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RESEARCH ARTICLE

Dynamics of ground beetle (Carabidae) populations at rock dumps in an open-pit coal mine: modeling the influence of environmental factors

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Abstract

Mineral mining's adverse environmental effects encompass pollution of air, surface, and ground waters, as well as soil disruption. Kuzbass (south of West Siberia, Russia) exemplifies this impact due to open-pit coal mining, leading to the emergence of man-made landscapes like dumps and quarries. Mining firms undertake reclamation efforts on post-technogenic zones. Evaluating dump restoration involves assessing vegetation and animal components, including soil invertebrates and ground beetles, which are sensitive bioindicators of environmental health. The ecological balance of any species hinges on various environmental factors, both biotic and abiotic. Determining the most influential factors for a species' ecological niche is challenging. This study is part of an extensive investigation into the succession of ground-dwelling arthropods across varying-aged coal mine rock dumps in Kuzbass. Pitfall traps were employed from 2013 to 2022, yielding over 47,000 ground beetle specimens. A unique statistical model, computed in R, gauged the impact of environmental factors on ground beetle abundance. Predictors encompassed ground level temperature, hydrothermal coefficient (HTC), soil pH, Soil Organic Carbon (SOC), Total N, vegetation cover, turf extent, and succession stage. All these factors significantly influenced beetle numbers. Probabilistic graphical models effectively elucidated key relationships between species groups and environmental variables. Monitoring ground beetle community succession in technogenic zones necessitates comprehensive consideration of intricate environmental interactions.

Keywords
Carabidae, Statistical modeling, Organisms response, Assessment, Coal industry, Degraded areas, Succession, Western Siberia

Introduction

Mining leads to significant transformations of natural complexes: land resources are degraded, the biota inhabiting these territories is destroyed, and atmospheric air and water ecosystems are polluted.

The coal industry occupies a special place in the global production complex. Many countries in the world where coal is mined face negative environmental consequences (Goswami 2015; Habib and Khan 2021). Therefore, for example, large areas of land are withdrawn from agriculture and the forest fund, which are significantly transformed. Technogenic landscapes are being created, consisting of high mounds of host rocks and sandstones, dumps, as well as deep depressions – quarries formed after the removal of coal.

Kuzbass is one of the main coal-mining regions of Russia, accounting for 60% of steam coal production and 75% of coking coal production (Ryabov et al. 2021). Intensive coal mining has a negative impact on the environment. In 2022, coal mining companies were the leaders in terms of total air pollutant emissions in Kuzbass (60.4 %) (Report on...2023). Furthermore, the development of coal mines and surface mines worsens the hydrochemical composition of groundwater: periodic exceedances of maximum permissible concentrations of heavy metals, oil products, and nitrites are observed (Sasaev et al. 2021). The mining companies in Kuzbass are the cause of soil cover degradation and destruction with the formation of technogenic landscapes. According to data from the Russian Federal Service for the Supervision of Natural Resources (https://rpn.gov.ru), 4.072 thousand hectares of land were disturbed on the territory of the region during the development of mineral deposits in 2022. The total area of disturbed land is approximately 170 thousand hectares (Fotina et al. 2022).

Restoration processes on dumps occur both naturally due to the penetration of organisms from the surrounding biocenoses, and with the participation of humans who implement programs for the reclamation of disturbed lands (Hüttl and Gerwin 2005; Macdonald et al. 2015). The resulting initial ecosystems of technogenic landscapes can be prospectively considered as models for determining the speed and direction of restoration successions.

Among the communities of terrestrial invertebrates that inhabit technogenic landscapes, representatives of the Carabidae family stand out in terms of diversity and numerical superiority. The ecological-faunal analysis of ground beetles can be an effective and inexpensive method of monitoring the restoration of disturbed lands (Tizado and Núñez-Pérez 2014).

Despite the importance of this area of research, in the scientific literature, only the taxonomic composition of ground beetles in dumps is mainly considered (Dolný 2000; Mordkovich and Lyubechanskii 2019). Few works have also studied the influence of environmental factors on the restoration of carabid fauna, and the available data are contradictory and individual for each study area (Kielhorn et al. 1999; Kašák et al. 2017).

The application of statistical modelling in ecological studies has recently gained in popularity (Caro et al. 2016; Kirichenko-Babko et al. 2019; Tsafack et al. 2021). Using different models, the effects of climatic, ecological and geographical factors and their interactions on spatial distribution, species richness, abundance, and intraspecific variability of ground beetles and other invertebrate groups can be studied (Pakhomov et al. 2019; Liu et al. 2021a,b; Luzyanin et al. 2022; Sun et al. 2023). Special attention should be paid to the combined effect of several factors, as the influence of individual factors on the considered parameters will be significantly smaller (Lange et al. 2023). Modelling procedures can be effective tools in ecological monitoring to provide reliable and accurate estimates of current and future distribution, abundance, and population dynamics of species (Lohr et al. 2017). Despite the great popularity of statistical modelling methods, there are currently no full-fledged studies on the influence of environmental factors on the formation of ground beetle communities of coal mine waste rock dumps.

Therefore, the aim of our investigation was to reveal the impact of environmental factors on the number of ground beetles in the rock dumps of an open-pit coal mine. Specifically, we asked the following questions: (i) Do beetle number dynamics differ at two investigated rock dumps of an open pit coal mine; (ii) Do the rock dump location and plot properties contribute to beetle dynamics; (iii) What environmental factors contribute most to beetles number variation.

Materials and methods

Research area

We sampled beetles during all-inclusive studies conducted in 2013-2022 in differently aged dumps from Krasnobrodsky and Kedrovsky open-pit coal mines (West Siberia, Russia). The first is located in the forest-steppe zone of the Kuznetsk Basin, and the second is located in the forest zone on the board of the the forest-steppe zone of Kuznetsk Basin and the northwest part of the Kuznetsk-Alatau subtaiga (Fig. 1).

Restoration had been done in each dump: the rock mass on the dumps had been levelled, as well as soil applied on the surface, and 5–7-year-old *Pinus sylvestris* Linnaeus, 1753 and *Betula pendula* Roth, 1788 had been planted there before our studies.

Figure 1. Study area.

When planning our samplings, we took into account the stage of succession in each dump. Consequently, the following age categories were found in our experimental plots (data for 2013):

Kedrovsky rock dump – plot Kedr1 (55°30'38"N; 86°04'00"E, was located at the levelled top of the 5- to 7-year dump); plot Kedr2 (55°30'31"N; 86°04'12"E, was located at the terrace ledge of the 15-year dump); plot Kedr3 (55°30'29"N; 86°04'52"E, at the foot of the 25-year dump).

Krasnobrodsky rock dump – Krb1 (54°08'40"N; 86°27'27"E, at the plateau-like terrace of the 2-year dump; we began sampling there in 2016 after its recultivation in 2012–2014); plot Krb2 (54°09'06"N; 86°31'19"E at the flat top of the 7-year dump); plot Krb3 (54°09'16"N; 86°31'40"E at the terrace of the 25-year dump); plot Krb4 (54°09'19"N; 86°32'18"E at the foot of the 25-year dump).

Birch groves were selected as a nearby control site Krb5 (54°14'72"N; 86°49'27"E). The site was undisturbed with open cereal and grassy meadow communities and located 2 km west of the mining area. For the Kedrovsky rock dump, the control plot (Kedr4 55°33'26"N; 86°10'02"E) was located 3 km north of the experimental plots. It was a fragment of a sparse aspen-fir forest with a small admixture of birch and spruce.

Material sampling

We sampled beetles from May to August with pitfall traps – plastic cups, 250 ml in volume, and with neck diameter 70 mm with 4% acetic acid as fixative.

Different methods are used for pitfall arrangement on experimental plots (Dolný 2000; Novotná and Šťastná 2012; Kalda et al. 2015). In 2013–2014, the traps were arranged in a linear transect – 10 exemplars with a distance of 10 m.

In 2019, the sampling methods were lightly changed. In each plot, 3 sites were laid, located at a distance of about 100 m from each other. Five soil traps were installed on the site using the "envelope" method so that the distance between the edge points was no more than 10 m. A scheme of pitfall trap arrangement is given in a previously published paper (Luzyanin and Blinova 2022). We tried to place the traps away from the ant paths and visible nests in similar conditions of microrelief and type of vegetation. We believe that this method made it possible to obtain a better representative sample and minimised the impact of random factors (for example, the destruction of traps by humans or animals, the influence of abiotic components of the environment, etc.) on the sampling of invertebrates.

All traps received their serial number (1, 2…), which corresponded to their location at transect or the site. Beetles were evacuated every 7–10 days and all were recorded as the sampling unit. More than 47000 specimens were sampled.

We measured the ground-level temperature at each site using Hygrochron DS1923 - F5 automatic recorders, which were installed from early May to late August. The temperature was recorded continuously every 3 hours. To assess the level of moisture availability of the territory, the Selyaninov hydrothermal coefficient (HTC) was calculated (Luzyanin et al. 2023). We also recorded an initial assessment of soil agrochemical parameters of the soil (pH of the water extract, SOC, total N) in the laboratory of the Kemerovo Agrochemical Service Center of the Federal State Budgetary Institution. We described phytocenoses according to Lavrenko and Korchagin (1976).

Data analysis

Before modelling we checked the variation of independent variables in the studied plots. A small number of different values characterised environmental parameters. They were highly divers and slightly bound with plot: we tried to separate plots effect (perhaps not visible) and plots specific effects.

The number of unique values for the plots in the coal mines is given in Table 1. The number of variations in environmental factors in the investigated plots is presented in Table S1. So, only the temperature and HTC could be taken to the qualitative non-linear models. The values in 'pH' increased from plot 4 to plot 1 successively, besides that they did not overlap. SOC increased in order: plot 1 – plot 2 – plot 4 – plot 3 with abnormal values at plot 4 on 26.05.2014. The same characteristics had 'Total.N' without any abnormalities. The values of 'Vegetation cover' increased successively from plot 4 to plot 1 successively, only in plot 2 one trap had an abnormally high value. The values in 'Turf extent' increased in order plot 1 – plot 4 – plot 3 – plot 2 with an abnormally low value in one trap in plot 2.

Table 1. The number of unique values (*df*)

pH	**Soil Organic Carbon (SOC)**	**TotalN**	**Temperature (T)**	**Selyaninov hydrothermal coefficient (HTC)**	**Vegetation cover (Veg.Cov.)**	**Turf extent (Tur.ext)**
			Kedrovsky coal mine			
10	10	16	149	25	9	7
			Krasnobrodsky coal mine			
27	30	24	200	26	20	10

The main suggestion in model design:

- We used the total number of animals in the plot on the concrete date, so we summarised the number and exposition for all traps and averaged the values of the environmental factors values;
- We took control plots as the model Intercept;
- The number (in individuals) was the dependent variable, so we used the Poisson distribution. Unlike such a model was, the model traditionally based on logarithmic scale. We added the offset in its right part (linear prediction) in order to take into account exposition. This leads to the ln(Count/Exposition) modelling;
- As the model was processed on the logarithmic scale, all additive relations on the logarithm became multiplicative on the original scale in individuals. In other words, we estimate the relative contribution of each factor to the number of animals (in %);
- As all the plots were on the different stages of succession, we propose a nonlinear, specific for each plot, relationship between temperature and animal number;
- For the reasons mentioned above we supposed the impact of other factors similar for all plots; we used a low degree smoothing spline for modeling;
- We added the variable fPlot into the model; it reflected the contribution of plots determined by other factors (not mentioned in the tables above) factors; that contribution was taken as the constant on the logarithmic scale or the multiplier on the original;
- We suppose a similar impact of date on animal number in all plots;
- We added the variable fMethod to the model, as in 2022 the sampling method had been changed; that had to take into account changes in number due to the changes in sampling.

The model formula for the estimation of the contribution of environmental factors to the number of beetles was as follows:

~ offset(lExp) + fMethod + fPlot + s(Year, k = 3, by = fPlot) + s(DoY, k = 4) + s(pH, k = 3) + s(SOC, k = 3) + s(Total.N, k = 3) + s(T, k = 3, by = fPlot) + s(HTC, k = 3) + s(Veg.Cov, k = 3) + s(Tur.ext, k = 3).

The adequacy was done with quantiles graph (Q-Q plot). The latter showed the normality of the residuals distribution and its independence from the main factors. All statistical modelling was performed using the software R (version 4.0.2).

Result

Carabids number at different plots fluctuated in their own direction. The modeling showed that the number of beetles was plot-biased (Table 2). In addition, the annual number of beetles was plot-biased, too. Other factors studied significantly affected the number of beetles (Table 3). We analysed how the contribution of factors correlated with changes in numbers.

Table 2. Results of linear modelling of the effect of the "Plot" factor on ground beetles abundance

	Estimate	**Standard Error**	**z value**	**Pr(>|z|)**
		Kedrovsky coal mine		
Intercept	23.3883	1.4203	16.467	< 2e-16 ***
fMethodTRUE	–2.2991	0.6871	–3.346	0.00082 ***
fPlotKedr1	–15.6667	2.8977	–5.407	6.42e-08 ***
fPlotKedr2	–61.6033	3.7261	–16.533	< 2e-16 ***
fPlotKedr3	–13.4574	1.0003	–13.453	< 2e-16 ***
		Krasnobrodsky coal mine		
Intercept	27.1470	1.4031	19.348	< 2e-16 ***
fMethodTRUE	6.3721	0.2726	23.375	< 2e-16 ***
fPlotKrb1	0.4637	0.1721	2.694	0.00706 **
fPlotKrb2	7.5733	1.6480	4.595	4.32e-06 ***
fPlotKrb3	–30.8667	1.7156	–17.992	< 2e-16 ***
fPlotKrb4	–47.4876	2.3020	–20.629	< 2e-16 ***
fPlotKrb5	–59.5814	2.7825	–21.413	< 2e-16 ***

Significance codes: 0 "***" 0.001 "**" 0.01 '*' 0.05 "." 0.1 ' ' 1.

Table 3. Results of the effect of linear modelling of environmental factors on ground beetles number

Factor	Empirical distribution function	Reference degrees of freedom	Chi-squared test	*p*-value
Kedrovsky coal mine				
s(Year):fPlotKedr4	2.000	2.000	33.585	5.21e-08 ***
s(Year):fPlotKedr1	1.897	1.988	25.692	2.59e-06 ***
s(Year):fPlotKedr2	1.567	1.783	4.118	0.187
s(Year):fPlotKedr3	1.946	1.996	214.978	< 2e-16 ***
s(DoY)	2.979	3.000	420.883	< 2e-16 ***
s(pH)	2.000	2.000	71.572	2.78e-16 ***
s(SOC)	2.000	2.000	192.831	< 2e-16 ***
s(Total.N)	2.000	2.000	67.353	2.42e-15 ***
s(T):fPlotKedr4	1.997	2.000	178.975	< 2e-16 ***
s(T):fPlotKedr1	1.000	1.000	71.817	< 2e-16 ***
s(T):fPlotKedr2	1.979	1.999	169.705	< 2e-16 ***
s(T):fPlotKedr3	1.998	2.000	127.741	< 2e-16 ***
s(HTC)	1.975	1.999	124.816	< 2e-16 ***
s(Veg.Cov)	1.841	1.947	25.657	4.80e-05 ***
s(Tur.ext)	1.000	1.000	139.476	< 2e-16 ***
Krasnobrodsky coal mine				
s(Year):fPlotKrb1	1.001e+00	1.002e+00	619.86	< 2e-16 ***
s(Year):fPlotKrb2	2.000e+00	2.000e+00	652.29	< 2e-16 ***
s(Year):fPlotKrb3	1.945e+00	1.994e+00	969.49	< 2e-16 ***
s(Year):fPlotKrb4	2.000e+00	2.000e+00	1416.16	< 2e-16 ***
s(Year):fPlotKrb5	2.000e+00	2.000e+00	846.28	< 2e-16 ***
s(DoY)	2.957e+00	2.998e+00	960.18	< 2e-16 ***
s(pH)	1.864e+00	1.978e+00	871.62	< 2e-16 ***
s(SOC)	1.001e+00	1.001e+00	163.62	< 2e-16 ***
s(Total.N)	1.000e+00	1.000e+00	765.34	< 2e-16 ***
s(T):fPlotKrb1	1.977e+00	1.999e+00	235.11	< 2e-16 ***
s(T):fPlotKrb2	1.999e+00	2.000e+00	404.17	< 2e-16 ***
s(T):fPlotKrb3	1.880e+00	1.985e+00	199.00	< 2e-16 ***
s(T):fPlotKrb4	1.759e+00	1.941e+00	63.27	1.58e-14 ***
s(T):fPlotKrb5	1.961e+00	1.998e+00	375.63	< 2e-16 ***
s(HTC)	1.991e+00	2.000e+00	607.24	< 2e-16 ***
s(Veg.Cov)	1.994e+00	2.000e+00	52.52	3.90e-12 ***
s(Tur.ext)	2.000e+00	2.000e+00	686.22	< 2e-16 ***

Significance codes: 0 “***” 0.001 “**” 0.01 ‘*’ 0.05 “.” 0.1 ‘ ‘ 1.

Year of succession (Fig. 2A). At Kedr1 the curve was concave with a positive contribution on the 7th (2014) and 16th (2022) year of succession and a minimal (negative) contribution on the 10th (2016). At Kedr2 the contribution became positive after 2017 (the 16th year of succession) and they increased until 2022 (the 24-th year of succession). At Kedr3, the curve was convex. It reached maximal values in 2017 (the 24-th year of succession), and the contribution of year decreased to 2022 (the 29-th year of succession). In Kedr4 - the control plot – contribution of the factor 'Year' became positive in 2022. As it was a control plot, the year of succession was not discussed. But it should be noted that at Kedr3 the contribution of year to the number of beetles was maximal and number increased. But at the control plot in the same year the contribution was minimal, but the number increased too. The other factors played a role. Their contribution we discuss later.

At the same time, we concluded that number dynamics is determined by year conditions (the outer conditions) and the stage of succession as well. And once again: the number of other multiple factors affected the number of beetles, which will be discussed later.

At the second coal mine, Krasnobrodsky, in all experimental plots the maximum year contribution was at the beginning of the studies – in 2013 (it was the seventh, 15th and 20th years of succession). Then it gradually decreased and became zero in 2016 (it was the 10th, 18th, and 23rd years of succession). A similar pattern occurred in the control plot (Fig. 2B).

Thus, at the Kedrovsky open-pit coal mine in all plots, except Kedr3. The curves of the contribution of the 'year' factor were similar with a certain increase towards the end of the investigations. At Krasnobrodsky open-pit coal mine the curves were similar at all plots everywhere with the decrease in year contribution to beetles number towards the end of investigations. And in every plot the abundance really decreased. Nevertheless, the contribution values and the real number.

We carried out an analysis of correlation between the year contribution into beetle number according to model results and their real numbers in the samples.

At the Kedrovsky open-pit coal mine at Kedr1 and Kedr2, the number gradually decreased, but the first plot contribution of year was practically close to zero and at the second, it increased towards the end of investigations. At Kedr3, number increased though year contribution has been decreasing beginning from the middle of investigation. On the control plot, similarly, the dynamics of contribution and real number were the opposite.

We have analysed whether the changes in number were coupled on different plots. In other words, we compared in pairs how the number at different plots changed in adjacent years. There were scarce similarly directed changes in Kedrovsky open-pit plots, only in 6 cases of 27 (22%). At the Krasnobrodsky open-pit coal mine, the concurrence was greater: In 33% of the comparing cases, the direction in beetles number changes in different experimental plots coincided. Together with the control plot, this number was 48%. Therefore, in Krasnobrodsky open-pit coal mine the number dynamics was determined by a variety of environmental factors (weather, soil conditions, etc.) but not by succession stage.

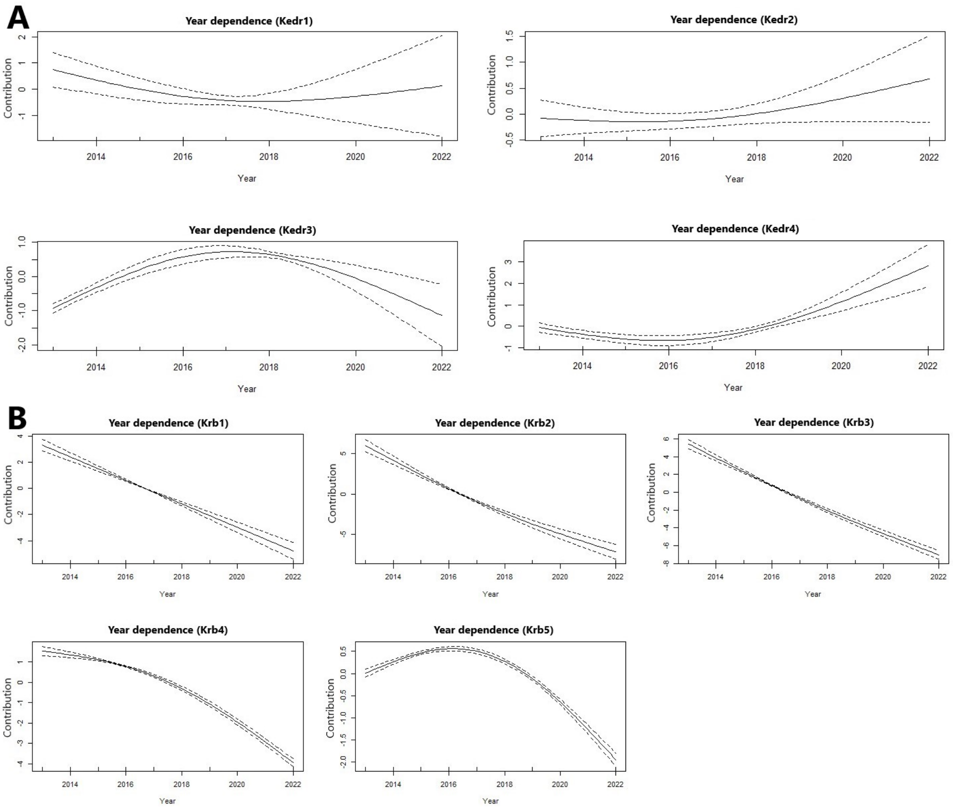

Figure 2. Contribution of the 'year' factor to beetle abundance on the plots: **A** – Kedrovsky coal mine; **B** – Krasnobrodsky coal mine.

Temperature. The temperature of 15 to 20 °C is believed to be optimal for the development of carabids. The modeling results confirmed this statement.

In Kedrovsky open-pit plots the positive contribution of temperature into beetle number really was observed at those temperatures and in the control plot it was even slightly shifted left (Fig. 3A). At the same time, the model showed that in the control plot and in part at Kedr3, the further increase in temperature would lead to the negative contribution of temperature to beetle abundance. It is also logic: at high temperatures, soil humidity decreases, and these phenomena negatively affect carabids larva growth.

At the Krasnobrodsky open-pit coal mine, the positive contribution of temperature to the number was also at 16–18 °C also. In the control plot, the shift to the left was also observed and the positive contribution of temperature to the number of beetles was observed at 13-14 °C (Fig. 3B).

Thus, at both open-pit coal mines, we observed similar patterns of temperature contribution into beetle number independently from succession stage.

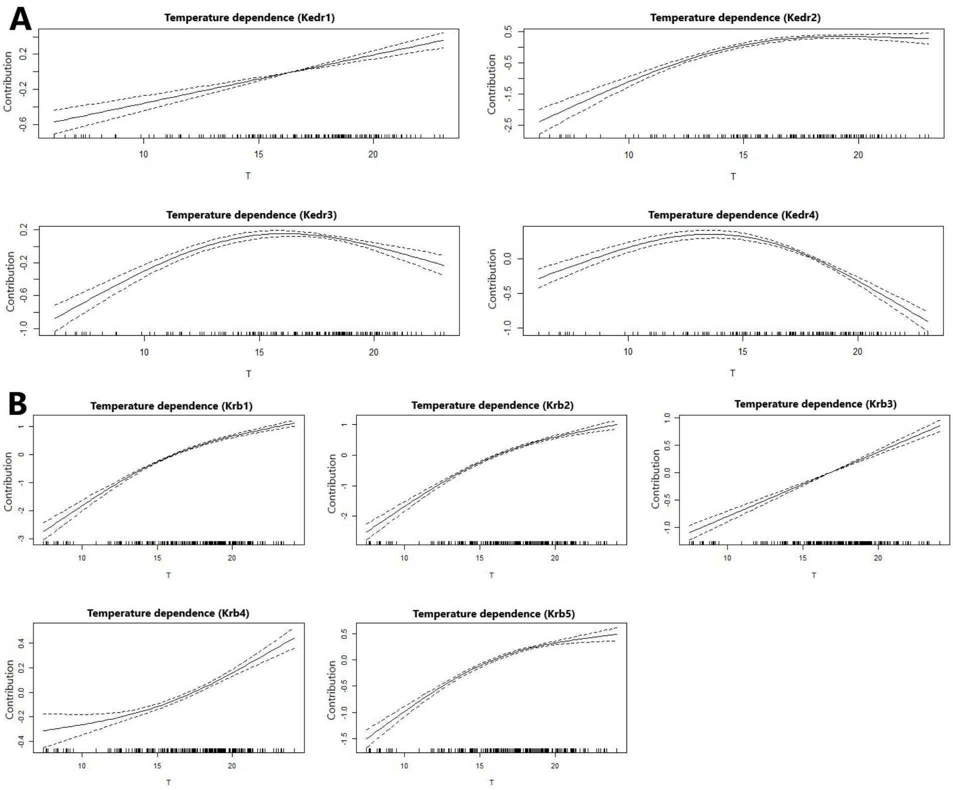

Figure 3. Contribution of the 'Temperature' factor to the abundance in the plots: **A** – Kedrovsky coal mine; **B** – Krasnobrodsky coal mine.

pH – its contribution was the largest at 7.5–8. It was at that level in Kedr3, Krb4. And we supposed that periodically the increase in number at those plots was promoted by pH (Fig. 4).

SOC – its contribution was the largest at 1. It was at that level in Kedr1. The curve was falling, then at Kedrovsky plots the more carbon was in soil, the lower was the density of beetles population. At the Krasnobrodsky open-pit coal mine, the situation was the opposite: The carbon content in the soil was positively correlated with the number of beetles.

Total nitrogen – its contribution was the largest at 0.4. It was at that level in Kedr4 and Krb5. But the type of contribution curves was fundamentally different: in the first case, a convex curve with a decrease in the contribution after the maximum value, and on Krasnobrodsky, the contribution of total nitrogen increases with an increase in its content in the soil.

HTC – contributed the most in abundance at 0 and 0.45. And it is the same on all plots. In Krasnobrodsky, it contributed the most at 2.5, but the data correlated with Kedrovsky, where the curve also went up from 0.45.

Vegetation cover – most of all contributed to the number at 65, it was at that level at Kedr1 and Kedr2. And in Krasnobrodskiy, a larger contribution was at 100, and such grass cover was in control.

Turf extent – its influence on Kedrovsky was unreliable. On Krasnobrodsky, it had the greatest contribution at minimum values. They were in the first plot.

Thus, the stage of succession could determine the number dynamics in carabids in our study. That thesis was supported by experimental data, similar values in number, and tendencies of its change in two independent plots (Kedr1 and Krb2).

But other factors also affected the number. For example, we observed an explicit difference in the number dynamics at Krb3 and Krb4. That case was determined by an optimal pH level, which contributed to that plots into number dynamics at the limit and led to its increase.

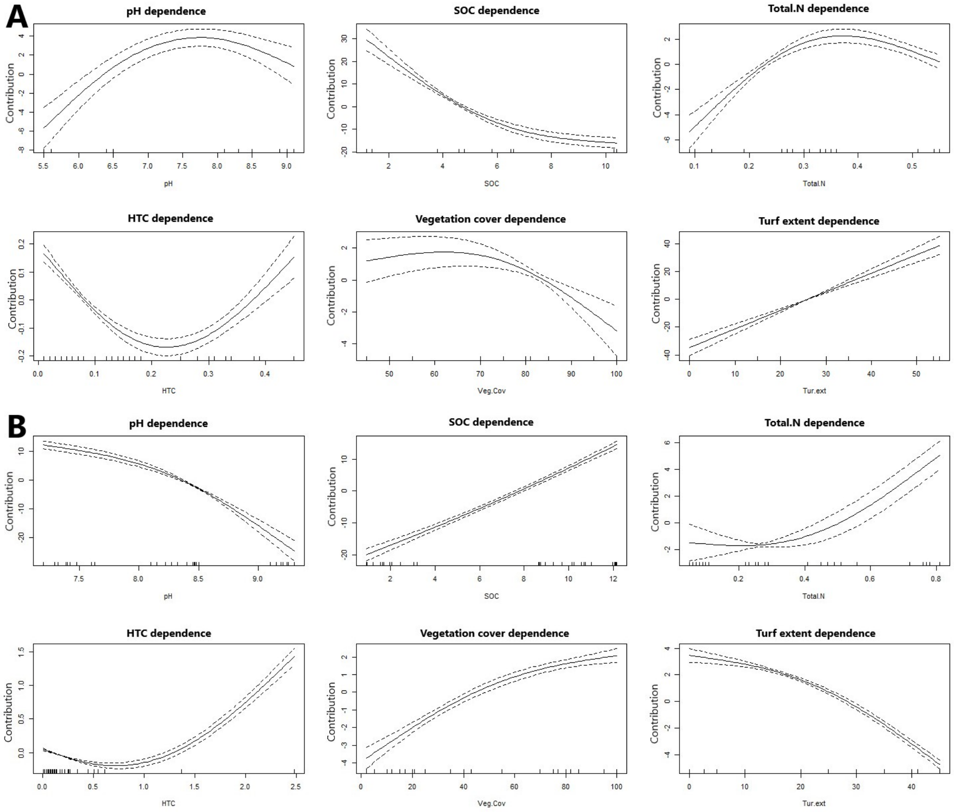

Figure 4. Contribution of environmental factors to the number of ground beetles: **A** – Kedrovsky coal mine; **B** – Krasnobrodsky coal mine.

Discussion

As we foresaw, the variation in the number of ground beetles differed at two investigated open-pit coal mines. All investigated environmental factors contributed significantly to that parameter. The year of succession did not show the largest contribution, as we proposed. Almost all environmental factors played in concert to determine the variations in the number of beetles. The latter increased when the set of environmental factors became optimal in a certain period of time for the reproduction of beetles.

Different environmental factors can affect the variation in the number of ground beetles. In our study, they were the temperature and the soil condition as well. Our study was carried out in open pit coal mine dumps. Naturally, the topography of the investigated plots differed. Topography is one of the soil forming factors that influences soil distribution soil properties and water erosion (Khan et al. 2013; Ziadat and Taimeh 2013; Bufebo et al. 2021). Hence, soil properties which varied on our different plots were the result of the interaction among soil formation factors and processes, making soil heterogeneous (Lawal et al. 2014). Such heterogeneity led to different curves in the variation in beetle number. The latter was recorded in our study. But modeling procedures confirmed the importance of succession stage in beetle number variation.

Our results showed similarity in the density of the Kedr1 in 2022 and Kedr2 in 2014. At that time, these plots were at the 15 to 16 years of succession. Similar similarity was observed at Krb1 and Krb2, when the stage of succession greatly contributed to the density of beetles. At the same time, out-modelling showed a significant interaction 'Year: plot', which explains the interaction of importance of the other environmental factors when regulating the number of ground beetles.

Soil biodiversity data is rapidly accumulating (White et al. 2020). In the large review of this article, the authors compiled already existing data on the abundance and diversity of soil animals (Hoogen et al. 2019; Lavelle et al. 2022). But practically none of them were related to the soil animals in the coal mine dumps. Papers on this topic are scarce. In one of them, the entire soil macrofauna was studied and the authors concluded that the colonisation of dumps depends not only on the age of the recultivated lands but also on habitat conditions (soil characteristics, vegetation parameters). At the beginning of the succession, the dumps are massively populated by small species that are tolerant of extreme conditions and have high dispersal abilities. The further development of vegetation entailed a change in the general structure of the ground dwelling communities of arthropods (Luzyanin et al. 2023). The latter fact undoubtedly concerned the ground beetle assemblages in our study. Modeling procedures showed that vegetation cover significantly contributed to the variation in beetle number. As vegetation tends to vary, the present soil ecology needs a temporal analysis of trends in soil organisms and functions (e.g., Eisenhauer et al. 2022; Körner et al. 2022). The undisputed advantage of our study was the long-term nature of the work. This allowed us to use modeling procedures.

We used original models in our study. Usually, a traditional tool is used to analyse the relationship between a response variable (e.g., species richness) and few environmental predictors. These are regressions with the akaike information criterion. The latter is considered the most 'important' drivers of the response variable. Probabilistic graphical models became powerful in identifying important links between groups of species and environmental variables (Ohlmann et al. 2018).

If we want to study soil biodiversity responses to environmental changes, manipulative experiments are relevant at the local scale (Blankinship et al. 2011; Eisenhauer et al. 2012; Phillips et al. 2019; Rillig et al. 2019). Such experiments are aimed at solving more broad problems on interactions between groups of soil organisms (Heemsbergen et al. 2004; Potapov, 2022). This fundamental knowledge is the basis for functional macroecology.

Moreover, we succeeded in targeted experiments to identify drivers and consequences of beetle number variation based on observational data. At each experimental plot, the set of environmental variables was unique. Most of soil-dependent factors (SOC and total N) did not change and only temperature during the seasons and the vegetation cover varied along the stages of succession. However, modeling results showed a significant contribution of all factors studied to the variation in ground beetle number.

Despite these advances, we still lack a generalised framework of aspects in beetle numbers at coal-mine dumps. We identified some key areas this may advance that understanding. This will allow us to develop predictive models for future changes in disturbed areas.

Conclusion

Much is unknown about how soil biodiversity and function will change in the future in response to simultaneous changes in climate and land use. It is crucial to understand the direct, indirect and interactive effects of soil environment on the number of ground beetles in their assemblages structure because soil biodiversity and functions are particularly complex to assess comprehensively. Hence, a combination of observational, experimental, and modelling approaches should be applied as we have done in our study.

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