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The Abiotic Habitat Factors and Soil Carbon Dioxide Release under Spontaneous Vegetation in Coal Mine Heaps

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ABSTRACT

This research is focused on examining the link between the abiotic conditions of coal mine heaps (specifically, the type of spontaneous vegetation) and their respiration rates. The hypothesis is that there is a significant correlation between the carbon content of the soil substrate and the respiration rate of the coal mine heap among the abiotic factors studied. The investigation was carried out on the mineral material found in coal mining heaps, which consisted of Carboniferous mineral rock material. The fieldwork spanned the vegetation seasons from 2018 to 2022. Various physicochemical parameters of the substrate samples were analyzed, including soil organic carbon content, electrical conductivity (EC), pH, total nitrogen (TN), available forms of phosphorus (P_2O_5) content, available magnesium (MgO) concentration, exchangeable cations (K^+, Na^+), and moisture. Soil respiration measurements were taken using the TARGAZ -1 analyzer. The amount of carbon dioxide released at the sites studied ranged from 0.00158 to 1.21462 [g CO_2/m^2/h]. It was found that the carbon content and all the environmental factors tested had a significant impact on soil respiration ($p = 0.001$), except total nitrogen ($p = 0.893$). The factors most strongly correlated with soil respiration were potassium (K), alkaline phosphatase, and SRL (soil respiration). Of the taxa analyzed, only the below-ground conditions provided by the vegetation communities dominated by *Centaurea stoebe* showed a significant correlation with SRL. Three dominant plant species influenced the development of below-ground conditions, leading to negative effects. On the other hand, the below-ground conditions associated with vegetation patches dominated by *Daucus carota* showed the strongest negative correlation.

Keywords: soil respiration, vegetation types, novel ecosystems, abiotic factors, coal mining heaps.

INTRODUCTION

The basis of ecology explains that the composition of vegetation trees and herbaceous species, along with the associated heterotroph species and saprotrophic organisms, is strictly dependent on habitat conditions. In this way, the ecosystem process reflects the relationship between habitat conditions. In all the ecosystem matter and energy flow functioning processes, soil respiration indicates various ecosystems and vegetation (Chen and Chen, 2019; Xiao et al., 2021). The release of carbon dioxide is among the crucial ecosystem functional processes. Soil respiration oxidizes organic carbon into inorganic CO_2 and releases energy. The CO_2 captured by plants is photosynthesized and transformed into organic compounds. This process is the basis of ecosystem functional processes in all ecosystems (Baral et al., 2016; Bark et al., 2016; Washbourne et al., 2020).

Photosynthesis and the autotrophic and heterotrophic carbon dioxide release are fundamental processes responsible for the carbon cycle in ecosystems. Respiration activity is releasing carbon as carbon dioxide from the soil's organic matter. Soil respiration is strictly related to the biochemistry of the composition of vegetation species. The composition of plant species influences vegetation and ecosystem biomass. In the natural and semi-natural ecosystems, it is known that both the vegetation biomass and the physical-chemical parameters of soil influence the carbon dioxide release processes (Bond-Lamberty and Thomson, 2010; Le Quéré et al., 2015). Soil carbon release, respiration is part of the global carbon cycle, releasing annually approximately ten times more carbon dioxide from all the habitats and ecosystems to the atmosphere than the fossil fuel used for heating per year (Bond-Lamberty and Thomson, 2010; Le Quéré et al., 2015).

Many factors influence carbon cycling and, as a consequence, soil respiration. It is challenging to distinguish the interactions between the factors. In the physiological processes of microbes and plants, soil respiration is sensitive to the most limiting or stress factors (Luo and Zhou, 2006). The soil microorganisms in the plant root zone are attracted by the selected chemical compounds, root exudates released by plant species in response to disturbances drought, salinity, or disturbances caused by mining (Luo and Zhou, 2006; Wolińska, 2019; Wolińska et al., 2014).

Estimating the below-ground respiration components is complicated and remains unresolved (Bouma and Bryla, 2000). The soil moisture, temperature, and texture are among the factors influencing soil respiration (Bouma et al., 1997a). The study conducted in agricultural lands found that soil moisture changes may influence respiration rates in fine sandy soil. In the wetland habitats, the soil CO_2 release was reduced; the more, the finer the texture, and the higher the clay content in the soil. However, the links between the root's architecture, soil texture, moisture, and respiration must be fully understood (Bouma and Bryla, 2000). The fine particles support the ability of water to hold well. The large particles interconnect, allowing air and water to exchange and move between the sphere - pedosphere (soil) and atmosphere. Bouma and Bryla (2000) tested the links between heterotrophic and autotrophic CO_2 released for soils, characterized by drying and wetting cycles in varied soil texture conditions. The soil carbon dioxide amount has been identified to influence the respiration rates of the soil microbial communities (Koizumi et al., 1991) and the respiration level of plant species roots (Bouma et al., 1997b, a; Burton et al., 1997; Scheurwater et al., 1998). The soil texture condition influences the soil water links considerably (Singer and Munns, 1991); the changes in CO_2 amount may also be modified along the soil texture gradient.

In agriculture, studies compare the influence of the soil CO_2 concentrations, soil water uptake, water content, soil texture (clay, silt, sand content), and root respiration on citrus species seedlings' growth (Bouma et al., 1997a, 1997b; Bouma and Bryla, 2000) The temperature, moisture, nutrient content, and level of oxygen, are factors that control the soil respiration rates. Human activity, such as mining, can influence the amount of soil respiration by altering the parameters. The above conditions can influence the rates of the soil's global respiration. The following should be listed: the agricultural increase of nitrogen and phosphorus fertilization over time and space scales.

Many abiotic factors (e.g., moisture, temperature, soil texture, micro-, macro-element, soil pH, nitrogen deposition (Fenn et al., 2010; Radosz et al., 2023) affect soil respiration (Heinemeyer et al., 2007; Mo et al., 2008). Temperature influences many aboveground and below-ground processes. Soil respiration is a fundamental ecosystem functional process (Atkin and Tjoelker, 2003; Moyano et al., 2008, 2007). The temperature-respiration models indicate the links between temperature and soil respiration rates (Davidson and Janssens, 2006; Zheng et al., 2009). The extreme of soil moisture (low or high) are factors that affect strongly the soil carbon release (Ilstedt et al., 2000; Borken et al., 2003; Wang et al., 2003). Physico-chemical factors, such as soil pH, impact some soil respiration parameters. The soil pH can modify the activities of soil microorganisms and, later, the respiration of soil organic matter and plant biomass (Ilstedt et al., 2000; Sitaula et al., 1995). Photosynthesis indirectly influences soil respiration (Zhang et al., 2013). In many studies' the role of abiotic habitat factors on soil respiration is analyzed separately from the other factors. Some parameters are synergic and do not act independently but interact with each other, e.g., due to feedback relations and affect soil respiration (Yu et al., 2015).

The abiotic and biotic links might become complicated when the spontaneous vegetation patches and the ecosystems are developing on novel ecosystem habitats (Hobbs et al., 2006), e.g., mining post-mineral excavation sites. The *de novo* established mineral sites allow research on the relations among the individuals of the dominant plant species and the biotic and abiotic mineral soil substrate characteristics along with the colonizing best-adapted plant species individuals, richness value, and biomass amount of the spontaneously developing vegetation. In novel ecosystems, the biotic and biotic relationships might be shaped by the effect of previously unknown relations resulting from the human impact on the ecosystems during the so-called Anthropocene Epoch (Zalasiewicz et al., 2016). The post-mineral excavation places represent the newly artificial habitats that are significantly different from the natural and semi-natural ecosystems in the neighborhood landscape. Some studies have shown that the living organisms intensively colonized these places through spontaneous succession, providing new non-analogous species compositions of flora and fauna (Hobbs et al., 2006; Kowarik et al., 2011; Frouz, 2018). The varied chemical and physical conditions of post-mineral mining habitats resulted in the development of new unknown, non-analogous species compositions of the spontaneous vegetation and other organisms (Woźniak, 2010; Helingerová et al., 2010; Keith et al., 2009). The non-analogous species vegetation composition growing on novel ecosystems post-mining heaps presents a mosaic of vegetation patches that are dominated by different species best adapted to the range of available microhabitats (Rawlik et al., 2018a, 2018b). The observed mosaic reflects the variety of biotic and abiotic habitat conditions (Woźniak, 2010). The influence of the early-successional stages of vegetation communities on the harsh mineral soil habitat site conditions is not understood (Woźniak, 2010; Lamošová et al., 2010; Orwin et al., 2014). The presented research aims to analyze the vascular plant species composition assembled on various mineral materials of post-mining sites.

Some studies on soil respiration (Rs) and temperature sensitivity (Q_{10}) concentration are focused on humidity, soil temperature, carbon and nitrogen, and root biomass (Arevalo et al., 2010; Wang et al., 2018). The soil microorganisms' composition shapes most of the soil functions (Xiao et al., 2021). The extreme habitat conditions of the coal mine heaps of novel ecosystem mineral material are crucial to how the abiotic site parameters and the plant species composition of developed vegetation types impact the soil substrate respiration parameters of the studied ecosystem. This study aims to analyze the links between the abiotic factors of the post-coal mining heaps (spontaneous vegetation types) and the carbon dioxide release rates of the soil substrate. We compared the respiration levels to the studied habitat field water content, the texture EC, pH, the water holding capacity (WHC), basic abiotic N_T, C_T, and exchangeable cations Mg, Ca, Na, K and soil CO_2 release of coal mine heaps novel ecosystems soil substratum under the recorded spontaneous vegetation types.

In particular, we tested which abiotic habitat conditions influence the carbon dioxide release rates most. We hypothesized (assuming) that the C content will influence the carbon dioxide release level most significantly. The abiotic parameters, like the WHC texture of the soil substratum, EC, and pH, will not significantly impact; only texture will significantly influence mineral soil substrate material, as it influences moisture and indirectly the other parameters.

MATERIAL AND METHODS

Site description

Several 324 study plots have been studied. The stratified random sampling method was used to select the plots for the study. The sampling method was based on research conducted by Woźniak, 2010, in the same habitats. The Silesian Upland is in a temperate climate zone, transitioning between continental and oceanic climates. Its weather is predominantly shaped by polar maritime air masses originating from the Atlantic (60% of the time) and polar-continental air masses originating from Eurasia (30% of the time).

The post-coal mine has heaps of Carboniferous rock mineral material. The heaps are sites with habitat conditions different from those known from natural or semi-natural ones. The new man-created landscape forms are unique sites because they provide oligotrophic conditions (very poor in nutrients, such as phosphorus, nitrogen, sulfur, and carbon) mineral substrates; after many years of study, it has been shown that plants and animals have colonized them despite unfavorable conditions (Woźniak, 2010; Radosz et al., 2019). During the field research, the object was analyzed: "Makoszowy" (Zabrze, Sosnica; 50°16′22″ N, 18°44′43″ E); "Kostuchna" in Katowice (50°11′04″ N, 19°00′33″ E); "Murcki Boże Dary" in Murcki (50°11′21″ N, 19°02′07″ E); and "Wesoła" in Mysłowice (50°10′28″ N, 19°5′44″ E).

Vegetation sampling and vegetation diversity analysis

Land cover data were made on study plots of inhomogeneous vegetation patches dominated by the dominant species studied of a circular shape of 3 m radius. Each study plot's geographic coordinates of its center point were recorded using a GPS receiver. In each plot, the species composition was written down, and the coverage of each vascular plant species was valued according to a 10 – grade scale (< 1%, 1–5%, 5–10%, 10–20%, 20–30%, 30–40%, 40–50%, etc. in 10% increments – Method Braun-Blanquet). The plant species individuals that cover the most significant area of the research plots compared to the rest of the vegetation were identified as the dominant species. The collected data were used to calculate diversity indices in the analyzed area of the post-mining heap. Based on the phytosociological records, the following indices were calculated: Shannon-Wiener H's diversity index, Evenness uniformity index, and Simpson's dominance index (Woźniak, 2010).

Biomass sampling

In the analyzed vegetation study plots of a circular shape (3 m radius) dominated by an identified dominant plant species (the species that covers the most significant area within the studied plot compared to the accompanying species, the vegetation biomass was sampled. The collected plants were stored in string bags. The samples were weighed in the field, and data were obtained on the fresh biomass of the dominant species and the other (rest) plant species separately. A representative biomass of 0.25 square meters was selected in the test plot, i.e., including the dominant plant species and best representative of the entire vegetation patch. The test plot frame is 0.5 m of one-side length.

Respiration measurement - CO_2 gas analyzer

Soil respiration values were taken using the TARGAZ-1 analyzer. Five measurements were taken on the vegetation patches analyzed to average the results and check the level of CO_2 emissions over the entire analyzed area. The design of the instrument ensures calibration stability. The soil carbon dioxide efflux level is obtained based on increased CO_2 in the chamber. CO_2 continues to accumulate within the closed chambers. The measurement periods are reduced to obtain a detectable linear concentration increase without an excessive build-up of carbon dioxide inside the chamber over time. During the measurement, the soil respiration chamber covers a surface area of 78 cm^2 and a volume of 1171 cm^3. The edge of the measurement chamber was placed into the heap soil substrate to a depth of about 1–2 cm.

Laboratory analysis – physicochemical analyses of soil substrate

The soil mineral substrate samples collected for the abiotic physicochemical analyses were air-dried. Later, the soil mineral substrate samples were ground and sieved to a fraction smaller than 2 mm. Substrate mineral samples were analyzed to assess the following physicochemical parameters: electrical conductivity (EC), pH, C loss of ignition, soil organic carbon content (SOC), total N (TN), available forms of phosphorus (P_2O_5) content, available Mg (MgO) concentration, exchangeable cations (K^+, Na^+) and moisture. The mineral soil substrate samples of about 1 Kg were taken to analyze soil abiotic physicochemical characteristics data. The soil substratum mineral samples were obtained from five subsampling points in each plot. The samples were collected at 0–15 cm profile depth at each plot sample site. The following have been collected and measured among the measured soil substratum parameters: the total soil porosity and maximum (WHC) water holding capacity. The concentration of bioavailable Mg (MgO) was determined using the Schachtschabel method; 0.0125 M calcium chloride was used as the extraction solution. Based on the Egner-Riehm method, the bioavailable phosphorus (P_2O_5) content was assessed following the Polish Standard PN-R-04023:1996. The amount of soil organic carbon (SOC) was determined using the Tiurin method. The total nitrogen amount was assessed using the Kjeldahl method. pH of the substrate was measured after 24 hours of equilibrium at a ratio of 1:2.5 substrate/solution (Bierza et al., 2023).

Data analysis

All statistical tests and visualization were performed in R language and environment ver. 4.2.2 (R Core Team 2022) and implemented therein packages. The Spearman rank correlation coefficients and probability were computed to analyze the relations between soil carbon dioxide release and particular abiotic mineral soil substratum variables. To explore overall relationships among physicochemical soil data, biotic variables of soil, and soil respiration, Principal Components Analysis (PCA) was done. Before the analysis, data were standardized to avoid impacts of different ranges and distributions of the variables. The PCA enabled us to select the most critical factors responsible for soil variation. The most contributing variables were subjected to Spearman rank correlation analysis with the vegetation matrix. The vegetation matrix was calculated based on raw vegetation data and Manhattan dissimilarity for abundance data (vegan: vegdist) and Manhattan distance as a metric for soil data. The function bioenv () was used to find the best subset of environmental variables to obtain maximum (rank) correlation with the factor of community dissimilarity.

We also used another approach based on fuzzy set ordination (Boyce, 1998; Roberts, 1986) to find environmental factors responsible for shaping vegetation. The FSO was followed by multidimensional fuzzy set ordination (MFSO) with step-wise variable selection using fso:fso() and mfso() functions. FSO is a direct ordination tool, an alternative to canonical correspondence analysis (CCA) and redundancy analysis (RDA). In FSO cases, partial membership (fuzzy) values are assigned ranging from 0 to 1, which denotes their degree of membership in a set (Roberts, 2008). In eigen-based ordinations methods like CCA and RDA, distance-based redundancy analysis db-RDA, the configuration of points is first calculated as a correspondence analysis CA or PCA, principal coordinates analysis PCO respectively, which is then subjected to weighted regression against environmental or experimental variables, keeping the fitted values of the regression as coordinates. Thus, CCA and db-RDA are sometimes referred to as “constrained ordinations” as they constrain the values of the underlying ordination to achieve what is typically referred to as their “canonical” axes. The FSO analysis is the first technique that directly incorporates the environmental data into the configuration calculation. Likewise, the responses of individual species to abiotic factors are not limited to a specific function. For example, the species’ responses can be discontinuous or nonlinear (Zaharescu et al., 2017). Sometimes, FSO is treated as a constrained version of polar (Bray-Curtis) ordination. In our study, FSO was done to assess the relationship between particular environmental factors and vegetation dissimilarity. In turn, MFSO provided goodness of fit criterion that is expressed by the correlation between Euclidean distances of all samples in the ordination space of vegetation plant species composition and their original dissimilarities. The high value of the correlation indicates an effective ordination. Environmental variables significantly affect species composition (Roberts, 2008). Both in FSO and MFSO, 1000 iterations of permutations were done based on Manhattan distance in the dissimilarity of vegetation using vegan: vegdist(). In MFSO, the default method was followed by a step-wise procedure where SRL content was included in the model due to its high significance in the initial results of MFSO and to find other significant environmental factors that influence species composition variation. To indicate the most affected plant species by SRL, the species with at least a frequency of 15% (i.e., 50 plots occupied) were selected and then correlated with SRL. The Spearman rank correlation was done with pairwise complete observations.

RESULTS

The preliminary analysis is focused on the diversity of spontaneous vegetation types. The diversity of vegetation types reflects habitat conditions and enables the measured biomass vegetation/ecosystem unit to be identified clearly. The analysis revealed different vegetation types. The studied sites were established from Carboniferous mineral material. The fieldwork was carried out in the 2018–2022 vegetation seasons. During this research, 210 plots were studied, vascular plant species were recorded, and detailed soil substratum analysis was performed. Substrate samples were analyzed for the following physicochemical parameters: pH, electrical conductivity (EC), soil organic carbon content (SOC), total N (TN), available forms of phosphorus (P_2O_5) content, available Mg (MgO) concentration, exchangeable cations (K^+, Na^+) and moisture. Soil respiration values were taken using the TARGAZ -1 analyzer. Five measurements were taken on the vegetation patches analyzed to average the results and check the level of CO_2 emissions over the entire analyzed area. The range of carbon dioxide released at the analyzed sites was 0.00158 - 1.21462 [g $CO_2/m_2/h$] (Fig. 1).

The four environmental factors, i.e., acid phosphatase and pH, were positive, and the content of potassium and potworms were negatively significantly correlated with SRL (Figure 1). According to PCA based on standardized variables, the high contribution to the presented gradients was revealed by Mg, K, Ca, pH aqua, pH KCL, Basic phosphatase, and NT (Fig. 2). The soil respiration level responding to the identified gradients. Nitrogen and carbon did not influence the intensity of soil respiration. The indirect phosphorus measure, the acid phosphatase, and pH (aqua)

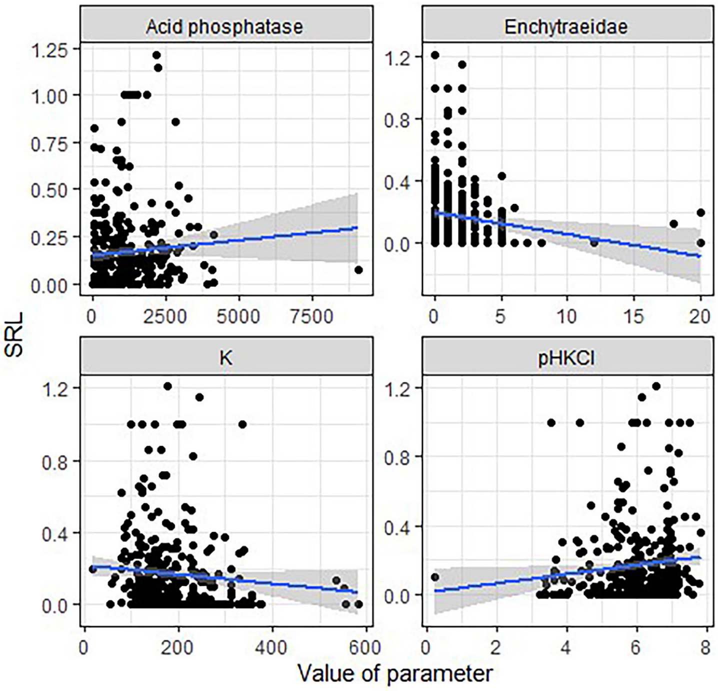

Figure 1. The Spearman correlation between SRL and soil variables (only significant factors are shown)

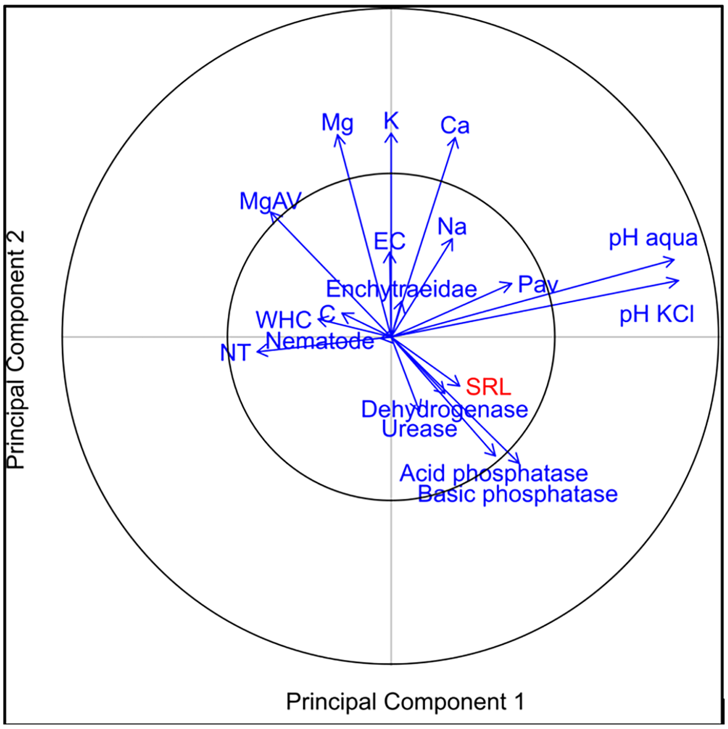

Figure 2. The principal component analysis of soil data and their relations with soil respiration SRL

were excluded due to the correlation with other variables. The Bioenv function revealed that the best fitting model had 9 parameters (with max. 13 allowed): WHC, pHKCl, NT, C, Mg, MgAV, K, and the indirect including Dehydrogenase, and Urease, with a correlation of 0.20. The function excluded SRL, either.

Figure 3 shows the links between vegetation dissimilarity and values of chosen environmental factors based on FSO. All studied abiotic factors were recognized as significant (p = 0.001) apart from the total nitrogen (p = 0.893). The potassium (K) content, the indirectly available phosphorus (essential phosphatase), and the soil respiration level revealed the highest correlation. The correlations among particular variables in FSO are shown in tab. 1. The relation has been identified between soil respiration level and total nitrogen, followed by pH, and negative ones with calcium and magnesium. In the MFSO, the relation between ordination distance and the matrix dissimilarity of vegetation is relatively (r = 0.748, Fig. 4). In the results of MFSO analysis, samples of vegetation are arranged mainly through soil respiration (especially in essential phosphatase, potassium) and further by other environmental factors what was confirmed by p-value (Table 2). In all cases most of samples are concentrated at lower value of SRL (Fig 4). Some vegetation plots present the association with higher values along axes represented by SRL. In the case of Mg and Ca, samples are also grouped similarly, suggesting that these variables are correlated.

Both in MFSO and more robust step-wise, MFSO soil respiration significantly improved the model of the impact of environmental parameters on vegetation patterns (Table 2). When SRL was included in the model, the other significant vital variables that explain species variation were magnesium, potassium, pH and essential phosphatase, while remaining factors (total nitrogen, calcium) were not significant (Table 2). Mapping the distributions of the sample point from the fuzzy topological space of fuzzy set ordination (FSO). Using the Euclidean space for the distributions of the sample points enables analysis using a broad range of parametric statistical methods. The results obtained by Roberts (2009) show direct interpretability, as each axis in an MFSO reflects a single environmental variable and is orthogonal

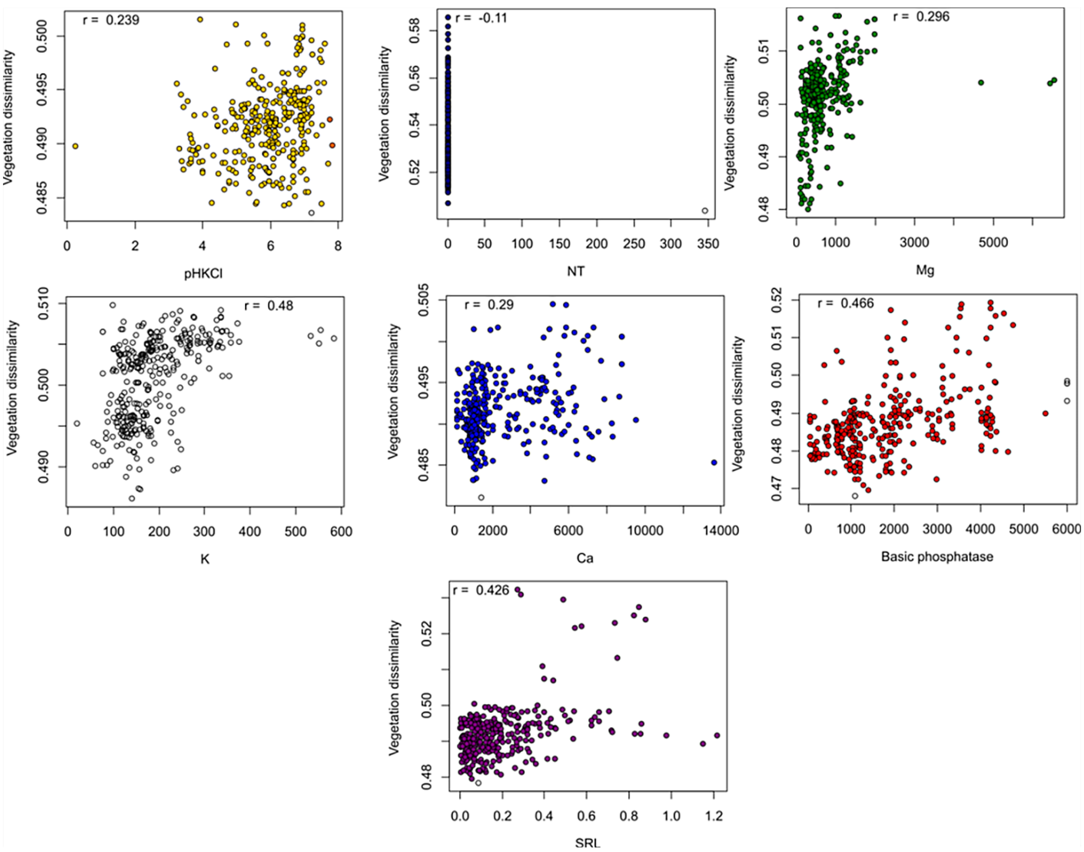

Figure 3. The relation linking the soil respiration level and particular soil variables on the background of vegetation based dissimilarity on the fuzzy ordination

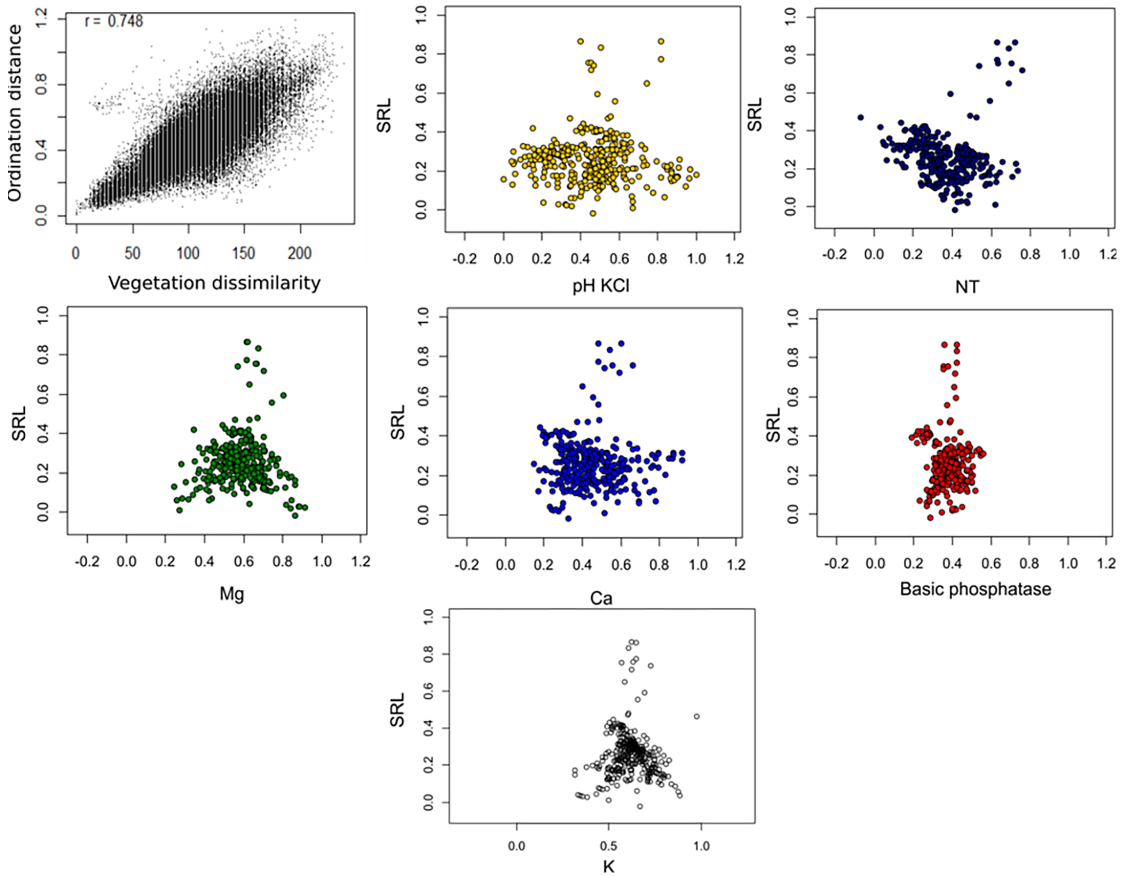

Figure 4. The plots of multidimensional fuzzy set ordination diagrams of coal mine heaps. The vertical axis represents soil respiration, and the horizontal axis – represents other soil variables

Table 1. The correlation of fuzzy set ordination between the soil substrate characteristics and the soil (substrate) respiration parameters

Soil substrate	pHKCl	NT	Mg	K	Ca	Basic phosphatase
pHKCl		-0.672142	-0.755854	-0.5754234	0.1957003	0.8574878
NT	-0.672142		0.4782322	0.6274184	-0.2250911	-0.5791621
Mg	-0.755854	0.478232		0.7848299	0.0708542	-0.8873671
K	-0.575423	0.627418	0.7848299		0.2511016	-0.7128900
Ca	0.195700	-0.225091	0.0708542	0.2511010		0.0671225
B. phosphatase	0.857488	-0.579162	-0.8873671	-0.7128900	0.0671225	
SRL	0.151741	0.169597	-0.1434519	-0.0024395	-0.1338680	0.1436176

Table 2. The results of multi-fuzzy set ordination (MFSO) and step-wise MFSO

MFSO			And step-wise MFSO			
Variable	Cumulative_r	Increment	P-value	Gamma	Delta_cor	P-value
pHKCl	0.3677557	0.36775571	0.670	1.0000000	0.07768200	0.01
NT	0.4408519	0.07309617	0.348	0.5482247	-0.14407976	0.59
Mg	0.5464880	0.10563616	0.379	0.4270644	0.22695488	0.01
Ca	0.6265471	0.08005902	0.280	0.8388148	0.04924796	0.40
K	0.6539962	0.02744911	0.837	0.1953713	0.12357905	0.01
Basic phosphatase	0.6610047	0.00700857	0.984	0.1281119	0.17304420	0.01
SRL	0.7477256	0.08672083	0.004	0.8264381	Included in the model	

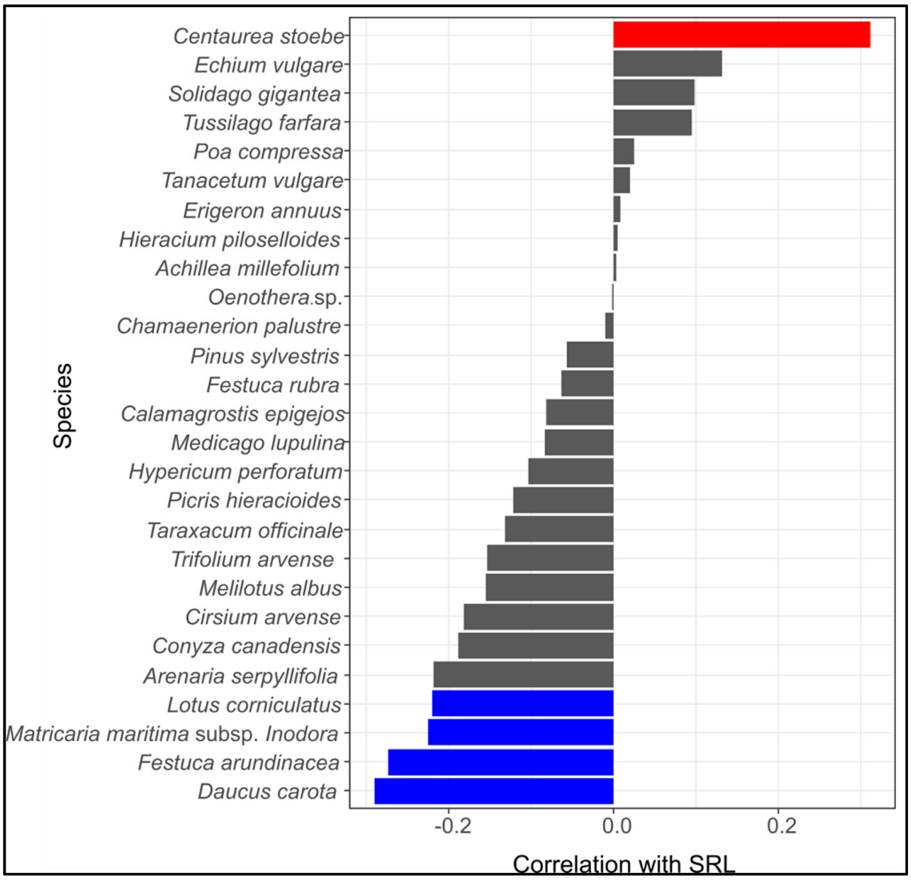

Figure 5. The analysis was performed using Spearman correlation coefficient values based on complete pairwise observations of the most frequently occurring plant species and soil carbon dioxide release values in coal mine heaps. Red indicates – positive significant relationships, and blue indicates significant negative correlations

to all other axes by design. Among 27 taxa (26 species), only the conditions associated with the patches of vegetation communities dominated *Centaurea stoebe* were correlated with the value of soil respiration level. The patches of vegetation communities of three other plant species dominants provide conditions that negatively impact the release of carbon dioxide. The most robust negative relation was provided by habitat conditions developed along with the vegetation patches dominated by *Daucus carota and, to a lesser extent, Festuca arundinacea and Matricaria maritima* subsp-inodora (Figure 5).

DISCUSSION

This study analyses the links between the abiotic conditions of the mineral site material of the coal mine heaps (spontaneous vegetation-type patches) and the respiration rates. We have tested the hypothesis that the soil substrate carbon content is significantly related to the coal mine heap spontaneous vegetation respiration rate among the studied abiotic factors. The habitats and vegetation types with higher carbon content are releasing more CO_2. Contrary to our expectations, soil carbon content did not significantly influence soil respiration intensity. There might be a few reasons why the results contradict our hypothesis. The carbon (C) cycle, together with nitrogen, is the primary nutrient cycle in ecosystems, and it has only sometimes been considered in detail (Cusack et al., 2011; Sinsabaugh et al., 2005). Carbon, phosphorus, and nitrogen cycles are frequently interlinked in ecosystems (Fahey et al., 2013; Zarif et al., 2020). In some ecosystems, and probably should also be considered in mineral soil substratum material of new coal mine ecosystems, the C:N ratio in the soil (subsoil) supports the available N uptake by plants (Eberwein et al., 2017; Zarif et al., 2020). In our study, some of the analyzed abiotic habitat factors have been revealed to be significant ($p = 0.001$). The exception has been stated for total nitrogen content ($p = 0.893$). The content of Potassium (K), the indirect measurement of the alkaline phosphatase, presented the highest correlation with the soil expiration level. The total nitrogen amount, followed by pH, presented the highest positive correlation with soil expiration level, while the carbon release was negatively related to magnesium and calcium.

The phosphorus content influencing the SRL

The phosphorus, particularly the available forms of phosphorus in soil or mineral soil substratum, is, to some extent, related and linked to the activity of the phosphatases. In our study, alkaline phosphatase was linked to the amount of carbon dioxide released by the mineral soil substratum. Chemically, the phosphorus component in soils is a low-mobility element. Plant roots are available only from the close vicinity of the roots and are highly pH- and temperature-dependent. The P cycle can be significantly connected with the N cycle (De Groot et al., 2001; Aber et al., 1989). In the presented study, the base phosphatase activity is a proxy for the phosphorus content parameter mineral soil substratum in the coal mine heaps novel ecosystems. The study showed a positive correlation between base phosphatase activity and the amount of carbon dioxide released.

Most of the previous studies analyzing the soil respiration levels have paid attention to the role of nitrogen in the first place. The phosphorus content has been considered as an element that interacts with nitrogen (Guo et al., 2016; Helfenstein et al., 2020; Zhang and Zhang, 2016; Zhang et al., 2020). The mineral inorganic phosphorus (Pi) changes to organic phosphorus (Po) and can take part in the soil P bioavailability (Helfenstein et al., 2020, 2018; Rosling et al., 2016). Some studies show phosphorus increases litter nitrogen, limiting nitrogen mineralization (Homeier et al., 2017; Mao et al., 2017). The constant nitrogen uptake, e.g., the inorganic nitrogen from the atmosphere is reducing the soil acidity, which can lead to the buffering effect caused by the additional phosphorus that keeps the soil pH at a stable level (Mao et al., 2017; Yang et al., 2015; Zarif et al., 2020). What is a factor that stabilizes soil respiration in developing ecosystems? This can be the possible interpretation of the results obtained in our research on mineral soil substratum respiration rate level, measured in the habitat from under the different spontaneous vegetation types.

The carbon dioxide released in the carbon life cycle

The carbon cycle through the inorganic and organic forms and the dynamic interaction with various nitrogen and phosphorus is the fundamental functional process in each ecosystem (Cusack et al., 2011; Sinsabaugh et al., 2005). Including the base cations and soil pH impact in the C, N, and P cycles in the biotic abiotic transition process are good practical eco-chemical indicators of soil health in a dynamic approach (Futa et al.,2016; Małek, 2009). The soil or mineral soil material development is dependent on the vegetation plant species composition in the ecosystem vegetation patches mosaic (Binkley et al., 1999; Rhoades, 1996), and likewise, the modifications in the local and global habitat conditions may impact the diversity and composition of plant species composition in the communities (Bardgett, 2005; Zarif et al., 2020; Bolan, 1991). The additional phosphorus content significantly increased by 60% in the soil exchangeable cations (Yang et al., 2015). The weathering of the selected base cations, including Ca > Na > Mg > K, can cause the reduction of the base cation amount and some metal ion imbalances in the mineral soil substratum, as has been presented by Lucas et al. (2011).

The understanding of the mechanisms of the mineral soil substratum carbon dioxide release level about the abiotic factors along the feedback relation of the plant species composition is crucial for a range of reasons (Bouma and Bryla, 2000; Šimůnek and Suarez, 1993; Skopp et al., 1990). Many studies conducted on soil respiration rate assessments are performed in agriculture, cropland, grasslands, and managed forests (Xiao et al., 2021). More research needs to be focused on studying soil respiration parameters in other, e.g., natural ecosystems and spontaneous ecosystems developed in, e.g., human-established habitats, such as the post-mining mine heaps providing specific habitat conditions of mineral soil material. Some studies show that the carbon dioxide released from soil declines from summer to winter. Additionally, this study has presented that soil temperature and moisture are crucial factors that support the explanation of the results obtained. The mean soil respiration in grassland (3.68 μ_{mol} m^{-2} s^{-1}) and tree stands or woodlands (3.81 μ_{mol} m^{-2} s^{-1}) appear higher than in abandoned agricultural land and cropland. In the projection values of the variable importance from the regression model, it has been presented that the soil temperature, pH, soil moisture, available nitrogen, microbial biomass carbon, nitrogen, and bacterial abundance were the crucial factors that have an impact on the soil respiration level in the studied under different land-use types habitats (Xiao et al., 2021). In our study, we could not include the measurements for root respiration. There are studies in which the importance of root respiration has been underlined. There are assessments that in some habitats, the roots can respire (use energy and release carbon dioxide to an extent more than 50% of plant daily photosynthesis efficiency, the produced biomass (Lambers et al., 2002).

The overall soil respiration includes two main components: the respiration of the microorganisms and plant roots and respiration both based on soil organic matter, plant biomass, soil animals, and litter (Scott-Denton et al., 2006; Bond-Lamberty et al., 2004; Hanson et al., 2000; Rodeghiero and Cescatti, 2006). The measurement of both elements of total respiration is methodologically challenging. For this reason, a relatively low number of studies have attempted to perform the separated measurement of the two above respiration components (Butler et al., 2013; Jiang et al., 2017; Kooijman, Welschen and Lambers, 1988; Bouma, Broekhuysen and Veen, 1996). The equipment most frequently used is the surface chambers or chambers buried with carbon dioxide sensors. Soil respiration is generally measured over a restricted area (< 1 m^2). The soil has a limited diffusivity, and carbon dioxide is more concentrated than in the atmosphere (Phillips and Nickerson, 2015). In the presented study, we have used one of the most frequently and commonly used soil respiration measurements. We have measured the total carbon dioxide released from the soil, including all the soil sources of carbon dioxide released from the habitat type, reflecting the specifics of particular vegetation types.

Soil respiration elements in managed forests

In the environmental studies, the research ecosystems are likely to be compared with forests. A study was also conducted on soil respiration in two forest types (Butler et al., 2012; Yu et al., 2015). This study revealed that respiration of litter was the primary source of heterotrophic respiration (88%). The heterotrophic respiration occurred after some time, as the soil litter carbon used by microorganisms was not immediate. The use of carbon by the microorganisms and high carbon amount in organic matter respiration of litter is characterized by a hysteresis phenomenon (Yu et al., 2015). The study of carbon dioxide release from the dead roots presented that the dead roots provide new soil organic material for microorganisms, and in this way, the heterotrophic respiration rate is increased (Bond-Lamberty et al., 2004; Lee et al., 2003; Yu et al., 2015). The other study presented that the low carbon/nitrogen ratio leads to the site conditions in which the respiration and carbon dioxide release levels are growing due to the increase of the soil microbe organic matter decomposition (Grant et al., 2001; Liu et al., 2011; Yang et al., 2015). Some studies performed in tree stands and managed woodlands have shown that soil substrate respiration can have a linear positive correlation when compared with the young tree stands (Chen et al., 2010; Franzluebbers et al., 2001).

The components of soil respiration to total soil respiration

The heterotrophic and autotrophic respiration is divided into different ratios to the total soil respiration in different ecosystem types, e.g., forests. In general, root respiration reveals 10–60% (–90%) of the overall soil carbon dioxide release in many forest ecosystems (Kuzyakov, 2004; Shen et al., 2011; Satomura et al., 2006). Some of the research sites were located in a nature reserve area with forest vegetation patches of abundant soil organic matter and litter layer, resulting in a high relative humidity level (Yang et al., 2015).

The study by Subke et al. (2006) indicated that the heterotrophic part of carbon dioxide releases 27–86% of total soil respiration in forest ecosystems. The results of the study referred to above are consistent with our assumptions. In our study, we have assumed that the total respiration amount will be related to the species' biochemical, organic carbon compounds, and composition, which is dependent on the plant species' spontaneous of the herbaceous vegetation type that has developed in response to the abiotic mineral material of the post-coal mine heaps novel ecosystem.

The effect of texture on the abiotic parameters on the soil respiration level

In our study, the mineral soil substrate texture characteristics are irrelevant and must be presented in the paper results section. Such a result was surprising because it is known that the finest soil texture material can impact soil water-holding capacity, influencing many other functional processes, including respiration intensity. The soil texture structure is known to be able to impact the nitrogen cycle in the ecosystem. The weak binding to the soil particles and nitrate leaching can be the reason for the decrease in soil pH and the base cations (Araujo et al., 2017).

The strong relation between the soil organic matter content and the amount of clay in the soil structure has been presented in most of the studies (Jenkinson, 1990; Parton et al., 1987; Franzluebbers et al., 2001; Wang et al., 2003; Müller and Höper, 2004). When the first clay particles appear, the process of clay particle aggregation can start, and the other particles can come together (Tisdall and Oades, 1982). The clay particle aggregation process can change the water holding capacity and, as a result, the soil moisture parameters, influencing the input of C into the soil using the photosynthetic plant species composition productivity and, as a result, the soil organic matter distribution (McLauchlan, 2006; Six et al., 2000).

The study performed in the way in which humidity and temperature were controlled revealed how the results of soil respiration rate can vary (Giardina et al. 2001). In the study conducted by Giardina et al. (2001), it has also been revealed that clay participation only partially influences the level of net N mineralization (Giardina et al., 2001; Côté et al., 2000; Schimel, 1995; McLauchlan, 2006). Opposite to our expectations, no significant relation between the mineral soil material texture and the respiration rate parameters has been revealed, and in our study, stones, gravel, and sand-sized particles influenced the texture of the mineral soil substratum material. This might be the reason for the unexpected results.

Soil water content and soil respiration

Identifying the environmental factors that control soil CO_2 release from the ecosystems is an essential step in assessing the potential effects of environmental changes (Schlentner and Van Cleve, 1985; Singh and Gupta, 1977). When modeling soil respiration (e.g., how the soil carbon dioxide release rates are dependent on moisture or temperature), the models have shown that an exponential equation best describes the temperature soil respiration relation (Borken et al., 1999; Kutsch et al., 2001; Rochette et al., 2013). The precipitation amount and soil moisture are crucial in addition to temperature in the soil respiration models (Savage and Davidson, 2003; Tang et al., 2005; Tüfekçioğlu and Küçük, 2004). Some additional factors are considered in the models, such as pH (Reth et al., 2005), land use (Ardö and Olsson, 2003), carbon amount (Kutsch et al., 2001; Rodeghiero and Cescatti, 2005), and the plant traits parameters such as maximum leaf area index (Skopp et al., 1990). In our above study, we analyzed pH and the amount of carbon.

Effect of salinity on SRL

The mineral material of the coal mine heaps can be frequently characterized as the habitat of high salinity. The salty waters and salt are associated with coal excavation and the geological layers. Soil salinity is regarded as a significant factor in forestry and agriculture, particularly with high evapotranspiration and low rainfall (Bossio et al., 2007; Rengasamy, 2006. Beltrán and Manzur, 2005; Pannell and Ewing, 2006). As Zeng et al. (2014) indicated, soil denitrification / nitrification and, consequently also, soil respiration depend on soil salinity. The stress related to salinity and drought are conditions to which the plants building the vegetation of natural and semi-natural ecosystems are susceptible. Some researchers understand that plant individuals are unable to adapt quickly to those stresses (Jarvis, Lane and Hijmans, 2008; Mittler, 2006). It is less frequently studied how the adaptation processes that can result in salt and drought adaptation might differ in the biochemistry of the plant individuals. The changes in plants' biochemistry influence the character of the soil organic matter and, as a consequence, the decomposition process, which is directly related to the release of carbon dioxide. The salinity can be changed by the occurrence of exchangeable cations and the conditions that might influence the exchange. The presence and amount of the exchangeable cations Ca^{2+}, Mg^{2+}, $Na^{+,}$ and K^{+} are essential in the soil functioning in the natural and semi-natural ecosystems. Exchangeable cations can become exchanged by a cation of an added salt solution (Ramos et al., 2018). In the presented study, the magnesium Mg, potassium K, and calcium Ca content and the pH value in coal mine mineral soil material are significantly related to the carbon dioxide release.

CONCLUSIONS

This study aims to analyze the links between the abiotic conditions of the coal mine heaps habitat variety identified as spontaneous vegetation types and the CO_2 respiration rates. We hypothesized that the soil substrate carbon content is significantly related to the coal mine heap respiration rate among the studied abiotic factors. The vegetation types of habitats with higher carbon content might release more CO_2. The post-black coal mining heaps mineral material soil substratum samples were analyzed for the following physicochemical parameters: pH, electrical conductivity (EC), soil organic carbon content (SOC), total N (TN), available forms of phosphorus (P_2O_5) content, available Mg (MgO) concentration, exchangeable cations (K^+, Na^+), and soil substratum moisture. The results revealed that the carbon dioxide range from the studied vegetation types varied from 0.00158–1.21462 [g CO_2/m^2/h]. The FSO analysis showed that contrary to the hypothesized expectations, the carbon content and all the analyzed habitat factors were significant ($p = 0.001$), apart from the total nitrogen. Potassium (K) and soil respiration levels presented a significant correlation among the identified vegetation community types dominated by 26 species, only the habitat conditions provided by the vegetation communities dominated by *Centaurea stoebe* significantly correlated with soil respiration level. Three plant species dominants caused the development of habitat conditions, resulting in a negative impact. In contrast, below-ground conditions associated with the vegetation patches dominated by *Daucus carota* demonstrated the strongest negative correlation.

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