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Changes in the Diversity of the Herb-Shrub Layer of Pine Forests Caused by Severe Pollution and Fire Disturbances in the Southern Urals

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Abstract—We assumed that the state of the herb-shrub layer of forest communities near a large enterprise in the Southern Urals is determined not only by technogenic impact, but also by fire disturbances. The purpose of this study is to assess the diversity of the herb-shrub layer in forests polluted by the Karabash copper smelter emissions with different time passed since the last fire. We analyzed 77 geobotanical descriptions performed in polluted and unpolluted pine forests, in both versions with different time passed since the last fire (from 1 year to burned long ago or probably unburned). Diversity was assessed using: traditional diversity measures that do not take into account species heterogeneity; functional diversity parameters; and estimation of the Grime's strategy type importance ratios. We have found that technogenic pollution is the main factor affecting the herb-shrub layer diversity. As the level of technogenic pollution increased, all diversity indicators decreased, the contribution of species with C- and S-strategy components to community formation increased, and the contribution of species with R-strategy component decreased. The effects of fire disturbance on the herb-shrub layer diversity have not been confirmed. Correlation of technogenic and pyrogenic impacts has not been found.

Keywords: plant community diversity, functional diversity, Grime's environmental strategies, pine forests, technogenic pollution, heavy metals, ground forest fires

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INTRODUCTION

The main plant diversity in temperate forests is represented by species of the herb-shrub layer, the state of which can indicate ecosystem processes and external effects. Among the different causes of herb-shrub layer dynamics, we were interested in technogenic pollution and periodic forest fires. Due to the Southern Urals specifics, the suboptimal conditions for forest vegetation in the zonal forest-steppe ecotone, combined with intensive industrial development of the territory, cause increased vulnerability of forests to climate change. The region near the town of Karabash is a geographically extensive impact zone with contrasting ecosystems, formed under the influence of emissions from a large copper smelter operating for more than 100 years (Kozlov et al., 2009). Another factor contributing to the state of the region's vegetation is periodic forest fires (Chibilev et al., 2016; Veselkin et al., 2022b). We assumed that the state of forest communities in this region is determined not only by technogenic impact, but also by regular fire disturbances.

According to (Zvereva et al., 2007), as pollution increases, the species richness of vascular plant communities generally decreases, but the effects are not uniform across studies. More recent papers also describe a decrease in forest plant diversity influenced by industrial emissions (Chernenkova et al., 2011; Chernenkova, 2014; Trubina et al., 2014; Chashchina et al., 2017). Thus, the trends of changes in the diversity of plant communities under technogenic impacts, in general, are well studied and predictable.

Forest fires are a constant and important factor in forest dynamics. Globally, plant species richness is positively associated with the number of fires (Pausas and Ribeiro, 2017). At the landscape scale, fires cause mosaic habitats (Robertson et al., 2019; Geraskina et al., 2021). The effects of fire on community diversity are highly dependent on the fire intensity (Richter et al., 2019; Strand et al., 2019; Geraskina et al., 2021). Although plant community diversity is reported to decrease after fires (Kovaleva and Ivanova, 2013; Makarov et al., 2019; Richter et al., 2019; Geraskina et al., 2021), probably their effects are not so unambiguous. For example, a decrease in plant richness was not found when estimating the long-term effects of fires in mixed forests of North America (Strand et al., 2019) and in mildly-damaged forests of the Urals (Braslavskaya et al., 2022). After controlled fires, vascular plant species richness increases on average, while it does not change in coniferous forests (Eales et al., 2018). Thus, the effects of fires on the plant community diversity are not always negative.

The correlation of technogenic pollution and fires with plant diversity has in fact only been discussed in a reconnaissance format (Chashchina et al., 2017). Other known cases of considering or comparing both fire and pollution effects are related to lichens (Gorshkov, 1994) and undergrowth of woody plants (Menshchikov et al., 2013).

The purpose of this study is to assess the diversity of the herb-shrub layer in forests polluted by emissions from a copper smelter with different time passed since the last fire. We tested three hypotheses: (1) community diversity decreases in polluted forests; (2) community diversity declines in forests disturbed by recent fires; (3) the effects of pollution and fires are additive, i.e. there is a correlation between the effects of pollution and fires.

MATERIALS AND METHODS

Area. The study area is located in the subzone of southern taiga pine-birch forests of the eastern macroslope of the Southern Urals (Chelyabinsk Region; the vicinity of the town of Karabash and the Ilmen State Reserve UB RAS, ISR). The typical heights of the uplands are 250–600 m a.s.l. Gray forest and sod-taiga acidic soils predominate. According to the Köppen–Geiger classification (Beck et al., 2018), the climate is cold with short warm summers (code—Dfb). The growing season is 160–170 days; precipitation is about 430 mm per year; snow cover height is up to 40 cm. The predominant vegetation types are forb pine forests and secondary grass-forb birch forests.

The ISR area is 30.4 thousand ha. The average age of the main generation trees in coniferous forests is 80–180 years. On average, 14–16 forest fires are registered in the territory of the ISR per year. The complete fire cycle for the entire reserve is 360 years (Dubinin et al., 2007). Between 1948 and 2014, the number of fires increased (Chibilev et al., 2016) and fire localizations changed (Veselkin et al., 2022b).

The Karabash copper smelter (KCS, Karabashmed JSC, Karabash) is a major source of emissions, the main of which are SO_2 and dust containing mainly Cu, Zn, Pb, Cd. The zone of disturbed ecosystems extends up to 15–25 km from the KCS (Kozlov et al., 2009; Koroteeva et al., 2015a, 2015b). Chemical pollution of ecosystems results in a decrease in phytomass and forest productivity (Usoltsev et al., 2012), a decrease in microbial diversity and biomass in soils (Mikryukov et al., 2015; Mikryukov and Dulya, 2017), changes in the conditions of mineral nutrition of plants (Chashchina et al., 2018; Veselkin et al., 2019; Veselkin et al., 2022a).

Sample plots (SP). We studied 77 SP in maturing, mature and overmature natural pine forests on the middle and lower parts of slopes on gray forest and sod-taiga acidic soils in the absence of waterlogging. Forty-one plots were located at distances of 3.5–12 km from the KCS (impact zone); thirty-six areas were located 25–50 km south of the KCS in the ISR forests (Fig. 1). Based on when the last fire took place, the SP were classified into two groups: “burned recently” (the last fire was from 1 to 15 years ago) and “burned long ago” (the last fire was more than 15 years ago; this also included SP with no signs of recent fires and no information on fires). Years of fires were established from the Forest Fire Record Books of the forest districts. The SP with ground stable medium-sized fires were considered burned; areas with crown fires were not considered. Within the ISR territory, 12 SP burned recently and 24 SP burned long ago. Near the KCS, 17 SP burned recently and 24 SP burned long ago.

Characteristics of plant species and plant communities. Geobotanical descriptions were performed on a 100 m^2 area in July and the first half of August: 2017—24 SP; 2018—33 SP; 2019—18 SP; 2021—2 SP. The number of herb-shrub species, total projective cover (%) of the aerial portions and projective cover (%) of each species were determined. The total cover of epigeic mosses on the SP was determined separately (%). Names of vascular plants are given according to Plants of the World Online (https://powo.science.kew.org/). The Shannon diversity, Berger-Parker dominance and Pielou’s evenness indices were calculated.

The Grime’s environmental strategies were determined by Pladias—Database of the Czech Flora and Vegetation (www.pladias.cz). Numerical representation of strategy coordinates was used to calculate the weighted average participation of plants of different strategies—the CSR coordinates of communities (Hunt et al., 2004). Strategy coordinates: C—competitors (1; 0; 0); S—stress tolerators (0; 1; 0); R—ruderals (0; 0; 1); CR (0.5; 0; 0.5); SC (0.5; 0.5; 0); SR (0; 0.5; 0.5); CSR (0.33; 0.33; 0.33). The CSR coordinates of communities or weighted average participation of plants of different strategies were calculated using estimates of the projective cover of species as weights (formula (1)):

$$D = \left(\sum P_i L_i\right) \Big/ \sum P_i, \quad (1)$$

where P_i—projective cover of the ith type; L_i—numerical characteristic of coordinates of the ith type in the Grime’s triangle along one of the C-, S- and R-axes; D—obtained coordinate value along each of the axes. When calculating the CSR coordinates of communities, species having undetermined environmental strategy type were not taken into account. Thus, the sum of C, S, and R coordinates was equal to 1 for each description.

Using the FDiversity program (Casanoves et al., 2011), we calculated the characteristics of community functional diversity—FAD and Rao. The FAD index—functional attribute diversity—is the number of different attribute combinations in a community; it is always less than or equal to species richness (Casanoves et al., 2008). Types of environmental strategies were used as attributes. The Rao diversity index quantifies how species functionally differ in a community and is calculated using the formula (2):

$$\text{Rao index} = \sum_{i=1}^{S-1} \sum_{j=i+1}^{S} d_{ij} p_i p_j, \tag{2}$$

where S—number of species, d_{ij}—difference between species i and j, p_i and p_j—proportions of the ith and jth species. Since the attributes we used were categorical, d_{ij} was calculated using formula (3):

$$d_{ij} = u_{ij} / n, \tag{3}$$

where u_{ij}—number of attributes with different values in species i and j, n—total number of attributes considered (Botta-Dukát, 2005).

Determination of technogenic impact. Concentrations of Cu, Zn, Pb and Cd were measured in samples from the forest litter OF horizon. On each SP, sampling was carried out on three plots at a distance of 5–6 m from each other. Samples were taken using the envelope method from an area of 1 m^2. One mixed sample was formed from the material collected from three plots. Decomposition with a mixture of concentrated nitric acid and hydrogen peroxide was used. This is how almost all forms of metals are determined (pseudo total concentrations). Concentrations of elements were determined on a VARIAN-720-ES atomic emission spectrometer (ICP-OES method). Measurements were carried out at the South Ural Collective Center for the Study of Mineral Raw Materials of the Institute of Mineralogy of the Ural Branch of the Russian Academy of Sciences (accreditation certificate no. AAS.A.00330, valid to November 3, 2026). The pollution index (formula (4)), characterizing the average excess (arbitrary units—number of times) of Cu, Zn, Pb, Cd concentrations compared to the least polluted area (Vorobeichik et al., 1994), was calculated as follows:

$$\text{Pollution index} = 1/4 \sum C_i / C_{\min}, \tag{4}$$

where C_i and $C_{\min}$—concentrations of one of the four metals (Cu, Zn, Pb, or Cd) in the litter on a sample plot (C_i) and minimal in the entire studied range ($C_{\min}$). The litter pollution index shows how many times the measured four metals are greater compared to the least polluted plot. The decimal logarithm (Log10) of the pollution index was used.

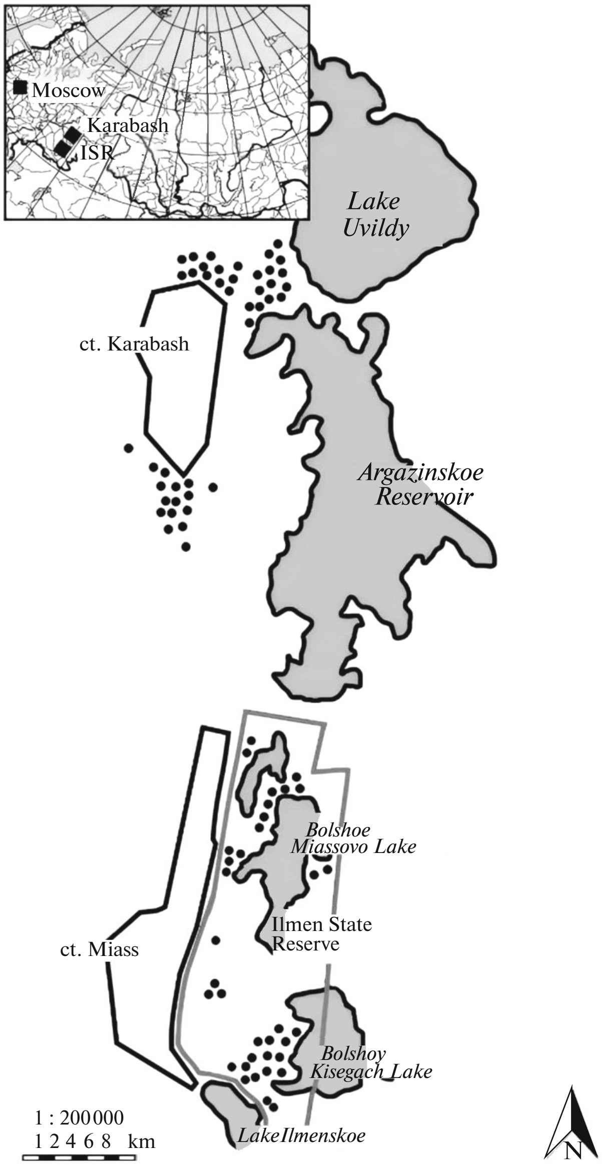

Fig. 1. Area and location of sample plots (●).

Data analysis. We used General linear models (GLM). Pollution level (the decimal logarithm of the pollution index) was considered as a continuous predictor. The time passed since the last fire was characterized in two ways: (1) using a quantitative representation by the number of full years from the last fire to the description; (2) combining communities into two groups—“burned recently” and “burned long ago”. The statistical unit was the sample plot. One of the GLM variants was one-factor analysis of variance (ANOVA) using the Tukey’s test for pairwise comparisons of average values. The arithmetic average was used as a characteristic of the central tendency; the ± symbol represents the error of the arithmetic average.

Table 1. GLM results explaining variation in herb-shrub layer structure and diversity characteristics

Characteristic	Two-factor GLM with factors "pollution" and "time since the last fire" [1]				R^2_{adj} in one-factor GLM; factor "pollution"
	factors significance levels (*P*)			R^2_{adj}	
	pollution [1]	time since the last fire [2]	[1] × [2]		
Epigean moss cover	<0.0001	0.0356	0.0075	0.50	0.44
Parameters of the herb-shrub layer					
general projective cover	<0.0001	0.8046	0.5774	0.58	0.59
number of species per 100 m^2	<0.0001	0.8880	0.8456	0.56	0.58
Shannon index	<0.0001	0.6406	0.6767	0.60	0.61
Berger-Parker index	<0.0001	0.8036	0.5287	0.31	0.33
Pielou evenness index	0.0002	0.8302	0.9436	0.14	0.16
Functional diversity of the herb-shrub layer					
FAD	0.0008	0.5453	0.9807	0.12	0.14
Rao	<0.0001	0.8196	0.5465	0.26	0.28
Weighted average participation of species of different strategies in the formation of the herb-shrub layer					
C	0.0074	0.8760	0.7320	0.06	0.09
S	0.0150	0.5226	0.2219	0.06	0.06
R	<0.0001	0.0725	0.6195	0.65	0.64

The characteristic "time since the last fire" is used in quantitative form.

RESULTS

The studied communities in the ISR are represented mainly by pine forb-grass, broad-grass, green moss, green moss-lingonberry forests. Steppe shrubs *Chamaecytisus ruthenicus*, *Cotoneaster laxiflorus* and meadow-steppe grasses *Achillea millefolium*, *Artemisia latifolia*, *Euphorbia subtilis*, *Filipendula vulgaris*, *Asperula tinctoria*, *Hieracium umbellatum*, *Origanum vulgare*, *Potentilla erecta*, *Veronica spicata*, *Viola canina*, *Thalictrum foetidum* et al. grow under the canopy. Forest species are abundant: *Vaccinium vitis-idaea*, *V. myrtillus*, *Calamagrostis arundinacea*, *Rubus saxatilis*, *Brachypodium pinnatum*, *Melica nutans*, *Chimaphila umbellata*, *Carex montana*, *Luzula pilosa*, *Lathyrus vernus*, *Pyrola chlorantha*, *P. media*, *Orthilia secunda*, *Moneses uniflora* et al. *Hemipilia cucullata*, *Platanthera bifolia*, *Goodyera repens* are rare. The moss layer is dominated by *Pleurozium schreberi*, *Rhytidiadelphus triquertus*, *Hylocomnium splendens* et al. The moss cover on burned areas is formed by species of the genus *Polytrichum* (Isakova, 2009). The communities near the KCS are represented by derivative pine forests with an admixture of birch (*Betula pendula* or *B. pubescens*). Due to epigeic mosses degradation, communities of the green moss group are missing. The herb-shrub layer is formed by single individuals or forms patches of clumps. The most common are *V. myrtillus* and *C. arundinacea*, less common are *Brachypodium pinnatum*, *V. vitis-idaea*, *R. saxatilis*, *O. secunda*, *Sanguisorba officinalis*, *Tussilago farfara*, *Pyrola* spp.

The initial stages of post-fire recovery in the ISR are usually dominated by *C. arundinacea* or *Chamaenerion angustifolium*; polycarpic species of different life forms such as *C. montana*, *Galium boreale*, *L. vernus*, *Maianthemum bifolium*, *O. secunda*, *Polygonatum odoratum*, *R. saxatilis*, *Seseli libanotis*, *Silene nutans*, *F. vulgaris*, and *Trifolium medium* are also frequently found. The initial stages of post-fire recovery near KCS do not identify sustainable dominants; the most abundant species on burned areas are *C. arundinacea*, *Ch. angustifolium*, *V. myrtillus* and *V. vitis-idaea*.

Characteristics of community structure and diversity. The main result obtained regarding the variability of traditional characteristics of community structure and diversity was that they strongly depend on the technogenic pollution level and do not depend on the time passed since the last fire. This is evidenced by the significance levels of the influence of factors in GLM (Table 1). The "pollution" factor is significant in relation to all variables, the "time since the last fire disturbances" factor is significant only in relation to the moss layer. In fact, the comparison of the R^2_{adj} values in the last two columns of Table 1 suggests that the "time passed since the last fire" factor is redundant in describing all variables except moss layer cover.

Epigeic moss cover decreased from an average of 42 ± 6% in the ISR forests to less than 1% near KCS. I.e., the moss layer disappeared under severe pollu-

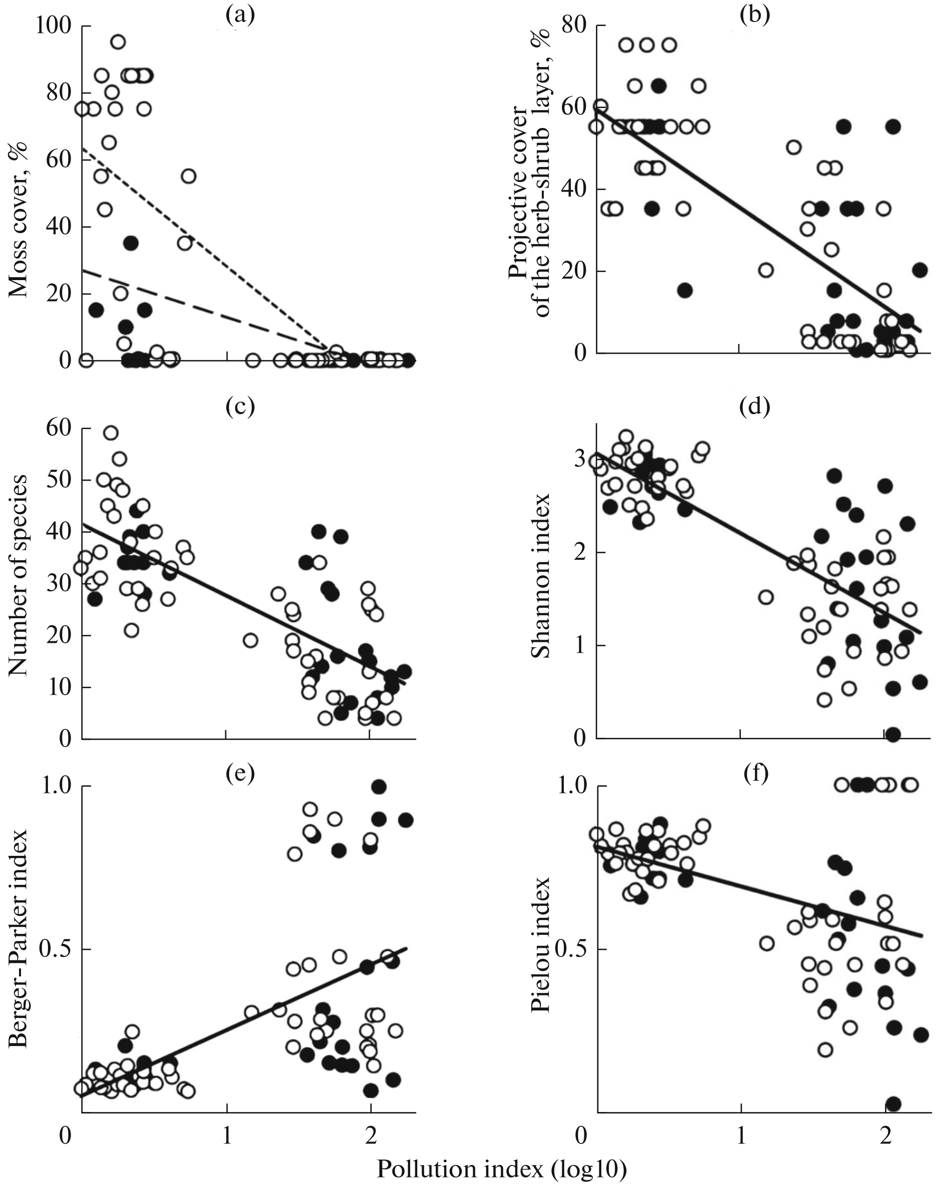

Fig. 2. Changes in projective cover of moss (a) and herb-shrub (b) layers, diversity parameters (c–f) of herb-shrub layer with increasing pollution in communities with different time passed since the last fire. Approximations for mosses are given separately for recently burned communities (line with long dashes) and communities burned long ago (line with short dashes). Here and in Figs. 3 and 4: black circles are burned communities; white circles are unburned communities.

tion. Moss cover in the ISR forests depended on the time of the last fire. In the long–term absence of fires, the average moss cover was 53 ± 7%, and in recently burned areas it was 20 ± 9%. According to the Tukey's test in two-factor ANOVA, these differences were significant ($P = 0.0011$).

The average total projective cover of the herb-shrub layer decreased from 50 ± 2% in the ISR forests to 15 ± 3% near the KCS, i.e. more than threefold. Similar decrease in species richness was more than twofold: from 37 ± 1 species/100 m^2 in the ISR to 16 ± 1 species/100 m^2 near the KCS. As pollution increased, average Shannon index values decreased twofold: from 2.81 ± 0.04 in the ISR to 1.44 ± 0.10 near the KCS. A noticeable decrease in diversity was accompanied by a slight, although significant decrease in evenness: average Pielou's index values were 0.79 ± 0.01 in the ISR forests, and 0.57 ± 0.04 near the KCS. A decrease in community diversity was accompanied by an increase in the level of dominance. The average Berger-Parker index values in the ISR forests were 0.11 ± 0.01, and in the case of severe pollution near the KCS—0.43 ± 0.05. The common dominants of the herb-shrub layer in the absence of pollution were *B. pinnatum*, *C. arundinacea*, *R. saxatilis*, *V. vitis-idaea*. The common dom-

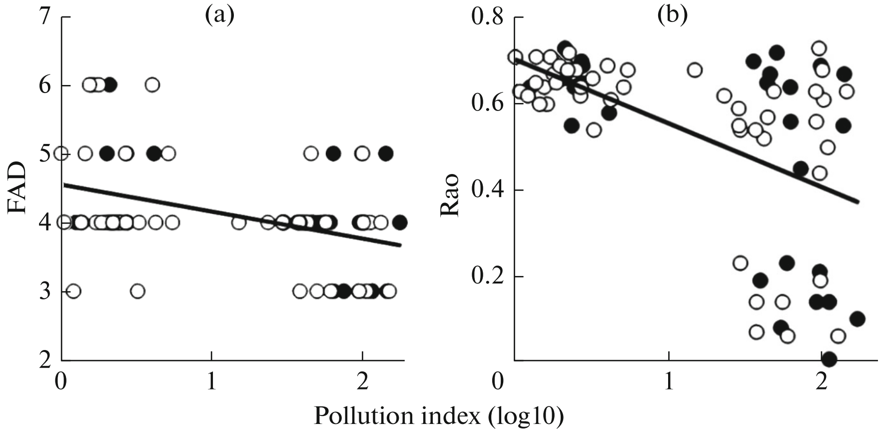

Fig. 3. Change of herb-shrub layer functional diversity parameters ((a) FAD; (b) Rao) with increasing pollution in communities with different time passed since the last fire.

inants in polluted areas are *C. arundinacea*, *V. myrtillus*, *V. vitis-idaea*. Some SP near the KCS showed no dominant species due to the thinned, free-growing cover, although a formal indicator of dominance—the Berger-Parker index—was calculated.

Functional diversity. Of 167 herb-shrub species recorded in 77 descriptions, the environmental strategy type was determined for 129 (77%). Among these 129 species, the entire possible range of strategies is represented. The largest number of species were with the CSR (47 species, typical representatives of which are: *Antennaria dioica*, *Luzula pilosa*, *Potentilla erecta*), C (38 species, for example: *Dactylis glomerata*, *Digitalis grandiflora*, *Pteridium aquilinum*), and SC (30 species, among which are: *Melica nutans*, *Stellaria graminea*, *Hieracium umbellatum*) strategies. The species of other strategies were less numerous or isolated: S (8 species, for example: *Pyrola chlorantha*, *Pyrola media*), CR (4 species, for example: *Aconitum septentrionale*, *Galeopsis bifida*), R (1 species—*Cacalia hastata*) and SR (1 species—*Impatiens noli-tangere*).

One description presented from 3 to 6 strategies, with an average of 4.1 ± 0.1 strategies. This characteristic—the FAD parameter—varied only in connection with the pollution level, but not with the time since the last fire (see Table 1). As species richness of the herb-shrub layer in the pollution gradient decreased, FAD values decreased (Fig. 3). The average FAD value was 4.4 ± 0.1 in the ISR and 3.8 ± 0.1 near the KCS; these differences were significant. As the pollution increased, the Rao parameter decreased from 0.66 ± 0.01 in the ISR forests to 0.43 ± 0.04 in the forests near the KCS. Thus, functional diversity parameters in the pollution gradient, although decreasing, were not as contrasting as the traditional richness/diversity parameters of communities.

CSR coordinates of communities. In general, plants with C-strategy components predominated. For 77 descriptions, the average coordinate values along the competitiveness axis were 0.53 ± 0.01. The average coordinates along the stress tolerance and ruderality axes were 0.32 ± 0.01 and 0.08 ± 0.01, respectively. Depending on pollution level, the average S- and R-axis coordinates of communities changed significantly (see Table 1), but the average C-axis coordinates did not change. As pollution increased, the contribution of species with the S-strategy component to the formation of communities increased significantly, and the contribution of species with the R-strategy component noticeably decreased (Fig. 4). The average R-axis coordinates of communities changed more than fourfold in the gradient: on average from 0.14 ± 0.01 in the ISR to 0.03 ± 0.01 near the KCS. No significant relationship between the CSR coordinates and the time since the last fire was found (see Table 1). The closest to the threshold that would allow us to speak of significant post-pyrogenic dynamics was the variability of the contribution of species with the R-strategy component.

DISCUSSION

Of the three hypotheses, only the first one was confirmed. All community parameters, including all herb-shrub diversity components, were lower in polluted forests compared to unpolluted ones. Effects that would indicate a dependence of the herb-shrub layer parameters on the time since the last fire were not determined; however, ground moss cover was associated with the time since the last fire.

Impact of pollution. The reactions observed with increasing pollution are expected. Similar decrease in community richness/diversity has been described many times (Zvereva et al., 2007; Chernenkova et al., 2011; Chernenkova, 2014; Trubina et al., 2014), including near the KCS (Kozlov et al., 2009; Chashchina et al., 2017). The decrease in moss cover with

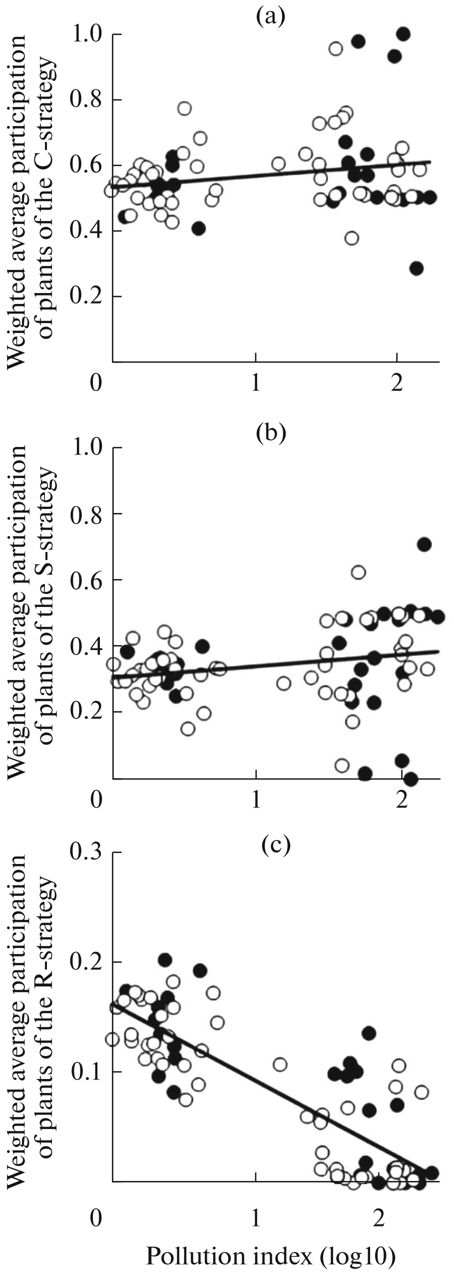

Fig. 4. Changes in the weighted average participation of C- (a), S- (b) and R-strategy species (c) with increasing pollution in the composition of communities with different time passed since the last fire.

increasing pollution also corresponds to the published data (Zvereva and Kozlov, 2011).

Our materials allowed us to compare the sensitivity of different herb-shrub layer parameters: traditional measures of diversity; functional diversity parameters; and CSR-strategy type importance ratios. Traditional measures not considering species heterogeneity—number of species, Shannon index—were more sensitive and changed significantly with increasing pollution than parameters considering species heterogeneity of different strategies. This is probably explained by functional duplication in communities, since the number of taxa is almost always greater than the number of functional types. A similar pattern of functional diversity relative sustainability was established when studying the effects of drought (Copeland et al., 2016). But there may be situations where functional diversity is as sensitive as traditional diversity measures (Mikryukov et al., 2014; Li et al., 2022).

The functional structure of the herb-shrub layer changed directionally when polluted. Near the smelter, the participation of species with C- and S-strategy traits increased and that with R-strategy traits decreased. Such changes are understandable, since as pollution increases, conditions for plants worsen. This is caused by an increase in substrate toxicity (Kozlov et al., 2009; Koroteeva et al., 2015a, 2015b), accumulation of a thick layer of litter, which is unfavorable for plant regeneration (Xiong and Nilsson, 2001; Loydi et al., 2014), and changes in mineral nutrition conditions (Veselkin et al., 2022a). Close community rearrangements are shown in many gradients: moisture (Zelnik and Čarni, 2008); impairments (Fazlioglu et al., 2021); high-altitude (Bricca et al., 2022; Novakovsky et al., 2023).

The decreased importance of the ruderal component of herb species strategies under pollution may indicate that the vulnerable, sensitive process under these conditions is regeneration. Ruderal (R) strategy species compared to C- and S-strategy species are characterized by a generally shorter ontogeny and therefore the seed regeneration success is more crucial for them. At the same time, it can be assumed that the regeneration process components—seed production or success of early ontogenesis—can be strongly affected by the negative effects associated with heavy metal pollution. In our opinion, the materials presented in the report do not give a comprehensive answer to the question of what biological or environmental traits allow some species to persist in polluted areas while others disappear. However, our materials allow us to formulate hypotheses worth testing to find this answer. It seems reasonable to analyze the sensitivity/resistance of: first, species of different life forms and, second, species with different seed dispersal types (diaspores).

Impact of fires. When studying pyrogenic effects, the severity of fires and the degree of post-fire disturbance should be considered (Kovaleva and Ivanova, 2013; Richter et al., 2019; Strand et al., 2019; Geraskina et al., 2021). We assessed the consequences of low-intensity ground fires, in which trees and forest stands did not die. The consequences of such fires on the herb-shrub layer have not been revealed, which does not contradict existing ideas. Along with evidence of negative changes in community diversity after fires (Kovaleva and Ivanova, 2013; Makarov et al., 2019; Richter et al., 2019), there is also evidence of positive effects (Eales et al., 2018; Strand et al., 2019; Braslavskaya et al., 2022).

It should be noted that our conclusion about the absence of post-fire dynamics in herb-shrub layer diversity is justified only for the implemented methodological scheme. Other ways of collecting or analyzing fire response data might show different results. Since post-fire successions in pine forests occur rapidly (Kovaleva and Ivanova, 2013; Malinovskikh and Kupriyanov, 2013), post-fire effects can be most pronounced in short time intervals. Hence, it is possible that GLM, which is based on linear regressions, is not flexible enough to evaluate potential nonlinear relationships if they are hidden in the data set. But the implemented observation scheme allowed us to establish explainable post-fire dynamics of the soil moss cover index. Moss cover not only dropped dramatically as pollution increased, but also was lower in recently burned areas within the reserve forests. Therefore, our scheme was able to detect sustainable fire disturbance responses.

Plant species are differently resistant to fire disturbances and therefore fires affect them differently (Peterson and Reich, 2007; Kovaleva and Ivanova, 2013; Malinovskikh and Kupriyanov, 2013; Eales et al., 2018; Arroyo-Vargas et al., 2022; Braslavskaya et al., 2022). This is the basis for distinguishing such groups as pyrophytic, early- and late-successional species. Our data revealed an increased position of species with ruderal strategy traits in recently burned forests (see Fig. 4c). This suggests that when assessing the consequences of forest fires, an approach focused on identifying the characteristics of community species compositions can provide results significantly complementing the results of the approach based on the identification of general, aggregate characteristics of communities implemented in this work.

CONCLUSIONS

Of the two types of disturbances—pollution and pyrogenic effects—the pollution factor is more important for the herb-shrub layer diversity in pine forests of the region, including the vicinity of the Karabash copper smelter and the Ilmen Nature Reserve. The effects of fire on the herb-shrub layer have not been established either using traditional diversity measures, or functional diversity parameters (perhaps because we measured functional diversity based on a limited list of Grime's environmental strategies), or by the strategy type importance ratios. No additive or any other correlation between technogenic and pyrogenic impacts was found. Fire impacts do not increase pollution-induced herb-shrub layer suppression. This pattern correlates with the idea that fire, unlike heavy metal emissions, is a natural and logical factor in formation of light coniferous forests. This is probably why fires do not cause as much change in the structure of forest plant components as pollution.

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This work does not contain any studies involving human and animal subjects.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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