly long period (30–50 years or more). The index makes it possible to estimate the moistening conditions in the period of interest (up to a month) in relation to the long-term average; SPEI values above 1.5 correspond to excessive moisture; values below 1.5 correspond to drought.

To analyze the taxonomic structure of invertebrate communities (at the level of a list of all identified families with abundance values), a dendrogram was constructed in the pvclust package [30] using the Ward method based on the Bray–Curtis dissimilarity index matrix. The reliability of the calculation of support numbers (AU) was determined using a permutation test (100,000 permutations).

RESULTS

The calculation of the SPEI showed that July 2014 was somewhat waterlogged in relation to the long-term average, however, the total amount of precipitation for the spring and summer periods did not go beyond the almost 80-year norm (Fig. 1).

Reaction of Meadow Herbage to Pollution

The total phytomass of the meadow vegetation differs in meadows of different types ($p < 0.001$), in different pollution zones ($p = 0.048$), and between count rounds ($p = 0.009$). The interaction of the factors "meadow type" and "zone" is insignificant ($p = 0.529$); other interactions are significant. The total grass stand phytomass in floodplain meadows is higher than in steppe meadows: in the background and buffer zones, by 1.6–1.7 times; in the impact zone, by 2.3 times. In the pollution gradient, the total phytomass is similar within the meadows of the same type, although it tends to decrease in the impact zone on steppe meadows (Tables 1 and 2).

The phytomass of graminoids in floodplain meadows is also higher than in steppe meadows: 2.5–2.8 times higher in the background and buffer zones and 4.4 times higher in the impact zone. In the pollution gradient within the meadows of the same type, the phytomass of graminoids is similar, although it shows a clear tendency to increase in floodplain meadows (Tables 1 and 2).

The phytomass of herbs in the background and buffer zones is similar in meadows of different types, in the impact zone it is higher in steppe meadows (3.2 times). In the pollution gradient, the phytomass of herbs changes in the same way in floodplain and steppe meadows: in the background and buffer zones it is similar, in the impact zone, it is reduced (by 6.6 and 2.0 times, respectively, see Tables 1 and 2).

The proportion of graminoids in the total phytomass in all zones in floodplain meadows is higher than in steppe meadows: in the background and buffer, by 1.2–1.3 times; in the impact zone, by 1.6 times. As the smelter approaches, the proportion of graminoids changes in the same way in floodplain and steppe meadows: similar in the background and buffer zones, and increased in the impact zone (by 1.9 and 1.4 times, respectively, see Tables 1 and 2).

The effect of technogenic pollution in the buffer zone is absent both for the total phytomass and for the phytomass of the fractions (Fig. 2). In the impact zone, a negative effect was found for the total phytomass in the steppe meadow and for the phytomass of herbs in the meadows of both types.

Response of Invertebrates to Pollution

The total abundance of invertebrates varies in different types of meadows ($p < 0.001$), in different pollution zones ($p < 0.001$), but is not affected by the reporting round ($p = 0.187$). At the same time, all variants of the interaction of these factors affect the abundance significantly ($p < 0.001$). In floodplain meadows, the total abundance is generally higher than in steppe meadows: in the background zone, by 1.9 times; in the impact zone, by 3.3 times; in the buffer zone, the abundance does not differ, both in general and for all groups. As one approaches the pollution source, the total abundance decreases both in floodplain meadows (by 1.4 times, similar in the buffer and impact zones) and in steppe meadows (2.9 times in the impact zone, similar in the background and buffer zones) (Tables 1 and 2). The effect of pollution at the level of total abundance was negative, except for steppe meadows in the buffer zone, where an insignificant positive trend was noted (Fig. 3).

Abundance of trophic and large taxonomic groups. The high abundance in floodplain meadows in the background zone is due to cicadas (2.7 times higher than in steppe meadows), spiders (4.9 times), and a group of hemophages (2.9 times). In the impact zone, on floodplain meadows, sucking herbivores are abundant (the abundance is 3.1 times higher than on steppe meadows), and they include cicadas (2.9 times higher)

Table 2. Results of multiple comparisons for the abundance of groups of invertebrates in the grass layer and phytomass of fractions of herbaceous vegetation between pollution zones within the same type of meadows

Trophic group/ Phytomass fraction	Pairs of pollution zones and meadow type					
	background - buffer		buffer - impact		background - impact	
	steppe	floodplain	steppe	floodplain	steppe	floodplain
Invertebrates						
Total abundance	0.134	<0.001	<0.001	0.977	<0.001	<0.001
Sucking herbivores:	1.0	0.452	0.062	0.945	0.116	0.940
Cicadinea	0.031	<0.001	<0.001	0.039	0.695	0.594
Heteroptera phytophaga	0.561	0.730	0.872	0.828	0.114	1.0
Diptera Brachycera	0.184	0.973	0.008	0.964	<0.001	0.614
Chewing herbivores:	0.493	1.0	0.132	1.0	0.771	1.0
Coleoptera phytophaga	1.0	0.997	0.968	1.0	0.926	0.984
Diptera Nematocera	0.004	0.998	<0.001	1.0	0.281	0.999
Gastropoda	–	0.942	–	–	–	–
Sucking predators:	0.485	0.880	0.306	1.0	0.996	0.945
Heteroptera zoophaga	0.999	0.492	1.0	0.999	0.999	0.563
Aranei	0.012	0.786	0.004	0.998	0.929	0.950
Chewing predators:	1.0	0.982	0.983	1.0	0.993	0.994
Coleoptera zoophaga	1.0	0.988	0.939	0.999	0.972	1.0
Hemophages	1.0	0.076	0.157	0.209	0.136	<0.001
Other groups	1.0	0.293	0.072	0.996	0.037	0.114
Herbaceous plants						
Total phytomass	1.0	1.0	0.108	0.968	0.054	0.988
Graminoids	1.0	0.997	0.996	0.188	0.976	0.061
Herbs	1.0	0.999	0.043	<0.001	0.027	<0.001
Proportion of graminoids	1.0	0.995	0.018	<0.001	0.034	<0.001

Significance levels are given (p) for a sample of 3 sampling plots × 2 survey rounds ($n = 6$). A dash means absence of group.

and phytophagous Diptera Brachycera (4.2 times); and, in addition, phytophagous Diptera Nematocera (by 7.7 times) and spiders (by 7.1 times) (Tables 1 and 2). As we approach the smelter, the abundance of the considered groups demonstrates different trends in different types of meadows. In floodplain meadows, the abundance of cicadas first decreases (by 1.7 times in the buffer zone), and then, in the impact zone, increases to background values. On the steppe meadows, the abundance of cicadas in the buffer zone, on the contrary, increases 1.6 times, while in the impact zone it decreases to the background level. The abundance of phytophagous Diptera Brachycera in floodplain meadows was similar throughout the pollution gradient, in steppe meadows it was similar in the background and buffer zones, and in the impact one it was reduced by 5.2 times. The abundance of phytophagous Diptera Nematocera in floodplain meadows was also similar in all zones, while on steppe meadows it increased by 3.0 times in the buffer zone, and decreased by 3.0 times in the impact zone. A similar trend was noted in spiders (abundance in steppe meadows in the buffer zone increased by 4.0 times, in the impact zone it decreased by 1.8 times).

The effect of pollution for most of the considered trophic and taxonomic groups was absent or was negative (see Fig. 3). A positive effect was noted only in the steppe meadows of the buffer zone for chewing herbivores (and belonging to the group of phytophagous Diptera Nematocera) and sucking predators (and spiders); there was an insignificant positive trend for cicadas.

Taxonomic structure of invertebrates. When analyzing the taxonomic structure, the differences between the types of meadows were greater than between the pollution zones. In the floodplain meadows, the communities of the background and buffer zones were similar, but differed from the communities of the impact zone. In the steppe meadows, the communities of the buffer and impact zones were more similar, but differed from the communities of the background (Fig. 4).

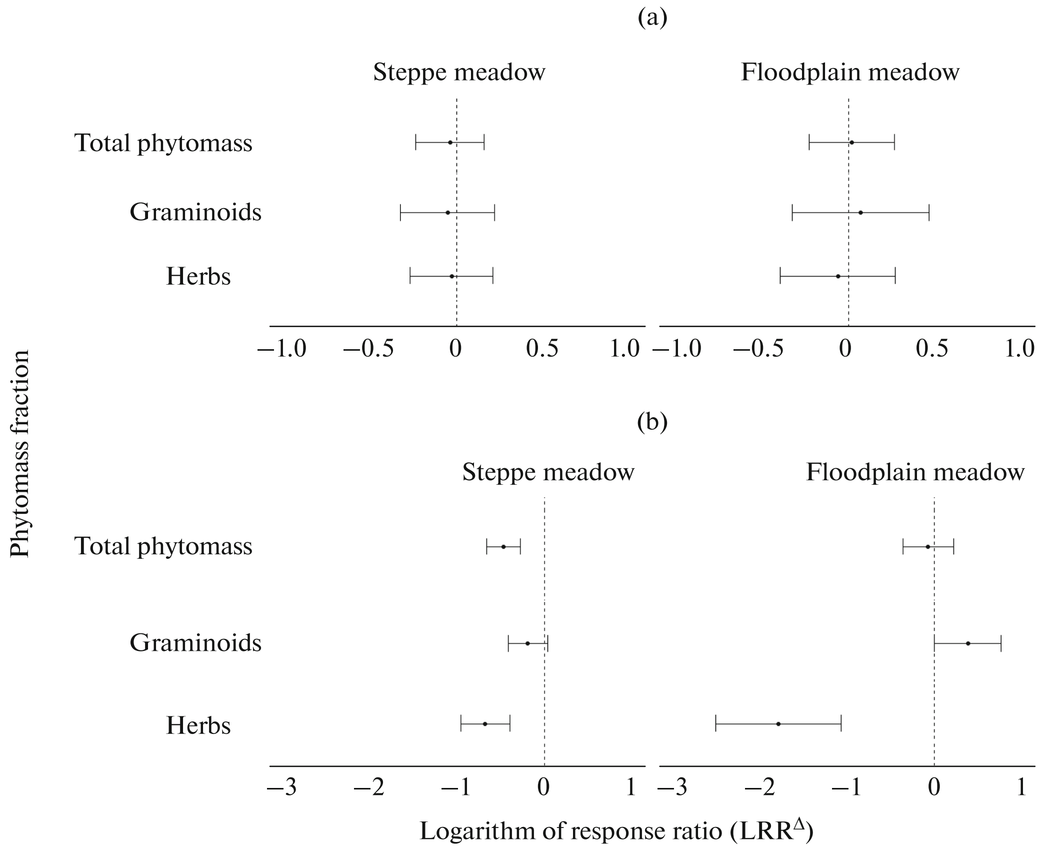

Fig. 2. The size of the effect of technogenic pollution for grass stand on steppe and floodplain meadows in the buffer (a) and impact (b) zones of pollution. Horizontal lines are the boundaries of the confidence interval.

DISCUSSION

Analysis of the SPEI did not reveal pronounced weather fluctuations for the territory under consideration in 2014. This allows us to regard the obtained data as "typical" when describing the state of meadow communities.

The total herbage phytomass in the pollution gradient in the meadows of both types changes similarly, as evidenced by the absence of a significant interaction between the factors "meadow type" and "pollution zone." Indeed, the total phytomass and graminoids phytomass are similar in all KCS pollution zones; the phytomass of herbs near the smelter is reduced, while the proportion of graminoids in the total phytomass, on the contrary, is increased. At the same time, in the impact zone on steppe meadows, a negative effect of pollution on the total phytomass is expressed, and on the floodplain, there is a tendency to an increase in the phytomass of graminoids.

In the dynamics of the total abundance of invertebrates in the grass stand, there is no single pronounced trend (all interactions of the factors "zone," "round," and "meadow type" are significant). Nevertheless, as we approach the KCS, the total abundance decreases: in floodplain meadows it is already in the buffer zone, and in steppe meadows it is only in the impact zone. In the buffer zone on steppe meadows, the abundance of a number of trophic (chewing herbivores and sucking predators) and taxonomic (cicadas, phytophagous Diptera Nematocera, and spiders) groups increases, isolated cases of a positive effect of pollution. Changes in the taxonomic structure in floodplain meadows were noted only in the impact zone, while in steppe meadows, already in the buffer zone.

Alterations in phytocenoses are generally typical of machined sources of pollution. According to the results of a meta-analysis of published data, the overall effect of point sources of pollution on the phytomass of vascular plants is negative, but varies depending on the vegetation layer and source type. Enterprises, whose activities lead to soil acidification of surrounding ecosystems, have the greatest negative effect on the grass layer due to the impact on herbaceous plants [31]. In the zone of action of the MUCS, which is a relatively close geographically and well-studied source of pollution of a similar type, the situation is somewhat different in the secondary upland meadows. A decrease in the phytomass of herbs and an increase in the proportion of graminoids was also noted, but at the same time, a decrease in the total phytomass and an increase in the phytomass of graminoids [2, 4]. How-

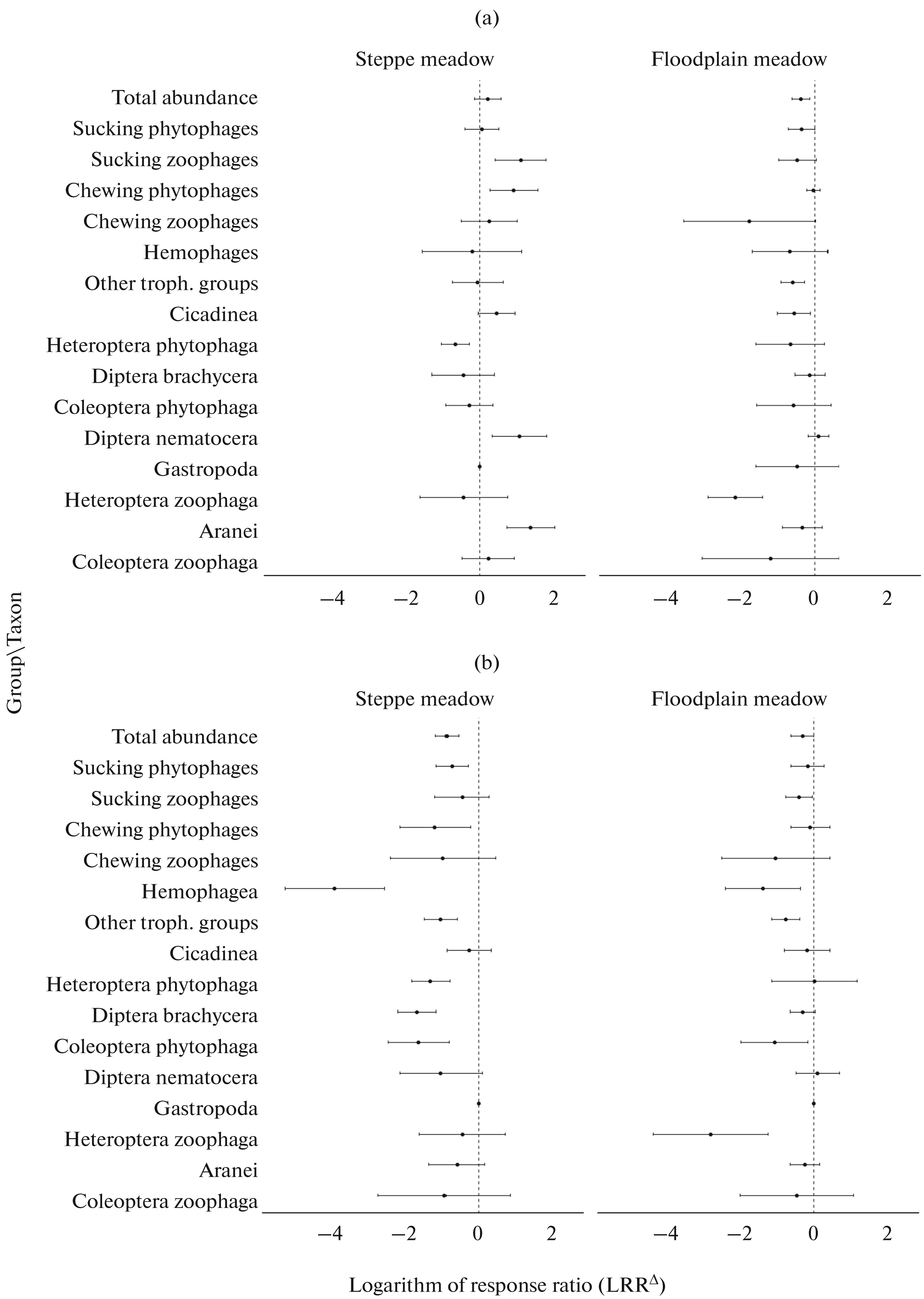

Fig. 3. The size of the effect of technogenic pollution for the total abundance, trophic, and taxonomic groups of invertebrates in the grass stand on the steppe and floodplain meadows in the buffer (a) and impact (b) zones of pollution. Horizontal lines are the boundaries of the confidence interval.

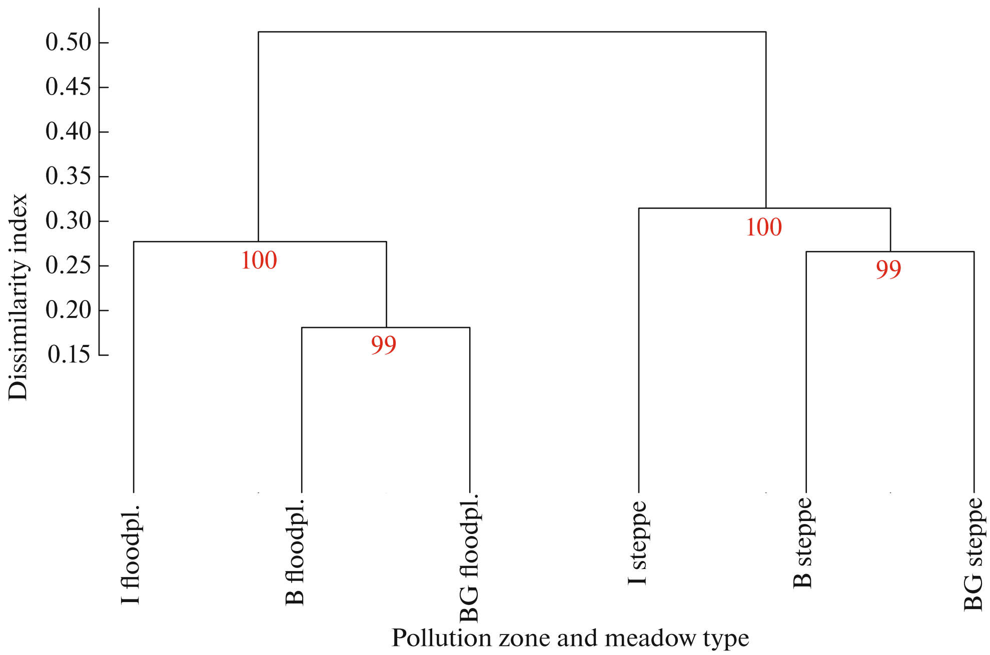

Fig. 4. Dissimilarity (Bray–Curtis index) of the taxonomic structure of grass layer invertebrates in the background (BG), buffer (B), and impact (I) pollution zones on the steppe (steppe) and floodplain (floodplain) meadows. The numbers at the bases of the dendrogram branches are relatively unbiased support numbers (AU, %). Clusters with AU ≥ 95% are considered statistically significant.

ever, earlier, at the period of high emissions of MUCS, the meadow phytomass near the smelter, on the contrary, was doubled due to graminoids [32]. Thus, the reaction of the total phytomass can be related to the current level of activity of the pollution source and, therefore, is not very informative. The reaction of graminoids is much more stable, the phytomass of which increases (against the background of a decrease in the total phytomass) also in the grass layer in the composition of forest ecosystems near the MUCS [33]. The dominance of graminoids was noted for meadow ecosystems near a copper smelter in England [34].

The trends described for grassland invertebrates in the KCS area differ from the results of a meta-analysis [35], according to which the total abundance of terrestrial invertebrates of different vegetation layers (but not soil dwellers) is increased near point sources that acidify the soils of surrounding ecosystems. The increase in abundance occurs due to both sucking (Hemiptera) and chewing (Lepidoptera) herbivores. The abundance of predators (including spiders) has been reduced; Diptera do not show a pronounced tendency [35]. In the meadow grass stand in the MUCS area, the total abundance near the smelter is also increased due to sucking herbivores (primarily cicadas). The abundance of all other taxa in the impact zone is reduced. However, in the buffer zone, chewing herbivores (as well as phytophagous Diptera Nematocera) and sucking predators (as well as spiders) demonstrate a relatively high abundance [2–4, 32], which is similar to the situation in the KCS. Data for other meadow communities under conditions of pollution of a similar type are not known to us. The population of forest ecosystems in the impact zone of the MUCS, as a rule, is in a depressed state. In the soil macrofauna of spruce–fir forests, the abundance and species richness sharply decrease with approach to the smelter [36, 37]. A decrease in abundance was also noted for communities of necrobionts [38], and abundance and species richness were noted for herpetobionts: ground beetles [39] and arachnids [40]. The trophic activity of birch phyllophages is reduced near the MUCS [41].

Thus, the specificity of changes in invertebrate communities of the grass stand in the gradient of KCS pollution consists mainly in the absence of an increase in the abundance of cicadas (and, consequently, the total abundance) in the impact zone. It is known that the structure of terrestrial invertebrate communities is determined by the composition and structure of plant associations [6, 42, 43]. At the same time, the toxic effect on plant diversity is more than 2–3 times higher than that for invertebrates [35]. Apparently, under the influence of pollution, sensitive plant species are eliminated, while resistant ones increase their phytomass. The latter include graminoids, which often predominate in the impact zones of metallurgical enterprises [4, 33, 34] and intensify growth under the influence of pollution [33, 44]. Some graminoids (for example, *Agrostis capillaris* L. and *Deschampsia cespitosa*) are pseudometallophytes that have the genetic potential to form metal-tolerant populations [45]. As a result, under polluted conditions, sucking oligophages (cicadas and hemipterans), which are trophically associated with pseudometallophyte graminoids capable of retaining metals at the level of the root barrier, gain an advantage [46]. The reasons for the absence of an increase in the abundance of cicadas in the KCS impact zone are currently unclear. Presumably, this is due to the absence of a significant increase in the phytomass of graminoids. One can also point to a relatively low proportion of graminoids in the grass stand of meadows in the impact zone of the KCS (53–85%; MUCS: 94–100%). In addition, the low abundance of cicadas may be the result of fluctuations that are taken into account only in long-term studies.

A comparison of the two types of meadows in the KCS pollution gradient demonstrates the general similarity of their response, although there are a number of features. For phytocenoses, this is the proportion of graminoids, which is higher in floodplain meadows in all zones and increases more pronouncedly on approaching the smelter. Also, in floodplain meadows in the impact zone, the phytomass of herbs is significantly lower than in steppe meadows. It can be assumed that the high primary productivity characteristic of floodplain ecosystems [47] under conditions of pollution allows a stronger increase in the phytomass of metal-tolerant species that have received the resources of eliminated species. In steppe meadows, a high proportion of forbs in the impact zone (almost 50%) may indicate the replacement of sensitive species by metal-tolerant representatives of herbs, rather than graminoids. In some cases, resistance to heavy metals has been described for non-graminoid plants, which can provide a competitive advantage under conditions of moisture deficiency [48].

For communities of invertebrates, a high abundance of spiders and phytophagous Diptera Nematocera in a steppe meadow in the buffer zone can be indicated as features. The curves of changes in the abundance of these groups in the KCS pollution gradient have a dome shape, which is relatively rarely described by researchers [35]. However, in the absence of long-term data, it is impossible to judge the reliability of the observed reaction. Note that both of these groups are also relatively abundant in the buffer zone of the MUCS, and this is presumably due to feeding habits [2, 4]. In phytophagous Diptera Nematocera, the mouthparts are of a chewing type, which provides an increased intake of metals compared to sucking herbivores [49]. Spiders have sucking mouthparts to avoid integument, in which some metals accumulate [50], but the total intake of toxicants in predators may be higher [51]. As a result, the groups under consideration are often numerous in the buffer zone, where, compared to the impact zone, pollution is reduced and the diversity of food resources (plants and potential prey) is increased, and, compared to the background zone, the pressure of predators and competitors is reduced (due to a general decrease in diversity).

It should be noted that the abundance of invertebrates is a rather variable parameter of the community structure, and its reliable assessment requires a comparison of long-term data. In view of this, in this study, priority should be given to a more conservative parameter, the taxonomic structure. Its preliminary analysis in the KCS impact zone showed a greater impact of pollution on the population of steppe meadows compared to floodplain ones.

CONCLUSIONS

Based on the material of 2014, the reaction of communities of floodplain and steppe meadows to emissions from the KCS was studied. While approaching the KCS, negative changes were noted in the meadow communities of both types. In phytocenoses, the phytomass of herbs decreases and the proportion of graminoids increases. In invertebrate communities, the total abundance decreases, although the abundance does not change in trophic and most large taxonomic groups. The main specificity of the changes in meadow ecosystems in the impact zone of the KCS is the absence of an increase in the phytomass of graminoids and the abundance of cicadas (and, consequently, the total abundance).

A comparison of the two types of meadows revealed certain differences in their response to pollution. In floodplain meadows, the proportion of graminoids in all zones is higher and increases more strongly when approaching the source of pollution; changes in the taxonomic structure of invertebrates occur only in the impact zone. Steppe meadows in the impact zone retain a high proportion of herbs; changes in the taxonomic structure of invertebrates have already been noted in the buffer zone. The data partially confirm the hypothesis that the response to pollution in floodplain meadow communities is less pronounced than in steppe meadows.

It should be noted that the work presents preliminary data, and to confirm the conclusions drawn, a generalization of many years of material is required. Nevertheless, the absence of pronounced weather fluctuations in the year under consideration allows us to hope for their relative reliability, and the lack of published factual data on the subject under consideration makes the work relevant.

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The collection and analysis of invertebrates were carried out with the approval of the Bioethics Commission of the Institute of Plant and Animal Ecology, Ural Branch, Russian Academy of Sciences (Protocol No. 13, dated November 1, 2022).

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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