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Original Article

Soil Respiration in Anthropogenic Disturbed Ecosystems Compared to Deciduous Forests in the Urban Industrial Area

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Abstract: In urban industrial area, mining activity directly affects the dynamic of carbon, and consequently, the release of carbon dioxide (CO_2) into the atmosphere. The main objective of this research is to study the impact of most important abiotic environmental factors on soil respiration in post-coalmine ecosystems. The moisture and temperature of the soil, along with CO_2 outflow from the soil, were measured over three consecutive seasons, using 92 samples from coalmine heaps and 10 samples from deciduous forests in the same urban industrial region. Based on a survey of 396 species, a cluster analysis distinguished all deciduous and 22 forest plots grown on coalmine heaps from herbaceous plots from same coalmine heaps. The lowest soil respiration rate (0.62 mg CO_2 per hour per square meter) was recorded in the herbaceous vegetation class on coalmine heaps, compared to (0.76 mg and 0.96 mg) from coalmine-heap forests and deciduous forests, respectively. Species richness and diversity positively affected soil respiration in heap herbaceous plots, though this effect was less pronounced in forests grown on coalmine heaps and in deciduous mixed forests. Unlike soil water content, soil temperature negatively correlated with soil respiration on coalmine heaps, diverging from the well-studied positive impact of soil temperature and respiration in deciduous mixed forests. Our spatial and temporal analyses emphasize that the water content of the substrate is the most significant abiotic element that affects the soil respiration on coalmine heaps positively during early vegetation succession.

1. Introduction

According to Global Circulation Model scenarios, a potential increase in CO_2 levels in the atmosphere accelerates global warming, raising concerns that forest ecosystems could become net carbon sources by 2050, rather than continuing to sequester carbon [1]. Annually, more than ten percent of the atmospheric CO_2 is released by soils [2], making soil respiration one of the most fundamental processes upon which natural ecosystem functioning depends. CO_2 release from European forests is the most determinant biological process in carbon balance [3], since boreal and temperate forests account for the most significant carbon sequestering pools on the earth.

The primary components of any ecosystem are the composition and functionality of the primary producers, mostly plants, which influence both above- and below-ground main processes [4–5]. The constant change in climate are driven indirectly and directly by human and natural forces [6]. The negative impact of human activities on climate, primarily through greenhouse gas emissions, is a major factor in intensifying global warming. In 2001, the Intergovernmental Panel on Climate Change (IPCC) reported an increase of 31%, 45%, and 249% in atmospheric concentrations of CO_2, N_2O, and CH_4, respectively, due to changes in land use and fossil fuel combustion [7]. The IPCC reported again in 2014 that there was an increase of 0.85°C in the global average temperature of both ocean and land combined from 1880 to 2012 [8].

Among all abiotic elements, soil temperature and humidity most significantly affect microbial and root activity, and consequently, are the most important factors driving soil respiration. Changes in precipitation patterns and ongoing global warming have raised interest in studying factors that not only affect the productivity of ecosystems but also alter the exchange of carbon between terrestrial and atmospheric systems [9, 10]. In boreal and temperate ecosystems, seasonal variation in soil respiration is much higher than diurnal variation due to the below-ground carbon processes that follow seasonal patterns [11]. Moreover, seasonal shifts in soil temperature have been described as having an exponential positive relationship with soil respiration [12]. Photosynthates serve as the main source of carbohydrates for root respiration and significantly contribute to soil microbial respiration through root exudates. This connection ties variations in soil respiration to plant phenological patterns, spanning from hourly to seasonal timescales.

In temperate regions, spontaneous vegetation succession in disturbed post-coalmine areas takes at least a decade to induce rapid shifts in species assemblages and associated organisms, before forming a new forest ecosystem at the final stage of succession [13]. Autotrophs, including plants, utilize energy, and engage in synthesis and decomposition processes to generate biomass [14, 15].

In woodlands, when the carbon is sequestered through the products of photosynthesis, it is stored either as living biomass form or as dead wood and fallen leaves above and below ground [16]. Less carbon is stored in monodominant forests due to reduced litter production and low soil biodiversity [17–19]. In forests, carbon is sequestered through the products of photosynthesis, which are stored in soil pools, as well as in above- and below-ground biomass, fallen leaves, and dead wood.

This work is part of a large project linking changes in biodiversity to soil physicochemical properties in a large industrial area, investigating hundreds of samples from coalmine heaps, managed deciduous forests, and timber production secondary forests. Results of the detailed spontaneous vegetation succession process of herbaceous vegetation [13] and forests [16] were published separately. This study illustrates carbon release in relation to abiotic factors and vegetation composition of herbaceous vegetation, surveyed forests grown on coalmine heaps, and managed mixed deciduous forests in the same urban industrial area.

2. Material and Methods

2.1. Study Area and Sampling Procedure

The hard-coal excavation in the Silesian Upland in southeast Poland directly disturbed 20 km^2 of various natural ecosystems [20], and negatively affected larger areas surrounding the coalmines. Upper Silesia is a transition zone between continental and ocean climates, favourable for forest development with 600-700 mm of annual precipitation and 8°C average temperature [21]. The by-product substrates left on the ground after the excavation of the hard black coal is a mixture of crushed coal left, sediment of Carboniferous layer, Precambrian crystal rock, in addition to mud- and sand-stones [22]. Coalmine heaps that have been in place for decades offer a unique opportunity to conduct large-scale experiments, having created habitats with varying plant community compositions [13, 16] and different disposal methods [23].

To ensure truly random sampling, a computer algorithm was used, which incorporated the light reflected from the vegetation and the surface of the substrate. Next, a hierarchical cluster analysis was performed based on values calculated from the differences in species composition within the plant communities [24]. Both methods successfully distinguished herbaceous vegetation samples, aged 2-12 years, from coalmine heap forest samples aged 14-56 years, and from deciduous forests. The variation in the number of samples across the three groups was due to the availability of sites (Figure 1).

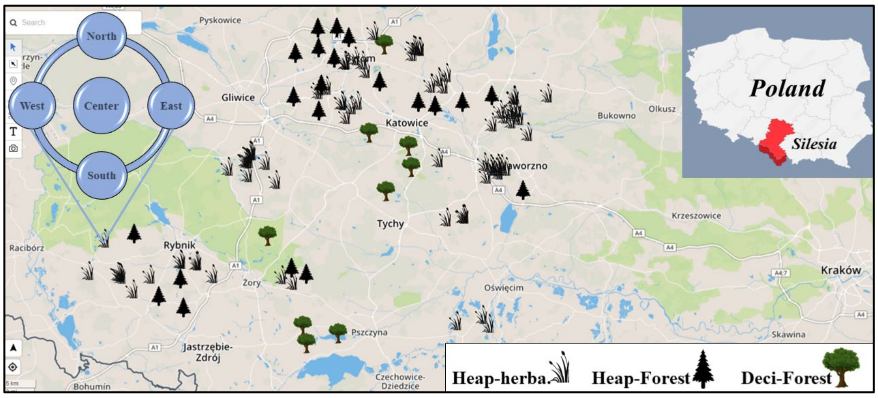


Figure 1: Study area map with the geolocation of all samples and a scheme of a plot and sub-plots layout.

2.2. *Vegetation Sampling*

Plant species composition in all habitats was surveyed from June to September in 2021 from 140m² plots, each consisting of five 28m² round-shaped subplots in a cross-design at distances of 50 metres (Figure 1). The visual estimation of all species was recorded as a percentage cover class following for all spatial layers (tree, shrub, and herbaceous) [25, 26]. The Mirek checklist was used for the scientific names of species [27].

2.3. *CO_2 Efflux*

CO_2 efflux from the soil was measured using a TARGAS-1 Portable Photosynthesis System device produced in Amesbury, Massachusetts, USA. The TARGAS-1 device was connected to an SRC-2 chamber for soil respiration to measure the CO_2 released from a 78 square centimeter soil surface covered by the chamber. The rugged PVC-made SRC-2 is equipped with a ring made of stainless steel that seals the soil surface to prevent gas leakage from the closed chamber.

A fan in the SRC-2 chamber circulates the air to the TARGAS-1 device, which records changes in CO_2 concentration over time. The TARGAS-1 PP-system relies on an auto-zero mechanism that sustains the CO_2 impulse and ensures accurate and robust reading. The measurements of CO_2 were taken in *situ* in three conscutive seasons and recorded as milligrams of CO_2 per hour per square meter.

2.4. *Substrate Parameters*

To assess the most important parameters related to soil physical and chemical properties, samples were taken from the 20 cm top layer from all five subplots. About 150 grams of air-dried mixture from the subplot samples was ground, and fine particles smaller than 2 millimeters were separated and recorded as volume percentage in all plots [28].

First, dried samples were weighed, then waterlogged overnight, left to percolate, and the saturated weight was recorded to calculation of the capacity of soil to hold water as:

$$Water\ Holding\ Capacity\ (\%) = \frac{[saturated\ \text{mass (gram)} - \text{oven dry mass}\ (gram)]}{saturated\ mass(gram)}\ X\ 100 \qquad (1)$$

Along with the soil respiration measurement (described above in section 2.3.), we measured the water content in the soil by the the moisture meter Delta-T HH2 produced in England, and the soil temperature using the DT1 Z Sonda ST01-1300 thermometer. A glass electrode was used for pH measurement from a soil sample mixed with distilled water in (1 soil/ 2.5 distilled water) ratio for a day, while (1 soil/ 5 distilled water) ratio was used to determine the electrical conductivity.

The Kjeldahl method [29] was used to measure nitrogen, Turin-protocol modified [30] for carbon, and atomic absorption spectrophotometer [31] to extract sodium from the soil. To extract available potassium, calcium, and phosphorus the solution Mehlich-3 was used [32, 33].

2.5. Data Analysis

The Shannon index for plant diversity, the number of species, and the evenness index were calculated using the Vegan package in R [34], while dominant plants indexed by the *dominance()* function in abdiv package. A hierarchical cluster analysis grouped all 102 main plots into two distinct vegetation community classes, considering dissimilarities among all plots and habitats [34].

A canonical component analysis (CCA) tested the impact of all environmental factors on species composition and distribution in a CCA-biplot. The envfit function has fit the abiotic parameters in the CCA-biplot, and the function (p.max= 0.5) eleminated insignificant fators. A Shapiro test [35] was conducted to check whether the samples are normally distributed within the groups. A linear model, [36] along with a permutation test in the lmPerm package, was conducted to compare independent variables. A non-prametric Kruskal test was used to compare variables did not meet the normality test assumption.

Plant functtional indices were quantified and calculated from seven plant traits using *dbFD()* function in FD package [37]. The *metaMDS()* function [38] was employed to perform a Nonmetric Multidimensional Scaling (NMDS), with samples arranged in the NMDS-biplot. The strength and direction of taxonomic and functional indices were visualised by *envfit()* function in the Vegan package.

To examine the direction and relashionship of each pair environmental variables, species richness, and species diversity, Pearson correlation [39] was used. A permutation test with 999 iterations was employed to check the significance of all tested relationships between each pair variables.

3. Results

3.1. Vegetation Classes Based on Species Composition

The hierarchical cluster analysis separated all 22 forest samples from post-coalmine heaps and 10 deciduous forest samples (Figure 2, first branch) from 70 herbaceous vegetation samples of the spontaneous vegetation succession, based on floristic species composition (Figure 2, second branch). *Betula pendula* and *Robinia pseudoacacia* were the most representative tree species in coalmine heap forests, while tree species such as *Q. robur, C. brizoides,* and *F. sylvatica* dominated the deciduous forests. The herbaceous vegetation class on coalmine heaps, with 70 cross-design plots aged 2-12 years, had the fewest plants initially colonised by *Calamagrostis epigejos, Tussilago farfara, Atriplex prostrata, Polygonum aviculare,* and *Puccinellia distans,* known for being expansive local species. Later, the diagnostic species *C. epigejos* expanded further, reaching its highest density point with a mixture of ruderal plants and meadow species at the end of the herbaceous succession stage.

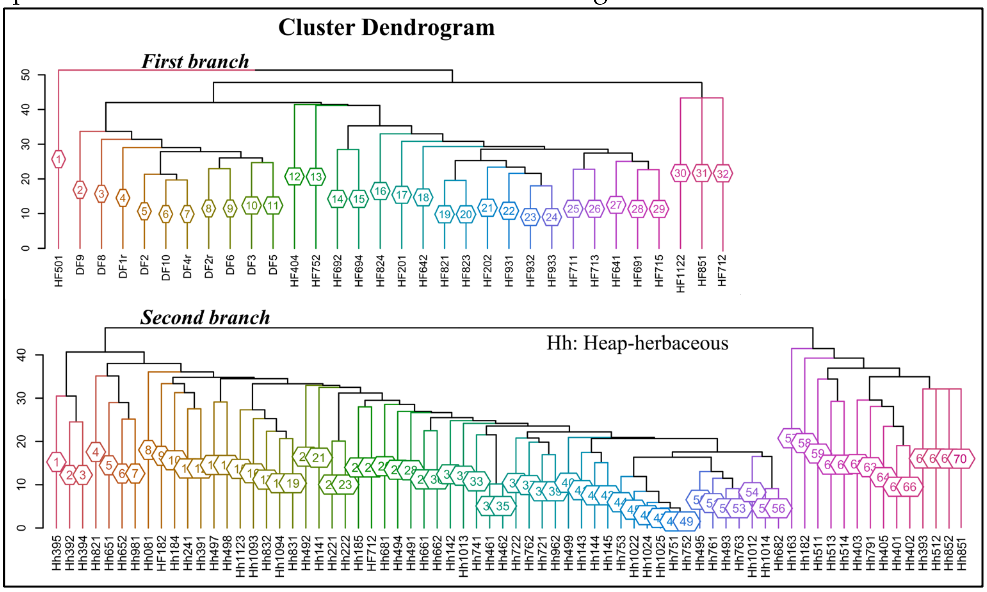


Figure 2. Hierarchical cluster analysis based on floristic plant composition separated all samples of herbaceous vegetation class (Second branch) from deciduous and heap forest samples (First branch).

3.2. *Taxonomic and Functional Diversity*

Significant differences detected by the qualitative test revealed higher number of species (36 species) in forests grown on coalmine heaps compared to the heap herbaceous vegetation class (31 species) and deciduous mixed forests (22 species). Both Shannon–Wiener diversity and evenness indices followed the same trend, with the highst values in heap forests (2.7 and 0.76, respectively) compared to both heap herbaceous (2.3 and 0.69, respectively) and deciduous forest (1.9 and 0.62, respectively). The dominance index showed the opposite trend, with the lowest value in heap forests (0.10) and higher in heap herbaceous (0.22) and deciduous forests (0.25).

The Nonmetric Multidimensional Scaling (NMDS) test projected all taxonomic and functional indices in the NMDS-biplot space, revealing positive correlations of functional divesity, Rao's quadratic entropy, and functional richness along the first axis, favouring both forest habitats (Figure 3). Functional eveness correlated negatively along the second axis, in the direction of the herbaceuos vegetaion.

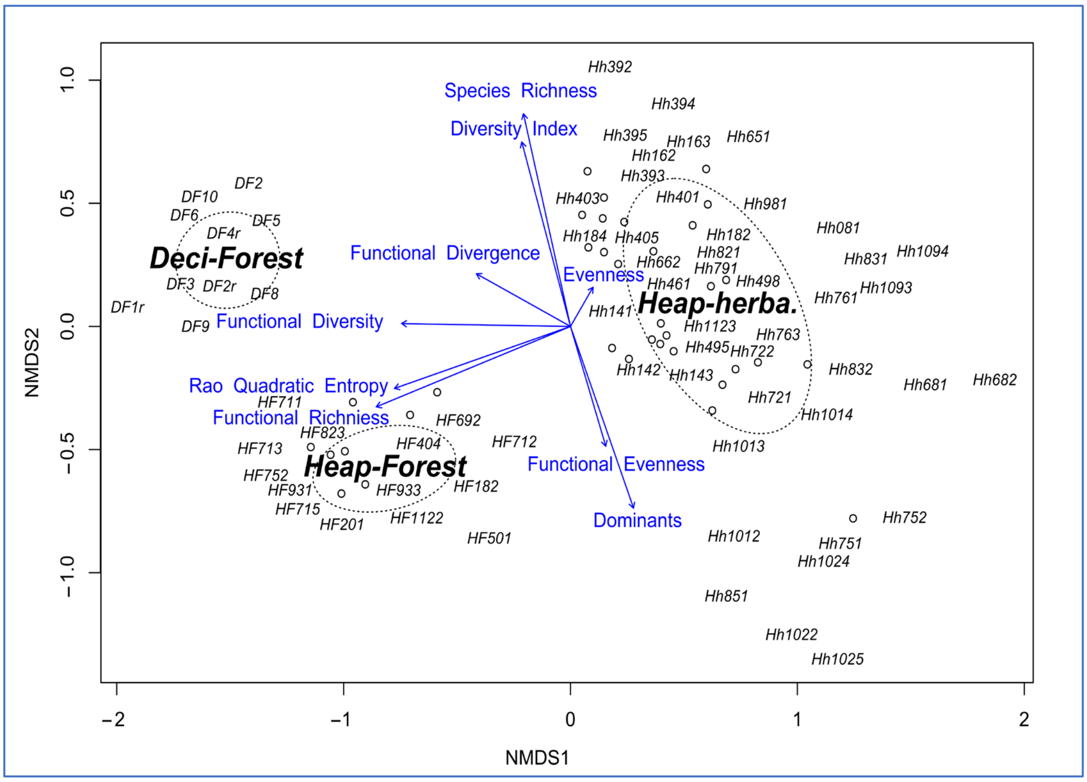


Figure 3: A Nonmetric Multidimensional Scaling illustrates samples distributed in the NMDS-biplot space and projects the impact, the direction and the strength of diversity indices.

3.3. *Changes in Environmental Abiotic Factors and their Impact on Soil Rispiration*

Soil temperature was highest (19.2°C) in heap herbaceous areas and decreased by 5 degrees in heap forests (14.2°C), with the lowest temperature (12.7°C) in deciduous forests. This gradual decrease in soil temperature contrasted with increases in water content, soil capacity to hold water, and fractions of fine particles in soil (Table 1). A quantitave test showed a similar trend in soil respiration, with the lowest respiration rate in heap herbaceous areas (0.62 mg CO_2 per hour per square meter) followed by heap forests (0.76 mg), and the highest respiration rate in deciduous forests (0.96). In heap forests, values for pH (6.25), total carbon (12.4%), potassium content (214), and contents of calcium (1844), resulting in significant differences except for total carbon. Sodium content was highest in heap herbaceous substrates (42 mg kg^{-1}), whlie magnesium was lowest in deciduous fores (50 mg kg^{-1}), compared to (175 and 186 mg kg^{-1}) in heap forest and deciduous forests respectively (Table 1).

Table 1: Analysis of variances assessing the environmental parameters in different habitats.

Environmental Parameters	**Soil Respiration** (mg CO_2/ h/ m^2)	**Soil Water Content %**	**Water Holding Capacity %**	**Fine particles** (%)	**Soil Temperature** °C	**pH**	**Electrical Con-ductivity** (mS cm^{-1})
Heap-herba.	0.62b ±0.4	13.5b±5	26.9c±5	35.1b±11	19.2b±2	6.10b ±0.2	5.9a±1
Heap-Forest	0.76ab±0.3	18.7b±6	33.5b±5	37.6b±10	14.2c±1	6.25a ±0.1	5.5b±1
Deci-Forest	0.96a ±0.2	33.4a±7	39.6a±6	51.0a±10	12.7d±1	6.07b±0.1	5.4b±1
P-values	0.0218	5.5 x 10-8	1.1 x 10-8	0.0006	1.1 x 10-13	3.8 x 10-6	4.6 x 10-5
Environmental Parameters	**Total Carbon** (%)	**Total Nitrogen** (%)	**Available P** (P_2O_5) (mg kg^{-1})	**Available K** (mg kg^{-1})	**Available Ca** (mg kg^{-1})	**Available Na** (mg kg^{-1})	**Available Mg** (mg kg^{-1})
Heap-herba.	09.6b ±5	0.26b ±0.1	41.5a±19	149b±43	1325b±993	42a±31	186a±57
Heap-Forest	12.4a ±6	0.46a±0.1	31.3a±07	214a±60	1844a±960	23b±08	175a±54
Deci-Forest	10.5ab±3	0.60a ±0.2	32.5a±05	149b±43	0357c±249	22b±04	050b±20
P-values	0.09ns*	2.5 x 10-9	0.24ns	0.0004	1.8 x 10-5	0.0017	1.9 x 10-6

The degree of freedom is 2, * ns is not significant.

The distribution and species composition were significantly affected by most of the environmental abiotic factors, as tested by CCA. The CCA test explained 17.90% of the total variance, with factors such as soil water content, soil temperature, water holding capacity, total nitrogen, potassium, and magnesium being significant at the alpha level (p ≤ 0.001). Fine particles, calcium, and sodium were significant at the alpha level (p ≤ 0.01), while phosphorus content and total carbon in the soil were significant at the alpha level (p ≤ 0.05). The qualitative CCA test showed no significant differences in terms of pH and electrical conductivity of the soil (Figure 4).

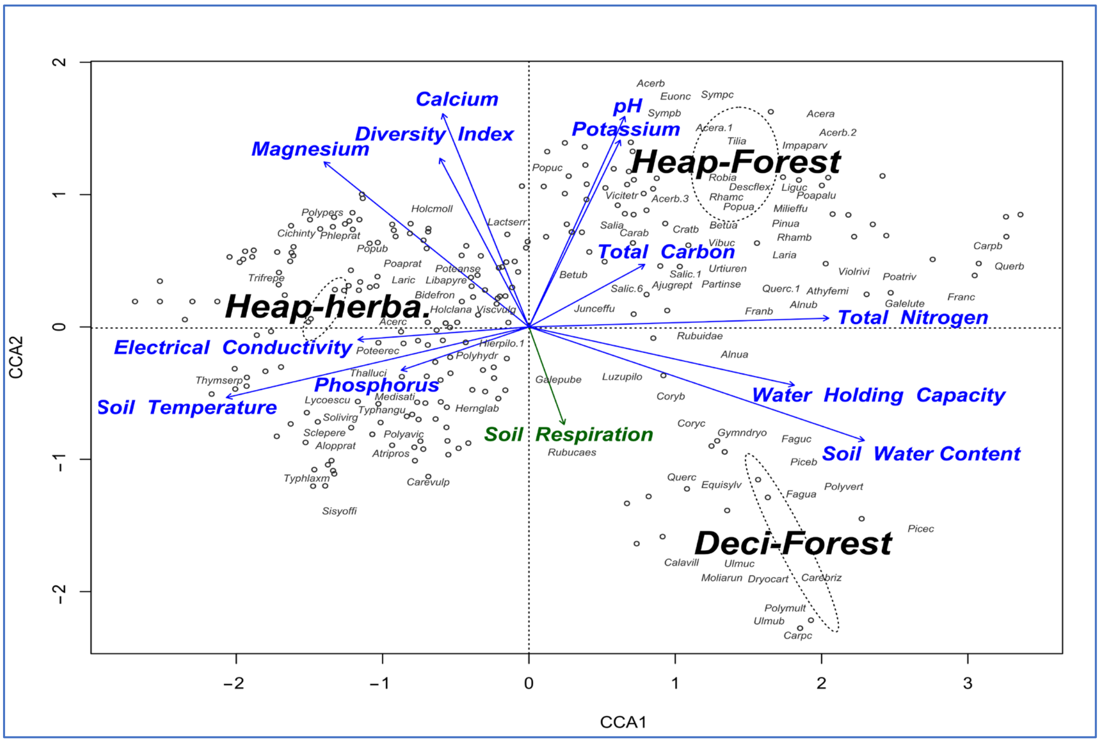
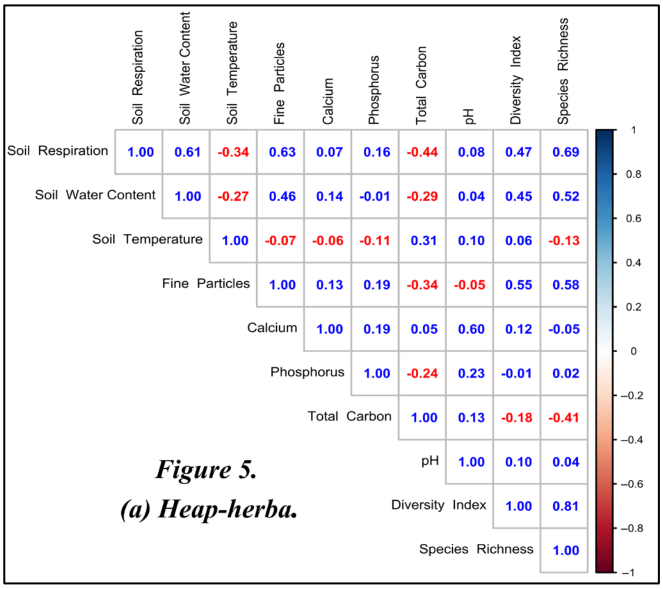
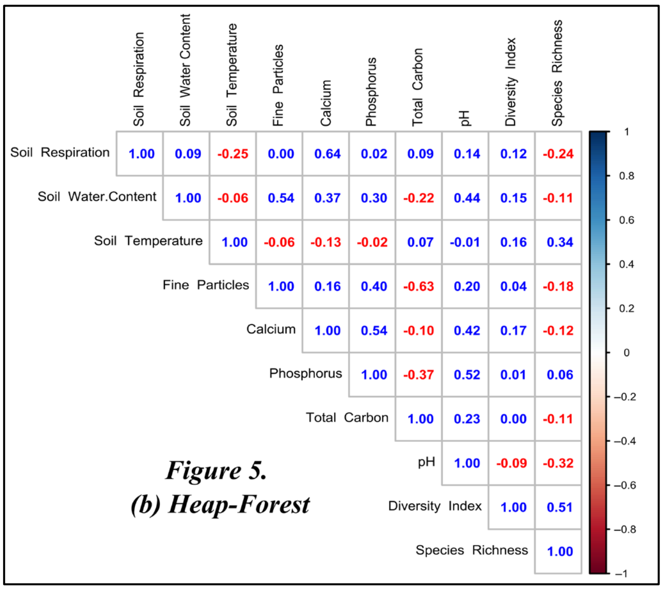


Figure 4: The strength and the direction of soil parameters affecting plant species composition as it is illustrated in the CCA-biplot ordination. Insignificant factors are excluded.

To examine the effects of environmental factors, species diversity, and species richness on soil respiration, each habitat was subjected to a correlation test separately (Figure 5). In the heap herbaceous habitat, soil respiration was strongly and positively correlated with soil water content (0.61), fine particles (0.63), diversity index (0.47), and species richness (0.69), and negatively correlated with soil temperature (-0.34) and total carbon (-0.44) (Figure 5a). In heap forests, soil respiration was positively and strongly correlated only with calcium (0.69) and negatively correlated with soil temperature (-0.25) (Figure 5b). In deciduous forests, soil respiration was affected differently by the most important environmental factors. Soil temperature crucially increased the soil respiration rate (0.60), while water surplus reduced it (-0.35) (Figure 5c).





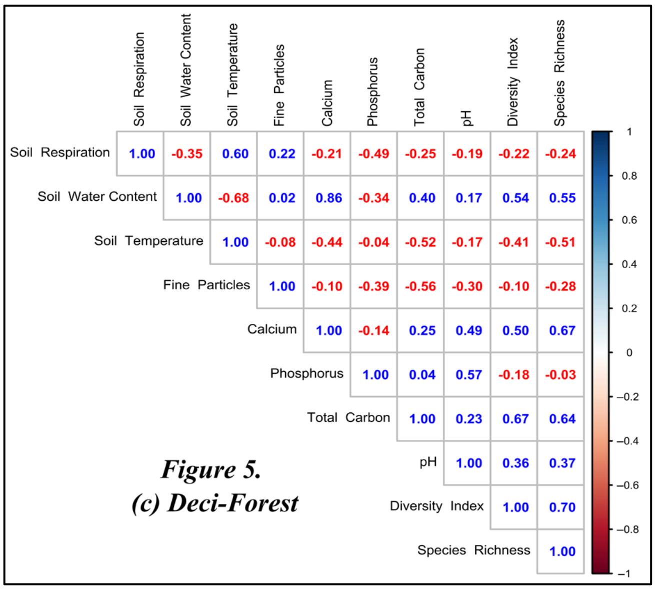


Figure 5: Correlation coefficient test for the most important abiotic factors, Shannon-Wiener diversity and species richness indices illustrated in the correlation matrix. Heap-herbaceous (Figure 5. a), Heap-Forest (Figure 5. b), and Deci-Forest (Figure 5. c).

4. Discussion

4.1. Species Composition Change on Coalmine Heap Habitats and Urban Forests

The three habitats classified by the hierarchical analysis differed in species composition, species richness, and dominant plants. The herbaceous vegetation class was initially colonized by pioneer species such as *T. farfara, P. aviculare, A. prostrata*, *P. distans*, and *C. rubrum*, which are known to tolerate erosion and sloping sites with newly disposed hard coal by-products [40]. During succession, many factors shape the plant composition, including the vegetation type surrounding the coalmine heap [40], the size of the coalmine heap [41], and disposal method of the hard coal by-products [23]. Unlike piled-up heaps, aquatic plants grown and created wetland ecosystems in the same region in sand pits, where water accumulates and forms ponds and water bodies [42]. The rapid development of the herbaceous vegetation class results in shifts in patch species composition, increases in species numbers, and the introduction of alien species such as *S. gigantea* and *S. canadensis* [43], as well as tall native forbs like *T. vulgare*, and *C. epigejos* [13]. Woody plants begin to colonise the herbaceous patches within several years, eventually leading to forest development on the coalmine heaps at the end of spontaneous succession, as reported earlier [16]. In temperate regions, the ultimate stage of vegetation succession on coalmine heaps is the development of woodlands [44].

The newly developed forests, which have undergone spontaneous vegetation succession in the herbaceous phase, shade the grass layer [45], suppressing dominant native forbs and alien invasive species [16]. Heap forests dominated by native *B. pendula* and the alien species *R. pseudoacacia* exhibited a higher number and greater diversity of plant species. Functional diversity indices, which assess co-occurring species redundancy and complementarity, offer various methods for estimating the range and distribution of individuals in both communities and ecosystems [46–50]. The functional diversity parameters calculated in this study, which assessed plant composition along a proposed gradient of stress, detected much higher functional diversity, functional richness, functional divergence, and Rao quadratic entropy in forests grown on coalmine heaps compared to the herbaceous vegetation grown on coalmine heaps. Greater functional performance indicates enhanced resilience in forests established on coalmine heaps, leading to improved ecosystem functioning and maintenance of these newly formed novel ecosystems [51].

4.2. Plant Species Impact on Soil Respiration

The variety, physical, and chemical properties of the mineral by-products disposed of from mining activities drive the plant colonisation process [52–54]. The habitat filtering concept alters plant assembly, shapes vegetation type [55], and consequently affects soil respiration on abandoned coalmine heaps. We observed higher soil respiration in heap forests compared to herbaceous vegetation habitats, mainly due to higher species richness and higher organic carbon content in the substrate. In forests, higher organic carbon attributed to the fact that forests store carbon in both above- and below-ground living and dead biomass, including leaf litter and dead wood from photosynthesis products sequestered earlier [56]. Soil respiration in herbaceous vegetation is more affected by temporal variation because herbaceous habitats have variability in vegetation growth. We measured soil respiration in three consecutive seasons to account for such variability, unlike studies that miss interannual measurements of soil respiration and rely solely on plant diversity to evaluate carbon dynamics [57].

4.3. Soil Respiration Driven by Environmental Abiotic Elements

Soil water content, fine particles, and water holding capacity are the most important factors affecting soil temperature and, and in turn, soil respiration, in addition to plant species number, species diversity, and species composition, especially on newly created coalmine heaps. A higher proportion of fine particles in soil increases the capacity of soil to hold water, which in turn increases soil humidity. Such improvements in soil physical properties also enhance the nutritional conditions of the disposed hard coal by-products, which are originally rich in elements [58]. We measured higher total carbon in heap forests, which resulted in higher levels of available potassium, nitrogen, and calcium compared to herbaceous vegetation on coalmine heaps. This increase is mainly attributed to the breakdown of organic carbon from dead biomass [56]. Except for total nitrogen and phosphorus, the content of potassium, calcium, and magnesium was also higher in heap forests than in deciduous mixed forests. The higher content of these elements in the organic layer enhanced also raised the pH, especially calcium, which is directly connected to pH levels.

Soil water content significantly increased soil respiration in herbaceous habitats on heaps, while a lesser effect was observed in forests grown on coalmine heaps. However, in deciduous forests, excess water content in the soil negatively impacted soil respiration. Aerobic respiration increases with rising soil moisture until it shifts to anaerobic conditions as water fills all the soil pores, leaving no space for air. Gliński and Stępniewski [12] studied the role of soil aeration in soil respiration and reported a positive exponential relationship between soil temperature and soil respiration. Similarly, we observed an increase in soil respiration with rising temperatures in deciduous forests, while the opposite effect was noted in post-coalmine habitats, including both herbaceous vegetation and forests. Additionally, the impact of soil temperature on respiration was greater in deciduous forests [59]. The rock waste from hard coal excavation is a mineral material with very high thermal conductivity, resulting in rapid changes in substrate temperature, which alternates between cold and hot conditions.

5. Conclusions

The process of succession on coalmine heaps spontaneously lasts for decades, initially creating diverse herbceous vegetation classes from the beginning before it turns to woodlands. Key abiotic factors are essential in determining vegetation patterns and affecting carbon release from the substrate in these newly formed ecosystems. Unlike in deciduous forests, soil water content drives soil respiration in post-coalmine habitats, regardless of vegetation type, while substrate temperature negatively impacts soil respiration. Despite having higher species richness and total carbon, heap forests release less carbon compared to deciduous forests in urban areas. This raises the question of whether coalmine heap forests act as carbon sinks. However, an uniterrupted method to measure gas exchange around the clock is necessary to capture daily or seasonal patterns of soil respiration and to avoid missing records during nocturnal, rainy, and hot periods throughout the year. Continuous nondestructive measurements would facilitate better estimation of soil respiration magnitudes in global climate models. Furthermore, additional studies on carbon sequestration are needed to deepen our understanding of carbon dynamics in urban industrial areas.

Data availability: Data will be available upon reasonable request.

Conflicts of Interest: The author declares no conflicts of interest.

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