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RESEARCH ARTICLE

Colonization of reclaimed post-mining habitats by Myriapoda (Diplopoda, Chilopoda) in southwestern Siberia, Russia

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Abstract

Post-mining landscapes undergo profound ecological transformations, yet the recovery of soil fauna remains poorly understood. This study examines the colonization patterns of myriapods (Diplopoda and Chilopoda) on reclaimed coal mining dumps in southwestern Siberia (Kemerovo Oblast, Russia) across different successional stages. From 2014 to 2017, we sampled two coal mining sites, comparing dumps of varying recovery ages with undisturbed control habitats. Results reveal stark contrasts between the two myriapod groups: Diplopoda exhibited low abundance and species richness, colonizing only at later successional stages, influenced by soil pH, organic carbon, and vegetation cover. In contrast, Chilopoda rapidly colonized young dumps, with pioneer species like *Lamyctes africanus* dominating early successional stages. Statistical modeling identified soil moisture (HTC), nitrogen content, and pH as key drivers of myriapod distribution. These findings highlight the slow recovery of millipede communities compared to centipedes, which act as early colonizers shaping trophic networks. The study underscores the need for targeted reclamation strategies that enhance soil conditions and vegetation to facilitate soil fauna restoration. Understanding these successional dynamics can improve biodiversity recovery in post-mining ecosystems.

Keywords
Diplopoda, Chilopoda, Lithobiomorpha, Geophilomorpha, terricon, post-mining reclamation, succession, Kemerovo Oblast

Introduction

Industrial mineral extraction inevitably impacts the environment due to imperfect mining technologies. In Russia, coal mining is a cornerstone of the economy, with the country hosting some of the world's largest coal basins, including the Kuznetsk (Kuzbass), Tunguska, Kansk-Achinsk, and Lena basins. However, coal extraction leads to biodiversity loss, hydrological disruption, and pollution of air, surface water, and groundwater. A particularly pressing issue is the expansion of disturbed lands, where technogenic landscapes – such as quarries and overburden dumps – form beyond mining fields.

Reclaiming these disturbed territories to restore biodiversity is a critical environmental priority. Ecologically, successful reclamation should establish sustainable biogeocenoses capable of transforming and stabilizing degraded ecosystems. A key component of this process is the recovery of soil-dwelling invertebrates, which play essential roles in nutrient cycling as phytophages, zoophages, saprophages, and mixophages. Among these, Myriapoda – particularly saprophagous Diplopoda (millipedes) and predatory Chilopoda (centipedes) – serve as vital functional links in soil trophic networks (Wolters and Ekschmitt 1997; Kunah 2013). Due to their sensitivity to environmental conditions, myriapods are also valuable bioindicators for monitoring ecological succession (Dunger and Voigtländer 2009; Godoy and Fontanetti 2010).

Despite their ecological importance, studies on myriapod colonization in post-industrial landscapes remain limited. Long-term research in Germany (Voigtländer and Balkenhol 2006; Dunger and Voigtländer 2009) and Hungary (Purger et al. 2007) has shown that myriapods begin colonizing coal mine spoil heaps within years of their formation, with community composition and dominance structures evolving over decades.

In southwestern Siberia's Kemerovo Oblast (Kuzbass), comprehensive research on soil macrofauna in coal mining spoil heaps was conducted from 2013 to 2022, with published findings on ants (Luzyanin and Blinova 2022), ground beetles (Luzyanin 2023), and rove beetles (Luzyanin et al. 2023a). However, the Myriapoda community's succession patterns in these disturbed habitats remain understudied. This study examines the faunistic and ecological structure of myriapod assemblages across different reclamation stages, evaluating how environmental factors influence their abundance using statistical modeling. The results aim to enhance reclamation strategies by identifying key drivers of soil fauna recovery in post-mining ecosystems.

Materials and methods

Study area

This study is based on the collection of millipedes and centipedes amassed from 2014 to 2017 in the territory of two coal mining enterprises in the Kemerovo Oblast: Krasnobrodskii and Kedrovskii open-pit coal mines (Fig. 1). The main criteria for selecting these open-pit coal mines were as follows: firstly, these coal mining enterprises are among the oldest in the region. The Krasnobrodskii coal pit was established in 1947, vs the Kedrovskii one established in 1954. As a result of long-term coal mining, their spoil heaps have been formed in the surrounding areas, representing different stages of recovery. Secondly, the study enterprises are located in different natural zones: the Krasnobrodskii coal pit is situated within the forested steppe belt in the central part of the Kuznetsk Basin, whereas the Kedrovskii coal pit lies in the forest zone of the sub-taiga of the Kuznetsk Alatau.

The monitoring sites were located on external dumps, i.e., outside the mining excavations. Reclamation was carried out on the dumps. The technical stage included leveling the dump surfaces, forming and terracing the slopes, as well as applying potentially fertile substrates. During the biological stage, 5 to 7-year old seedlings of *Pinus sylvestris* L. were planted, and on the young dump of the Krasnobrodskii coal mine, *Betula pendula* Roth was planted in addition to that. A total of seven habitats on the dumps and two control sites were studied. When selecting control sites, natural habitat types of the mining areas were matched as close as possible (Suhartoyo et al. 2012). A more detailed description of the study sites is presented in Suppl. material 1: Table 1S, as well as in previously published studies (see Luzyanin and Blinova 2022; Luzyanin 2023; Luzyanin et al. 2023a).

Environmental factors

To assess the moisture availability of the area, the Selyaninov hydrothermal coefficient (HTC) was calculated (Kurganova et al. 2023). A preliminary evaluation of the soil agrochemical properties (pH of water extract, organic carbon content (C), and total nitrogen (N)) were conducted in the environmental monitoring laboratory of the Kemerovo State University. Additionally, a description of the phytocenoses was carried out, including the identification of plant species composition, dominant species, the vegetation cover, and the turf extent of the study sites (Braun-Blanquet 1964).

Sampling methods

Material was collected throughout entire growing season using pitfall trappings, the traps being set along a linear transect at each site, with 10 pitfall traps set at 10 meter intervals. Since 2017, three sampling plots have been established at each site, spaced approximately 100 meters apart. On each plot, five pitfall traps were arranged in a square pattern with a single pitfall trap in the center (envelope method), ensuring that the distance between the outermost points did not exceed 10 meters (Luzyanin and Blinova 2022). A 4% acetic acid solution was used as fixative in pitfall traps. The pitfall traps were checked every 7–10 days, and each pitfall trap was considered as a separate sampling unit. The number of the myriapod specimens captured was standardized to 10 traps per 24 hours to obtain relative values (dynamic density).

The material treated here has been deposited in the collections of the Altai State University, Barnaul, Russia (Diplopoda and Geophilomorpha), and the Perm State University, Perm, Russia (Lithobiomorpha).

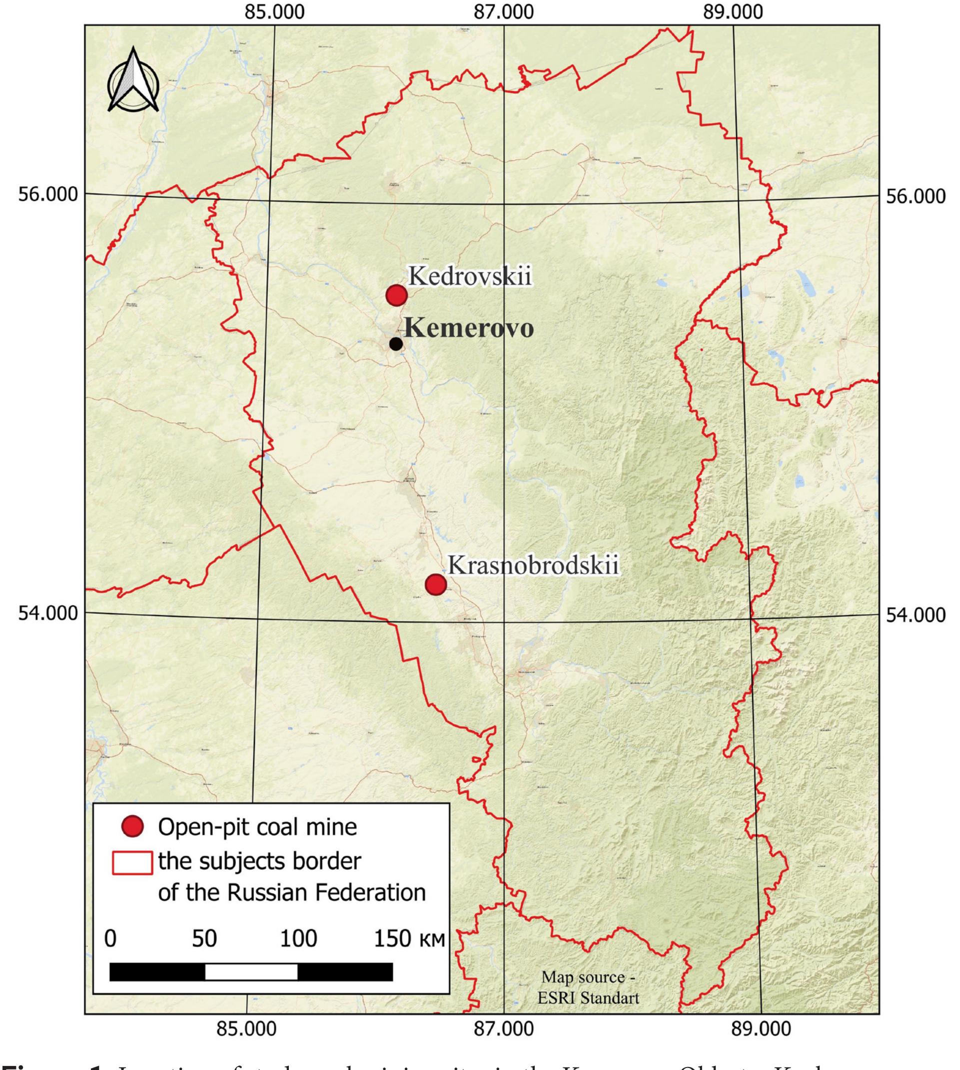

Figure 1. Location of study coal mining sites in the Kemerovo Oblast – Kuzbass.

Statistical analysis

To evaluate myriapod community structure, species diversity indices – Simpson's dominance index (*D′*), Shannon's diversity index (*H′*), and Pielou's evenness index (*E′*) – were calculated for each site using PAST 5.1 software (Hammer et al. 2001). To determine the influence of environmental factors on myriapod abundance, we constructed a statistical model using Type II ANOVA (analysis of variance). Two approaches were applied:

Variable Removal Test: Factors were sequentially excluded from the full model, with negative deviance values indicating reduced model quality.

Variable Addition Test: Factors were added to a minimal model, with positive deviance values reflecting improved explanatory power.

Model adequacy was verified using quantile-quantile (Q-Q) plots, confirming normal residual distribution and independence from predictor variables. All calculations were performed in R (v. 4.0.2), with statistical significance set at $p < 0.05$. The model's formulation and theoretical framework follow established methodology (Luzyanin et al. 2023b).

Results

A total of eight species of millipedes and thirteen species of centipedes were identified in the study area (Tables 1, 2).

At the sites of the Krasnobrodskii open-pit coal mine, three species of Diplopoda were recorded, vs seven species at the control site for this mine. At the Kedrovskii open-pit coal mine sites, three millipede species were found, vs five species at the control site (Table 1). Since two species of the genus *Altajosoma*, *Altajosoma deplanatum* (Stuxberg, 1876) and *Altajosoma bakurovi* (Shear, 1990), were encountered in the study area; females and juveniles were referred to as *Altajosoma* sp., as no identification methods for these stages have been developed yet.

The millipede population in the spoil heaps is less diverse compared to the control sites. On the 2-year old spoil heap of the Krasnobrodskii mine (Krb1), individual specimens of *Altajosoma* sp. females were recorded only in 2014. On the 7-year old (Krb2, Kedr1) and 25-year old (Kedr2, Krb3) spoil heaps, the numerical abundance of millipedes did not exceed 0.04 % of the total structure of ground-dwelling arthropods. At the base of the 25-year old spoil heaps (Krb4, Kedr3), the number of millipede species was slightly higher than on the spoil heaps proper. At the Krb4 site, *Orinisobates sibiricus* (Gulička, 1963), *A. bakurovi*, and *Altajosoma* sp. (most likely *A. bakurovi*, although *A. deplanatum*, which was recorded at the control site Krb5, cannot be ruled out) were observed. At the Kedr3 site, the species recorded were *O. sibiricus*, *A. deplanatum*, *Altajosoma* sp. (very likely *A. deplanatum*, as no other *Altajosoma* species were found at the control site), and *Schizoturanius tabescens* (Stuxberg, 1876). Notably, among the *Altajosoma* sp. individuals, subadults and juveniles were present along with adults, indicating active reproduction of this species (Table 1).

The highest species richness and abundance of millipedes are characteristic of the control sites: seven species at the Krb5 ($D` = 0.66$, $H` = 1.89$, $E` = 0.46$) and five species at the Kedr4 ($D` = 0.72$, $H` = 1.95$, $E` = 0.64$). Many of the listed species are widely distributed across southwestern Siberia. They predominantly inhabit various forest types, including deciduous and mixed woodlands, and dark coniferous taiga (Nefediev et al. 2021).

At the control site Krb5, the collections are dominated by the lowland to mid-montane species *Sibiriulus profugus* (Stuxberg, 1876), accounting for 51.3 % of the millipede samples. Co-dominant species include the ecologically plastic lowland to high-montane millipedes *Julus ghilarovi* Gulička, 1963 (17.9 %) and *Schizoturanius clavatipes* (Stuxberg, 1876) (17.7 %). At the control site Kedr4, the collections are dominated by *S. clavatipes* (31.5 %), the lowland to high-montane *Orinisobates sibiricus* (35.9 %), and the lowland to mid-montane *Ghilarovia cylindrica* (Stuxberg, 1876) (20.6 %).

The dynamic density of diplopods on coal mine spoil heaps was extremely low, averaging 0.04 ± 0.24 ind. / 10 traps per 24 h. (Fig. 2). At the Kedrovskii coal mine, compared to the Krasnobrodskii mine, a higher capture rate was recorded at the base of a 25-year old spoil heap (2.98 ± 5.15 ind. / 10 traps per 24 h.). Peak values of Diplopoda dynamic density were observed at the control sites (Krb5 and Kedr4), reaching 17.04 ± 15.21 and 16.41 ± 21.12 ind. / 10 traps per 24 h., respectively.

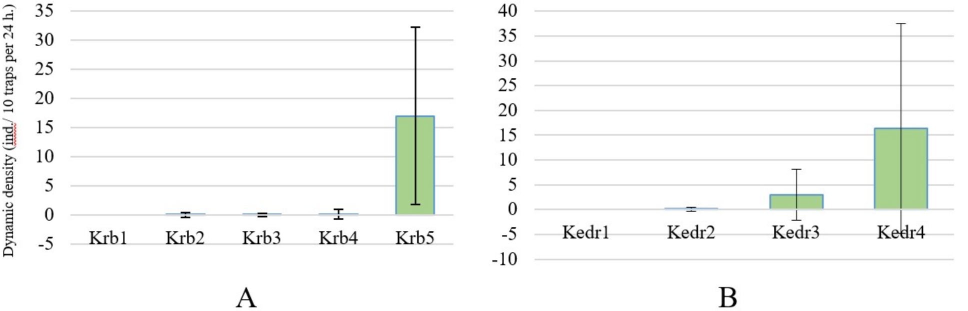

Figure 2. Comparative dynamics of millipedes populations across successional stages at reclaimed coal mines in southwestern Siberia: (**A**) Krasnobrodskii and (**B**) Kedrovskii open-pit mines. Values represent mean dynamic density (ind. / 10 traps per 24 h ± SD), demonstrating significantly depressed populations on spoil heaps (0.04 ± 0.24) compared to control sites (Krb5: 17.04 ± 15.21; Kedr4: 16.41 ± 21.12).

Table 1. Sex and age composition and some characteristics of millipede (Diplopoda) communities at the studied sites of open-pit coal mines

Species	Site								
	Krasnobrodskii open-pit coal mine					Kedrovskii open-pit coal mine			
	Krb1	Krb2	Krb3	Krb4	Krb5	Kedr1	Kedr2	Kedr3	Kedr4
Julus ghilarovi Gulička, 1963	–	–	–	–	53♂♂, 25♀♀, 23 subadult ♂♂, 13 subadult ♀♀, 40 juv.	–	–	–	–
Sibiriulus profugus (Stuxberg, 1876)	–	–	–	–	167♂♂, 170♀♀, 7 subadult ♂♂, 96 juv.	–	–	–	–
Orinisobates sibiricus (Gulička, 1963)	–	–	–	1♂	6♀♀, 2 juv.	–	–	1♂, 1♀	76♂♂, 105♀♀, 1 subadult ♂, 10 juv.
Altajosoma bakurovi (Shear, 1990)	–	–	–	2♂♂	2♂♂	–	–	–	–
Altajosoma deplanatum (Stuxberg, 1876)	–	–	–	–	1♂	–	–	8♂♂	1♂
Altajosoma sp.	2♀♀	1♀	4♀♀, 1 subadult ♂	12♀♀, 2 subadult ♂♂, 7 juv.	11♀♀, 14 subadult ♂♂, 7 subadult ♀♀, 63 juv.	–	–	10♀♀, 31 subadult ♂♂, 12 subadult ♀♀, 53 juv.	7♀♀, 16 subadult ♂♂, 10 subadult ♀♀, 27 juv.
Ghilarovia cylindrica (Stuxberg, 1876)	–	–	–	–	1 subadult ♂, 3 subadult ♀♀, 3 juv.	–	–	–	1♂,13♀♀, 17 subadult ♂♂, 79 juv.
Schizoturanius clavatipes (Stuxberg, 1876)	–	–	–	–	42♂♂, 42♀♀, 1 subadult ♀, 67 juv.	–	–	–	80♂♂, 68♀♀, 4 subadult ♂♂, 2 subadult ♀♀, 14 juv.
Schizoturanius tabescens (Stuxberg, 1876)	–	–	–	–	–	–	–	1 juv.	2♂♂, 1♀
Number of species	1	1	1	2	7	–	–	3	5
Individuals	2	1	5	24	859	–	–	117	534
Simpson (*D*`)	–	–	–	0.24	0.66	–	–	0.17	0.72
Shannon (*H*`)	–	–	–	0.72	1.89	–	–	0.57	1.95
Pielou (*E*`)	–	–	–	0.55	0.46	–	–	0.37	0.64

Representatives of the class Chilopoda more actively colonize newly formed technogenic landscapes. In the spoil heaps of the Krasnobrodskii open-pit coal mine, nine species of centipedes were recorded, vs only five species in the control area (Table 2). On the 2-year old spoil heap Krb1, *Lamyctes africanus* (Porath, 1871) dominated in terms of numerical abundance, accounting for 54.8 % of the total number of centipede individuals. A closely related species in terms of ecology and biology, *Lamyctes emarginatus* (Newport, 1844), comprised 41.1 % of the collected specimens. On a 7-year old spoil heap (Krb2), three centipede species were identified: *Lithobius crassipes* L. Koch, 1862, *L. forficatus* (Linnaeus, 1758), and *L. curtipes* C.L. Koch, 1847, with dynamic densities not exceeding 0.12 ± 0.27 ind. / 10 traps per 24 h. The species *L. forficatus* was represented solely by the epimorphic, sexually immature stage. On the older spoil heap Krb3, the centipede population consisted of five species, with domination of the eurytopic *L. forficatus* (75 %). Additionally, the rare species, *Lithobius vagabundus* Stuxberg, 1876 (2.8 %), which is very uncommon in southwestern Siberia, was recorded there (Nefediev et al. 2018).

The highest species richness of centipedes was observed at the base of a 25-year old spoil heap (Krb4), where seven species were revealed ($D' = 0.68$, $H' = 1.47$, $E' = 0.54$). The dominant species in the collections was *L. forficatus*, accounting for 30.3 %. Notably, *Lithobius nordenskioeldii* Stuxberg, 1876 (9.1 %) was recorded at this site alone. In the control area (Krb5), only five species of centipedes were observed, with domination of *L. ostiacorum* Stuxberg, 1876 (71.3 %).

At the study sites of the Kedrovskii open-pit coal mine, directly on the spoil heaps, seven species of centipedes were recorded (Table 2). On an older spoil heap (Kedr2), only *Lithobius sibiricus*, a trans-Siberian species ranging across the Asian part of Russia and northern Mongolia (Nefediev and Farzalieva 2020), was observed. At the Kedr1 site, this species was dominant, accounting for 93.2 % of the collected specimens, these including both mature individuals and juveniles. Additionally, only on the 7-year old spoil heap Kedr1, *Lithobius crassipes* (4.5 %) and *Lamyctes emarginatus* (2.3 %) were revealed. The centipede taxocene of the control site (Kedr4) comprised nine species, with predomination of two south Siberian boreal species, *Lithobius ostiacorum* and *L. nordenskioeldii* (38.1 % and 29.2 % of the total centipede abundance, respectively). As previously noted, *L. ostiacorum* was also dominant at the control site of the Krasnobrodskii open-pit coal mine.

Compared to older spoil heaps, the dynamic density of centipedes was higher on younger spoil heaps (Fig. 3). For instance, on the 2-year old spoil heap Krb1 of the Krasnobrodskii open-pit coal mine, it reached 2.59 ± 4.16 ind. / 10 traps per 24 h., vs 1.63 ± 3.41 ind. / 10 traps per 24 h. on the 25-year old spoil heap Krb4. A similar trend was observed at the Kedrovskii open-pit coal mine sites: Kedr1 showed a dynamic density of 1.61 ± 5.32 ind. / 10 traps per 24 h., vs 0.79 ± 2.42 ind. / 10 traps per 24 h. at the Kedr2 site. Notably, the dynamic density of centipedes at the base of 25-year old spoil heaps showed interesting results. At the Krb4 site, the trap efficiency at the base of the heap was 1.14 ± 3.12 ind. / 10 traps per 24 h., lower than on the 25-year old spoil heap itself (1.63 ± 3.41 ind. / 10 traps per 24 h.). Conversely, at the Kedrovskii open-pit coal mine, the dynamic density at the base of the 25-year old spoil heap was higher than on the old spoil heap: 3.33 ± 5.16 ind. / 10 traps per 24 h., vs 0.79 ± 2.42 ind. / 10 traps per 24 h., respectively. The highest values of centipede dynamic density were recorded at the control sites: 10.19 ± 10.85 ind. / 10 traps per 24 h. at the Krb5 site, and 19.55 ± 21.56 ind. / 10 traps per 24 h. at the Kedr4 site.

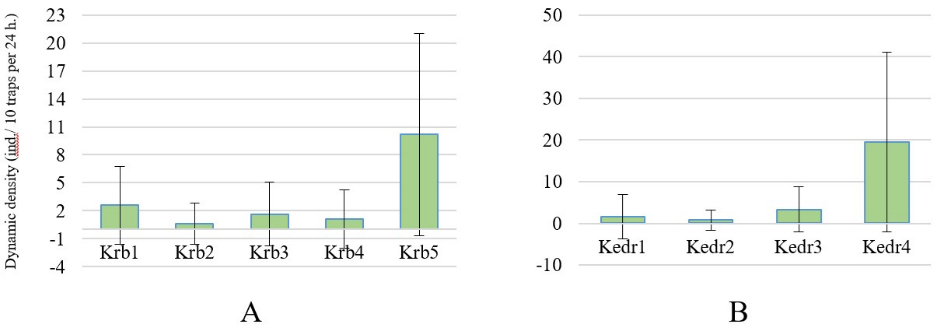

Figure 3. Comparative dynamics of centipedes populations across successional stages at reclaimed coal mines in southwestern Siberia: (**A**) Krasnobrodskii and (**B**) Kedrovskii open-pit mines.

An analysis of statistical modeling data revealed that the environmental factors studied can exert multidirectional effects on the abundance of myriapods (Suppl. material 1: Tables 2S, 3S). The extent to which the contribution of these factors correlated with changes in abundance was examined. Table 3 presents only the statistically significant results of the assessment of the factors influencing each of the myriapod groups considered.

Soil pH does influence the abundance of myriapods, particularly at lower pH values. As illustrated in Figures 4A and 5C, the dependency curves show a downward trend. On the sites of the Kedrovskii open-pit coal mine, a threshold value (where the factor's contribution becomes negative) is observed at a pH range of 7.8–7.9. For the Krasnobrodskii open-pit coal mine, this threshold occurs at a pH of 8.6.

An interesting relationship was observed between the abundance of centipedes and the concentration of soil organic carbon (SOC factor). For the Kedrovskii open-pit coal mine sites, a positive contribution was noted within an SOC range of 0 to 4.4, beyond which the curve shifts into the negative zone (Fig. 4E). In contrast, at the Krasnobrodskii open-pit coal mine, the situation was reverse, as the soil carbon content correlated positively with the abundance of centipedes (Fig. 5D).

The contribution of total nitrogen (Total N) to centipede abundance was positive within a range of 0–0.36. However, with Total N increasing further, the contribution curve shifts into the negative zone (Fig. 5E). The contribution curve for millipedes at the Kedrovskii open-pit coal mine sites showed a fundamentally different pattern: as the nitrogen content increases, the strength of the factor's contribution to abundance also rises (Fig. 4C).

Table 2. Sex and age composition and some characteristics of centipede (Chilopoda) communities at the studied sites of open-pit coal mines

Species	Site								
	Krasnobrodskii open-pit coal mine					Kedrovskii open-pit coal mine			
	Krb1	Krb2	Krb3	Krb4	Krb5	Kedr1	Kedr2	Kedr3	Kedr4
Lithobius crassipes L. Koch, 1862	1♂	2♂♂, 7♀♀	1♂, 1♀	1♂	–	1♂, 3♀♀	–	–	–
Lithobius curtipes C.L. Koch, 1847	–	2♂♂	1♂, 4♀♀	3♂♂, 3♀♀	1♂	–	–	1♂, 1♀	15♂♂, 18♀♀, juv.7
Lithobius forficatus (Linnaeus, 1758)	–	1 juv.	4♂♂, 18♀♀, 5 juv.	4♂♂, 3♀♀, 3 juv.	–	–	–	–	–
Lithobius insolens Dányi et Tuf, 2012	–	–	–	–	33♂♂, 20♀♀, 29 juv.	–	–	8♂♂, 5♀♀, 8 juv.	1 juv.
Lithobius nordenskioeldii Stuxberg, 1876	–	–	–	3♂♂	–	–	–	–	80♂♂, 135♀♀, 10 juv.
Lithobius princeps Stuxberg, 1876	–	–	–	1♀	–	–	–	–	1♀
Lithobius ostiacorum Stuxberg, 1876	–	–	–	1♂, 3♀♀, 5 juv.	159♂♂, 154♀♀, 39 juv.	–	–	25♂♂, 20 ♀♀, 10 juv.	106♂♂, 128♀♀, 60 juv.
Lithobius sibiricus Gerstfeldt, 1859	–	–	–	–	32♂♂, 22♀♀, 3 juv.	25♂♂, 50♀♀, 7 juv.	8♂♂, 6♀♀	6♂♂, 1♀♀, 3 juv.	25♂♂, 7♀♀, 11 juv.
Lithobius vagabundus Stuxberg, 1876	–	–	1♀	–	–	–	–	24♂♂, 4♀♀, 1 juv.	76♂♂, 50♀♀, 38 juv.
Lamyctes africanus (Porath, 1871)	72♀♀, 8 juv.	–	–	–	–	–	–	–	–
Lamyctes emarginatus (Newport, 1844)	64♀♀, 1 juv.	1♀	1♀	3♀♀	–	2♀♀	–	–	–
Escaryus koreanus Takakuwa, 1937	–	–	–	–	1♂, 1 juv.	–	–	–	1♂, 1 juv.
Escaryus japonicus Attems, 1927	–	–	–	–	–	–	–	–	1♀
Number of species	3	4	5	7	5	3	1	5	9
Individuals	146	13	36	33	494	88	14	117	771
Simpson (*D*`)	0.51	0.53	0.43	0.78	0.45	0.13	–	0.68	0.72
Shannon (*H*`)	1.05	1.52	1.31	2.45	1.19	0.44	–	1.88	2.04
Pielou (*E*`)	0.69	0.72	0.49	0.78	0.46	0.45	–	0.74	0.46

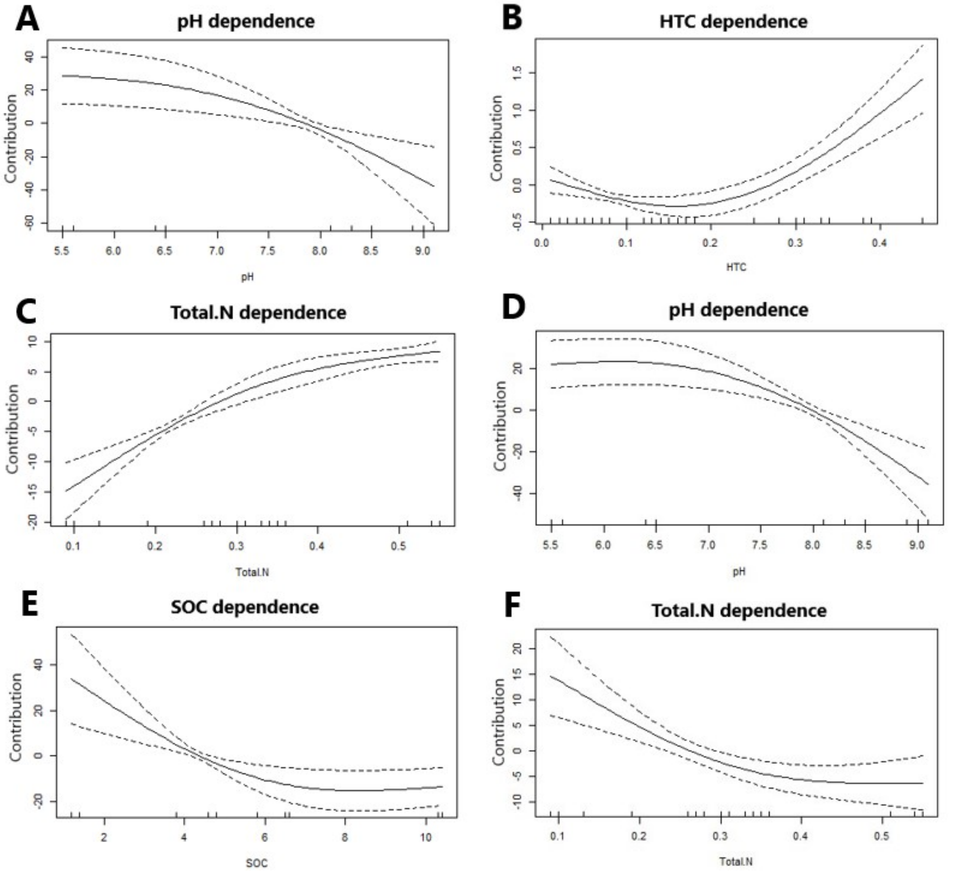

Figure 4. Contribution of environmental factors to the numbers of myriapods at the Kedrovskii open-pit coal mine: **A**, **B**, **C** – millipedes; **D**, **E**, **F** – centipedes.

For the hydrothermal coefficient (HTC), which characterizes substrate moisture levels, statistically significant results were obtained only for millipedes at the Kedrovskii open-pit coal mine sites. As shown in Fig. 4B, the contribution of this factor is increased substantially (exceeding 0.4) with higher HTC values.

Regarding the vegetation cover and turf extent (degree of sod formation), statistically significant results were obtained only for the Krasnobrodskii open-pit coal mine sites (Table 3). The influence of turf extent was unreliable, with a positive contribution value within a range of 0–25 % (Fig. 5B). The vegetation cover had the greatest impact on centipede abundance at 50–55 % levels. Conversely, the factor's contribution was maximized at low values of the vegetation cover for centipedes (Fig. 5F).

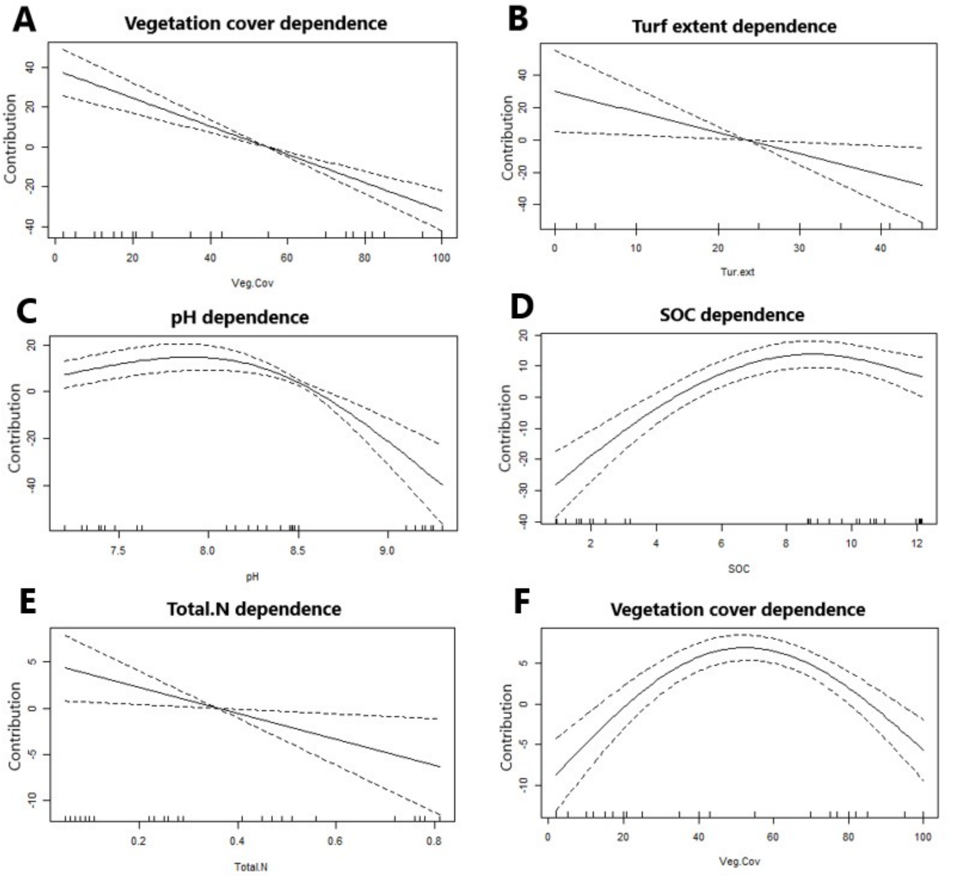

Figure 5. Contribution of environmental factors to the numbers of myriapods at the Krasnobrodskii open-pit coal mine: **A**, **B** – millipedes; **C**, **D**, **E**, **F** – centipedes.

Table 3. Results of linear modeling of environmental factors' impact on myriapod abundance

Factor	Empirical distribution function	Reference degrees of freedom	Chi-squared test	p-value
		Kedrovskii open-pit coal mine		
		Diplopoda		
s(pH)	1.999	2.000	11.730	0.00286**
s(Total.N)	1.856	1.978	131.147	< 2e-16***
s(HTC)	1.428	1.670	13.782	0.00199**
		Chilopoda		
s(pH)	2.000	2.000	19.089	7.14e-05***
s(SOC)	1.907	1.982	11.551	0.002889**
s(Total.N)	1.938	1.995	15.037	0.000596***

Factor	Empirical distribution function	Reference degrees of freedom	Chi-squared test	p-value
		Krasnobrodskii open-pit coal mine		
		Diplopoda		
s(Veg.Cov)	1.000	1.000	40.651	1.82e-10***
s(Tur.ext)	1.000	1.000	5.793	0.01609*
		Chilopoda		
s(pH)	1.990	2.000	58.779	1.37e-13***
s(SOC)	2.000	2.000	41.418	1.05e-09***
s(Total.N)	1.000	1.000	5.971	0.0145*
s(Veg.Cov)	2.000	2.000	79.417	< 2e-16***

Significance codes: 0 "***", 0.001 "**", 0.01 "*".

Discussion

Our research reveals that myriapods only slowly colonize waste rock dumps formed during coal mining. Within the overall population structure of ground-dwelling arthropods in technogenically transformed landscapes, myriapods account for only approximately 0.04 % numerical abundance. This contrasts sharply with native ecosystems, where their abundance reaches 3.3 %. On the waste rock dumps directly, we observe both species richness and numerical abundance of millipedes being low, likely due to habitat conditions unfavorable to their survival. The existing evidence (Kicaj 2023) indicates that millipedes are heliophobic, and their physiological activity depends on high air humidity. The study waste rock dumps, particularly at the early stages of reclamation, consist of open spaces with sparse weed vegetation. These areas experience high levels of insolation and extremely low soil moisture (with the maximum surface soil temperatures recorded at +34.24 ± 12.77 °C and a hydrothermal coefficient (HTC) of 0.12 ± 0.09). Furthermore, representatives of this class are predominantly associated with litter layers, which are absent from young dumps and only begin to gradually get formed by the 25th year of reclamation.

The quality and characteristics of edaphic conditions, as well as the nature of the vegetation cover serve as direct factors affecting the formation of myriapod communities (Schreiner et al. 2012).

Our model reveals a relatively strong dependence on the soil pH parameter, with this effect being particularly pronounced at low pH values. Several studies dedicated to the biology of these invertebrate groups have established that most species are sensitive to acidic habitats, as such conditions reduce the availability of calcium and magnesium (Scheu and Poser 1996; Berg et al. 1997). Millipedes accumulate calcium and magnesium for the construction of their exoskeletons, rendering them vulnerable to limited availability of these minerals (Berg and Hemerik 2004). Furthermore, millipedes are considered to show selective feeding behavior, preferring litter with high calcium content (Neuhauser and Hartenstein 1978).

In addition to soil pH, a correlation has been identified between population abundance and factors such as the hydrothermal coefficient (HTC), total nitrogen, and organic matter concentration. The HTC data obtained agree with previously published studies (Schreiner et al. 2012; Bachvarova et al. 2015), which indicate that, firstly, over time, as the territory recovers, the abundance of millipedes is increased, and secondly, moisture stands out as one of the primary environmental factors influencing the distribution and activity of this group of arthropods.

The nature of vegetation that is developed on post-technogenic territories affects myriapod communities to varying degrees. For example, millipedes as active saprophages play significant roles in the decomposition of plant residues and soil formation processes. Consequently, the colonization of spoil heaps by millipedes is particularly important for the reclamation of disturbed lands. Millipedes show a strong trophic dependence on the composition of vegetation and the nutritional base it provides (Striganova 1969). In this context, the dietary specialization of certain species that are capable of feeding on coarse coniferous litter which typically remains unprocessed by most soil invertebrates seems to be of particular interest (Babenko 2006; Babenko et al. 2009). This key feature of their feeding behavior is highly beneficial for many technogenically disturbed ecosystems, such as spoil heaps, where coniferous tree species are commonly planted as the most widespread method of forest reclamation. The subsequent processing of coniferous needles by millipedes facilitates the restoration of embryozems (rudimentary soils) on these spoil heaps. To enhance millipede populations, we recommend incorporating fast-growing deciduous tree species (e.g., birch, poplar) along with coniferous species in the reclamation of post-technogenic territories. This approach would significantly accelerate the input of plant material into embryozems, thereby improving soil formation processes and contributing to the development of more productive and economically valuable landscapes.

Somewhat different results have been obtained for the class Chilopoda, which act as versatile predators leading a cryptic lifestyle and playing significant functional roles in the trophic networks of soil animal communities both in natural and anthropogenic habitats (Wolters and Ekschmitt 1997; Kunah 2013). Unlike millipedes, centipedes are capable of colonizing spoil heaps within the first few years of their formation. According to literature data obtained in Germany (Dunger 1968, 1998; Dunger and Voigtländer 1990; Wanner et al. 1998), the immigration of this arthropod group occurs primarily through active phoresy from adjacent territories. Wind has been proposed as a dispersal mechanism only for small species or juveniles, which are transported over considerable distances as aerial plankton (Haacker 1968; Voigtländer 2000). The dispersal capacity varies significantly among species.

Lamyctes africanus can be considered an active colonizer of young spoil heaps. This species is of particular interest in terms of its biology and distribution. Originally described from South Africa, it has since been reliably recorded from Australia, Madagascar, the Hawaiian Islands, England, Denmark, the Czech Republic, Germany, France, China, and Russia (Qiao et al. 2019; Nefediev et al. 2020). A closely related species, *Lamyctes emarginatus*, accounts for only 7.5 % of our collections. Notably, in the coal mine spoil heaps of Germany, it is considered as representing the pioneer macrofauna, which establishes itself within the first year after deposition (Voigtländer 2003; Dunger and Voigtländer 2009). Biotopically, the species is associated with areas of poorly developed vegetation, including anthropogenically disturbed habitats. It seems noteworthy that both in Europe and Asia, *Lamyctes emarginatus*, like *L. africanus*, is only known from females (Farzalieva and Esyunin 2008), suggesting parthenogenesis. This reproductive strategy enables rapid population growth, with multiple generations per year. This factor, along with their high stress tolerance to unfavorable environmental conditions, collectively determines their vast distribution on anthropogenically transformed lands (Dunger and Voigtländer 2009). Notably, at the Krb1 site, both adult specimens and juveniles of these species were recorded, this probably indicating their reproduction within this habitat.

On 7-year old dumps, we observe a completely different assemblage of centipedes. At the Krasnobrodskii open-pit coal mine, *Lithobius crassipes* stands out as the dominant species in the collections. According to some researchers (Matic et al. 1979), this species spreads across various habitats and demonstrates resilience to drought and intense solar radiation. At the same time, Voigtländer (2003) reported that *L. crassipes* preferred habitats with sparse shrub and tree vegetation, this generally being observed in our study areas.

At the Kedrovskii open-pit coal mine, the centipede community on a 7-year old dump is primarily composed of *Lithobius sibiricus*. This species is readily adapted to anthropogenic habitats as well as open, human-cultivated agricultural lands (Nefediev et al. 2020). It seems particularly interesting that juveniles of *L. sibiricus* show low migratory activity, in contrast to the adults (Dunger and Voigtländer 1990).

Conclusions

Our study demonstrates that the colonization of coal mine spoil heaps by myriapods follows distinct successional patterns, strongly influenced by both the age of the disturbed sites and their edaphic conditions. Chilopoda (centipedes), as mobile predators, emerge as primary colonizers during early succession, rapidly adapting to extreme substrate conditions. In contrast, Diplopoda (millipedes) – specialized saprophages dependent on stable microhabitats – only establish populations during later stages of ecosystem recovery.

Statistical modeling identified key environmental drivers of myriapod community dynamics, including soil pH, moisture (HTC), organic matter, nitrogen content, and vegetation structure. Millipedes exhibited particularly strong dependence on stable substrate conditions and litter accumulation, while centipedes demonstrated greater ecological flexibility, facilitating their role as pioneer species in nascent trophic networks.

These findings highlight the critical importance of targeted reclamation strategies for restoring biodiversity in post-mining landscapes. To accelerate soil community development, we recommend integrated revegetation using fast-growing deciduous trees to promote humus formation and saprophage food resources; edaphic optimization through pH adjustment and organic matter enrichment, and long-term monitoring of myriapod succession as a bioindicator of ecosystem recovery.

Future research should focus on temporal scaling of these processes to refine bioremediation approaches for anthropogenically disturbed habitats.

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Supplementary material 1

Table 1S. Characteristics of the study sites
Table 2S. The results of the ANOVA evaluation for the «Diplopoda» group
Table 3S. The results of the ANOVA evaluation for the «Chilopoda» group

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