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Article

Post-Extraction Novel Ecosystems Support Plant and Vegetation Diversity in Urban-Industrial Landscapes

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Abstract: Long-term exploitation of mineral resources has significantly changed the natural environment in urban-industrial landscapes. The changes on the surface of the extraction sites as a consequence of excavation of mineral resources provide specific mineral oligotrophic habitats on which plant species and thus vegetation can establish spontaneously. Some of these sites fulfill the prerequisites of novel ecosystems. This study was conducted on the spontaneous vegetation of post-extraction sites. Lists of species spontaneously covering these sites were prepared based on published data and our own records. This research revealed that species composition and vegetation types vary in time. These post-extraction novel ecosystems are also important for the presence of rare, endangered, and protected species noted in patches of different vegetation types. The variety of habitat conditions provided by these sites facilitates the occurrence of a wide spectrum of plants (both in terms of their socio-ecological origin and their ecological spectrum). This research proves how important these post-extraction novel ecosystems are for supporting plant and vegetation diversity in urban-industrial landscapes. Enhancing the biodiversity significantly increases the ecosystem services delivered by these sites and also the functioning of entire ecosystems. These natural processes on human habitats are essential in urban-industrial ecosystem landscape mosaics.

Keywords: plant and vegetation diversity; rare, endangered, protected plant species; natural processes; post-extraction novel ecosystems; urban-industrial landscapes

1. Introduction

In addition to the growth of cities, human industrial activity has increased all over Europe in recent centuries. Since 1800, urbanization has progressed much faster and reached proportions greater than at any other time in the history of the world. Industrialization and commercialization and the development of transport and communication have increased the economic pull of the city, and educational and recreational facilities have also played a crucial role in the growth of cities [1]. All of these are connected with the human pressure on the environment. The long duration of increasing exploitation of mineral resources has changed the natural environment significantly. Changes in the surface of the landscape influence not only the presence of plants and the conditions for developing vegetation but also the biological and environmental processes [2–7].

Long-term studies have shown that specific mineral oligotrophic sites which enrich the mosaic of urban-industrial environmental habitats are present as side-products of these places of extraction of mineral resources. These novel ecosystems can provide crucial ecosystem services in the landscape [8,9]. On such sites, biological systems develop spontaneously with previously unknown plant and animal species compositions [10–13]. This study of the spontaneous flora and vegetation of de novo established habitats such as opencast sandpits, quarries, coal-mine heaps, subsidence reservoirs, and post-coal mine sedimentation pools proved that these habitats are unique and very interesting and not only from the botanical point of view. The species composition and floristic richness of the spontaneous vegetation includes not only common but also rare, endangered, and protected species [14].

We have studied the spontaneously developed vegetation on post-coal mining sites in Upper Silesia for many years. Our long-term study has revealed that the species composition of vegetation patches is based on dominant plant species. Some much less abundant species accompany individuals of the dominant plant species. Furthermore, more than one hundred dominant species were recorded in spontaneous vegetation patches on the mineral substrate of post-coal mining sites. The main dominant herbaceous species of these sites are: *Agrostis stolonifera*, *Calamagrostis epigejos*, *Carex hirta*, *Centaurea stoebe*, *Chamaenerion palustre*, *Chenopodium album*, *Cirsium arvense*, *C. vulgare*, *Daucus carota*, *Diplotaxis muralis*, *Echium vulgare*, *Eupatorium cannabinum*, *Hieracium pilosella*, *Hypericum perforatum*, *Leontodon autumnalis*, *Lotus corniculatus*, *Medicago lupulina*, *Melilotus albus*, *Odontites serotina*, *Phragmites australis*, *Picris hieracioides*, *Poa compressa*, *Puccinellia distans*, *Solidago gigantea*, *Tanacetum vulgare*, and *Tussilago farfara*.

The following species were the most frequently recorded accompanying species of these sites: *Cardaminopsis arenosa*, *Hieracium laevigatum*, *Petrorhagia prolifera*, *Phleum pratense*, *Sanguisorba minor*, and *Senecio viscosus*. Our study revealed that this group of species is associated with a higher content of K+. According to the results of our study, there was also a group of species related to a higher content of water holding capacity (WHC%): *Calystegia sepium*, *Dipsacus sylvestris*, *Epilobium parviflorum*, *Filago arvensis*, *Galeopsis tetrahit*, *Leontodon autumnalis*, *Lythrum salicaria*, *Petrorhagia prolifera*, *Phleum pratense*, *Plantago major*, *Rubus caesius*, and *Urtica dioica*. Species associated with a higher pH and a high percentage of small substrate particle size were *Apera spica-venti*, *Artemisia vulgaris*, *Crepis biennis*, *Reseda lutea*, and *Solidago virgaurea*. Species associated with a high carbon content (TOC) in the soil were *Agrostis vinealis*, *Chaenorhinum minus*, *Hieracium umbellatum*, *Senecio vulgaris*, and *Sonchus asper*.

The accompanying species which occurred less frequently in our study were *Achillea millefolium*, *Agrostis gigantea*, *Apera spica-venti*, *Arenaria serpyllifolia*, *Artemisia vulgaris*, *Astragalus glycyphyllos*, *Cardaminopsis arenosa*, *Centaurea* jacea, *Chaenorhinum minus*, *Cichorium intybus*, *Crepis biennis*, *Deschampsia caespitosa*, *Elymus repens*, *Erigeron annuus*, *Festuca arundinacea*, *F. rubra*, *Hieracium laevigatum*, *H. sabaudum*, *H. umbellatum*, *Juncus inflexus*, *Lactuca serriola*, *Lolium perenne*, *Lupulus polyphyllus*, *Melandrium album*, *Melilotus officinalis*, *Mentha arvensis*, *Oenothera biennis*, *Pastinaca sativa*, *Petrorhagia prolifera*, *Phleum pratense*, *Plantago lanceolata*, *P. major*, *Poa palustris*, *Reseda lutea*, *Rumex acetosa*, *R. acetosella*, *Sanguisorba minor*, *Senecio viscosus*, *S. vulgaris*, *Sisymbrium altissimum*, *Solidago virgaurea*, *Symphytum officinale*, *Thlaspi arvense*, *Trifolium arvense*, *T. campestre*, *T. pratense*, *T. repens*, *Verbascum lychnitis*, *Vicia angustifolia*, *V. cracca*, *V. hirsuta*, and *V. tetrasperma*.

Extraction sites of mineral resources are scattered all over the urban-industrial region of Silesia, Poland, causing much alteration of the landscape. The long-term careful study of spontaneous colonization succession and the subsequent natural processes associated with the establishment of novel ecosystems provided much data. It has been shown that sites on which the novel ecosystems are established are very effective at obtaining benefits from spontaneous ecosystem functioning and ecosystem services when natural processes, i.e., succession, are involved [9,15–22]. The novel ecosystems of post-extraction or post-industrial sites are places where the ecological threshold must be crossed. Some studies have shown that the effectiveness of restoration within its classical definition is not possible anymore [23–25]. Novel ecosystems are developing on intensively transformed sites or have arisen and established de novo. These are characterized as unusual habitats. The vegetation and hence these ecosystems are composed of new plant and animal species assemblages selected by mechanisms of environmental filtering which are determined by synergetic feedback relations that have previously been unknown, unobserved, and not recorded in natural and semi-natural ecosystems [23,25,26].

The aims of the research were to: (i) present some aspects of the diversity of plant species composition and the spontaneous vegetation of highly transformed and newly created mineral habitats of novel ecosystems; and (ii) show the ecological spectrum of the assembled plant species with particular emphasis on the rare, endangered, and protected species growing spontaneously on the studied habitats.

2. Materials and Methods

2.1. Characteristics of the Research Area

The examined post-extraction sites (Table 1) are located all over the Silesian Voivodeship, which is located in the south of Poland, within three river basins: the Odra and the Vistula, and in a small part of the Danube [2,27]. Considering the physical and geographic division of Kondracki's Poland [28] modified by Solon et al. [29], the Silesian Voivodeship is located within three units: Central European Lowlands, Polish Highlands, and Western Carpathians with Podkarpacie [29]. The Śląskie Voivodeship is distinguished by its rich mineral resources. The main mineral resources excavated in this region are hard coal, sand, gravel, and limestone. Intensive industrialization and urbanization have resulted in the transformation of the geographical environment [2,8]. The study area includes the largest urban and industrial agglomeration in Poland (Figure 1).

Table 1. Characteristics of the studied post-mineral extraction sites.

Types of Post-Mineral Extraction Site	Characteristics of Site Types
Quarries	The Silesian Upland is an area where carbonate rocks and coal mining are inherently related. Limestone excavation areas are suitable habitats for the growth and development of limestone rock and xerothermic species as well as shade-loving and photophilous (light-loving) species. Water accumulating at the bottom of the excavation contributes to the formation of water reservoirs and such habitats are inhabited by wetland plant species and peat bog vegetation [30].
Opencast sandpits	In the Silesia region, sand excavations cover about 50 km^2 [31]. Only a few of these are still active. The closed opencast sandpits have been managed to establish forests, some of which are subject to secondary vegetation succession, while others are filled with water. These studied post-mineral extraction sites are habitats for rare plant species.
Heaps	Post-black coal mine heaps are very common in the Silesian Upland. On the other hand, heaps associated with zinc, lead ores, and smelters are less common [6]. Heaps are different in petrographic, mineral, chemical, granulometric, and pH composition. These areas provide mineral soil substrates suitable for colonization by living organisms. Plant communities formed during constant spontaneous biological processes are composed not only of common but also rare species under legal protection [26].
Subsidence reservoirs	The water reservoirs in the Silesian Upland are connected with subsidence and arose as a result of the side-effects of direct or indirect human activity, and are sometimes referred to as the "Silesian anthropogenic lake district". They were created as a consequence of underground mining. These reservoirs, due to their function, constitute an essential natural resource [32–34]. They contribute to forming wetland habitats for plant and animal species not previously found in the area. These areas are vitally important as breeding habitats for birds [32].
Sedimentation pools	During the extraction of black hard coal, water comes out of the geological layers with dissolved mineral substances. The salty water is pumped out from the mine along with the coal dust into special areas with sedimentation pools. In these pools, the coal dust is deposited by gravity onto the bottom. These types of de novo establishment sites provide habitats with wide moisture gradients from aquatic habitats, through wetland to damp terrestrial ones [15].

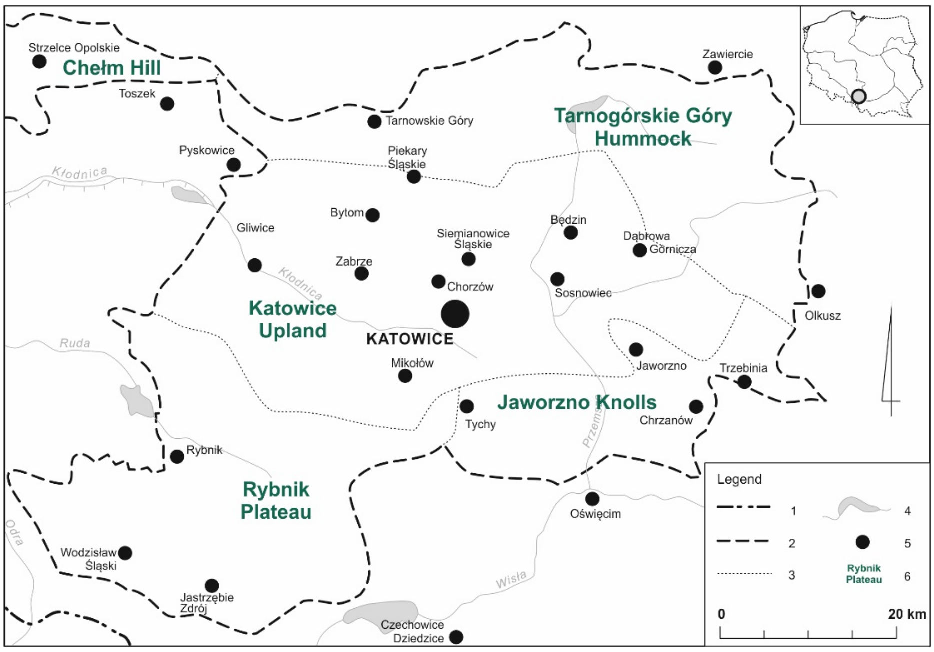

Figure 1. The location of the study area (south Poland), ([26]—modified): 1—state border, 2—border of the Silesian Upland, 3—minor geographical borders [28], 4—rivers and lakes, 5—towns and cities, 6—the name of physical and geographical regions.

2.2. Data Acquisition

Plant species and vegetation communities have been recorded during the study focused on the analysis of the diversity of spontaneous vegetation patches on post-coal mine heaps [26] and sedimentation pools (authors' own study); additionally, records from quarries, opencast sandpits, and subsidence reservoirs from the Silesia Region have mostly been obtained [35].

Most of the analyzed data were collected during the authors' own field studies. Some of the data about the vascular plant species assembled in vegetation spontaneously occurring on post-mineral extraction sites were obtained from published papers [16,36–48]. All of these publications have been analyzed to show that some of the vascular plant species and subspecies spontaneously colonizing the studied post-mineral extraction sites are rare, protected, or endangered [49–51].

Based on the available published data [16,36–51] and our own field records, lists of species colonizing the mineral post-extraction sites were prepared. These articles were found using the different databases of peer reviewed journal articles (e.g., Google Scholar, Scopus, Web of Science, or Science Direct). The following habitats were analyzed during the research: quarries, opencast sandpits, post-coal mining heaps, subsidence reservoirs, and sedimentation pools. Our ecological analysis included: light index (L), thermal index (T), moisture index (F), trophism index (Tr), and soil acidity index (R). The values of the listed indicators were taken from the Pladias scale [52]. The use of this scale was connected with adjusting this scale to our flora. The syntaxonomic affiliation of plant species was also determined in this research [53,54]. Most of our analyses were based on data obtained during fieldwork at post-coal mine heaps. In order to present a wider perspective on mineral habitats, a comparison was made of the heaps with quarries, opencast sandpits, subsidence reservoirs, and sedimentation pools. The limitations of this study were connected with the number of available mineral extraction habitats as well as with the difficulties in accessing their location which were often in very difficult to access anthropogenic areas.

The significance of the variety in the analyzed socio-ecological groups of species of different ages and areas of heaps was presented. For the differences in participation of threat categories, contingency tables were used. The G-test, instead of the Chi-square test, was used (because of the possible zeros in the database table) with *p*-level at $p < 0.05$. The R language and environment with the package "DescTools" has been used for statistical analyzes.

3. Results

3.1. The Plant and Vegetation Diversity of the Post-Extraction Sites

Post-mineral extraction novel ecosystems play a crucial role in the urban-industrial landscape. These sites, including post-coal mine heaps and sedimentation pools, are spontaneously colonized by living organisms because these sites provide specific habitat conditions for growth and development of plants, and the living organisms associated with them, and their different plant communities [26]. Among the autotrophic organisms, the plant species accumulated energy into biomass and started the matter-energy ecosystem flow. Over 500 vascular plant species have been recorded, both on the post-coal mine heaps and the post-coal mining sedimentation pools [8,15,26,41,55]. Similar to these two types of post-coal mining sites, the vascular plant species flora of opencast sandpits, and quarries also showed high floristic richness [8,16,17,36–48]. Among the notable vascular plant species, 154 interesting species have been recorded which are rare, endangered, and protected.

The study of the habitat conditions affecting the diversity of the species composition of spontaneous vegetation on post-coal mining heaps and sedimentation pools in Upper Silesia has shown that both plant species number and abundance along with vegetation diversity are varied in time. In early establishment post-coal mining heaps (aged up to 10 years) and sedimentation pools, the development of the vascular plant species composition of the spontaneous vegetation patches is highly diverse.

Considering the diversity of the vegetation and the age of the heap, attention should be paid to the fact that it is a similar dependence to the diversity of the species composition of spontaneous vegetation. Vegetation types also vary with time. The highest diversity is found on the youngest sites (post-coal mining sites aged up to 10 years). The most common socio-ecological groups are karst vegetation, agricultural weeds, and patches of ruderal species. On the older sites (aged up to 30 years and older), the vegetation patches cover larger areas and mosaic patches are recognizable. With increasing age of the heap, the diversity of vegetation types is lower, and the share of the species associated with the forest socio-ecological group increases; hence, the sites aged more than 60 years are mainly dominated by forest species (Figure 2).

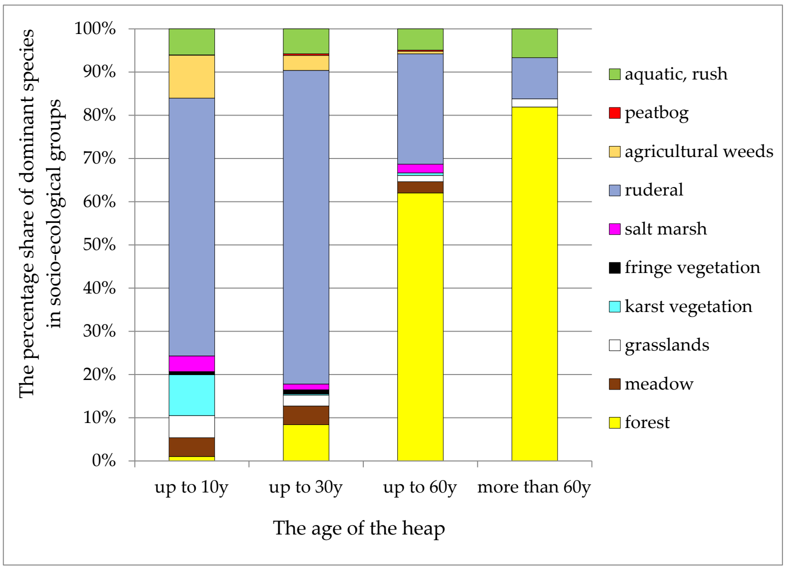

Figure 2. The percentage share of dominant species in socio-ecological groups in relation to the age of the heap. Explanations: y—years.

By analyzing the diversity of the vegetation species composition on post-coal mining heaps in relation to different areas (ha) of heaps, it was found that the post-coal mining heaps with an area of up to 50 ha are covered by the most diverse number of vegetation types. The vegetation patches recorded on these heaps are represented by all the main vegetation types. The patches of ruderal, aquatic, forest, and agricultural weed vegetation types were the most frequent (Figure 3).

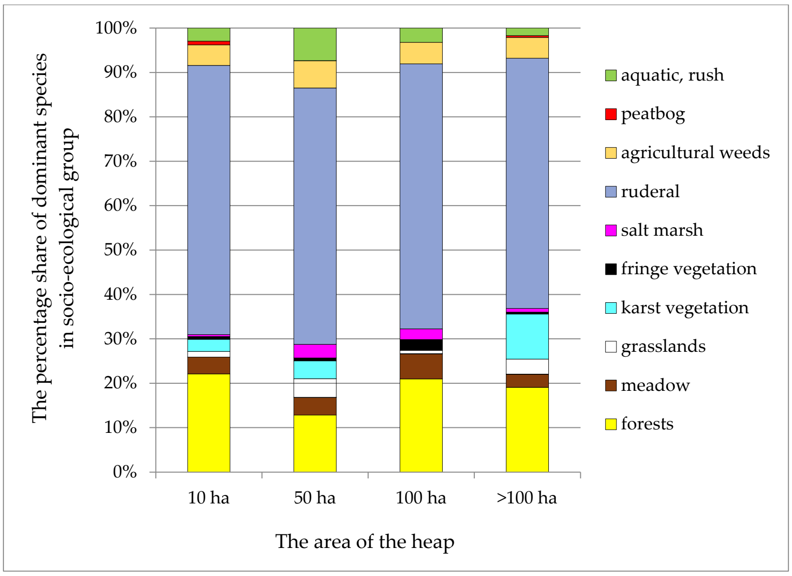

Figure 3. The percentage share of dominant species in socio-ecological groups in relation to the area of the heap.

Among the agricultural weeds, the following species are listed: *Apera spica-venti*, *Chenopodium album*, *Ch. rubrum*, *Echinochloa crus-galli*, *Galeopsis tetrahit*, *Geranium robertianum*, *Senecio vulgaris*, *Tussilago farfara*, *Urtica dioica*. The main karst species is *Chamaenerion palustre*, which is very abundant on post-coal mining heaps. The frequent salt marsh species are *Atriplex prostrata subsp. salina*, *Puccinellia distans*, *Spergularia salina*, and *Triglochin palustre*. The main fringe vegetation species are *Calamagrostis epigejos*, *Calystegia sepium*, *Epilobium parviflorum*, and *Geranium robertianum*. Grassland species recorded are *Arenaria serpyllifolia*, *Cardaminopsis arenosa*, *Festuca rubra*, *Pastinaca sativa*, *Rumex acetosella*, and *Trifolium arvense*, while among the forest species the following should be listed *Betula pendula*, *Deschampsia flexuosa*, *Mycelis muralis*, *Pinus sylvestris*, *Populus tremula*, *Rubus caesius*, *Salix cinerea*, *Sambucus nigra*, *Solidago virgaurea*, *Sorbus aucuparia*, and *Trientalis europaea*.

The studied sites are vitally important for many interesting vascular plant species. Rare, endangered, and protected species appear in all the studied habitat types. Most of them appear on heaps and sedimentation pools which are also rich in these species. According to Woźniak [8] as well as Bacler-Żbikowska and Nowak [30], the rare, endangered, and protected vascular plant species were recorded on different post-mineral extraction sites. These are the following: *Centaurium erythraea* subsp. *erythraea*, *Epipactis atrorubens*, *E. palustris*, *Eriophorum latifolium*, *Liparis loeselii*, *Malaxis monophyllos*, *Melampyrum sylvaticum*, *Myricaria germanica*, *Najas marina*, *Neottia nidus-avis*, *Polypodium vulgare*, *Pyrola chlorantha*, *P. minor*, *Schoenoplectus tabernaemontani*, and *Utricularia australis*. Among the rare, endangered, and protected plants species recorded on post-mineral extraction sites, many of them are threatened at the regional and country scale and represent different threat categories. Many of them are vulnerable (VU) on a regional scale, and on the other hand, near threatened (NT) at a country scale. It is worth noting that there are also high-risk species at the European and world scale among the studied species, e.g., the numerous and developing populations of *Liparis loeselii*. This species deserves particular attention because it is listed in Annex II of the EU Habitats Directive [56]. These rare, endangered, and protected plants species are a valuable element of the studied flora and enrich not only the diversity of these types of habitats, but also other urban and industrial landscapes.

3.2. The Ecological Spectrum of the Rare, Endangered, and Protected Plant Species of the Novel Ecosystem Habitats

The ecological spectrum of rare, endangered, and protected plant species establishing, colonizing, spreading into, and assembled in vegetation patches on novel ecosystem habitats is presented here. The analysis of abiotic habitat conditions has been divided into groups in terms of the indicators of light, temperature, moisture, trophism, and soil acidity (Figure 4).

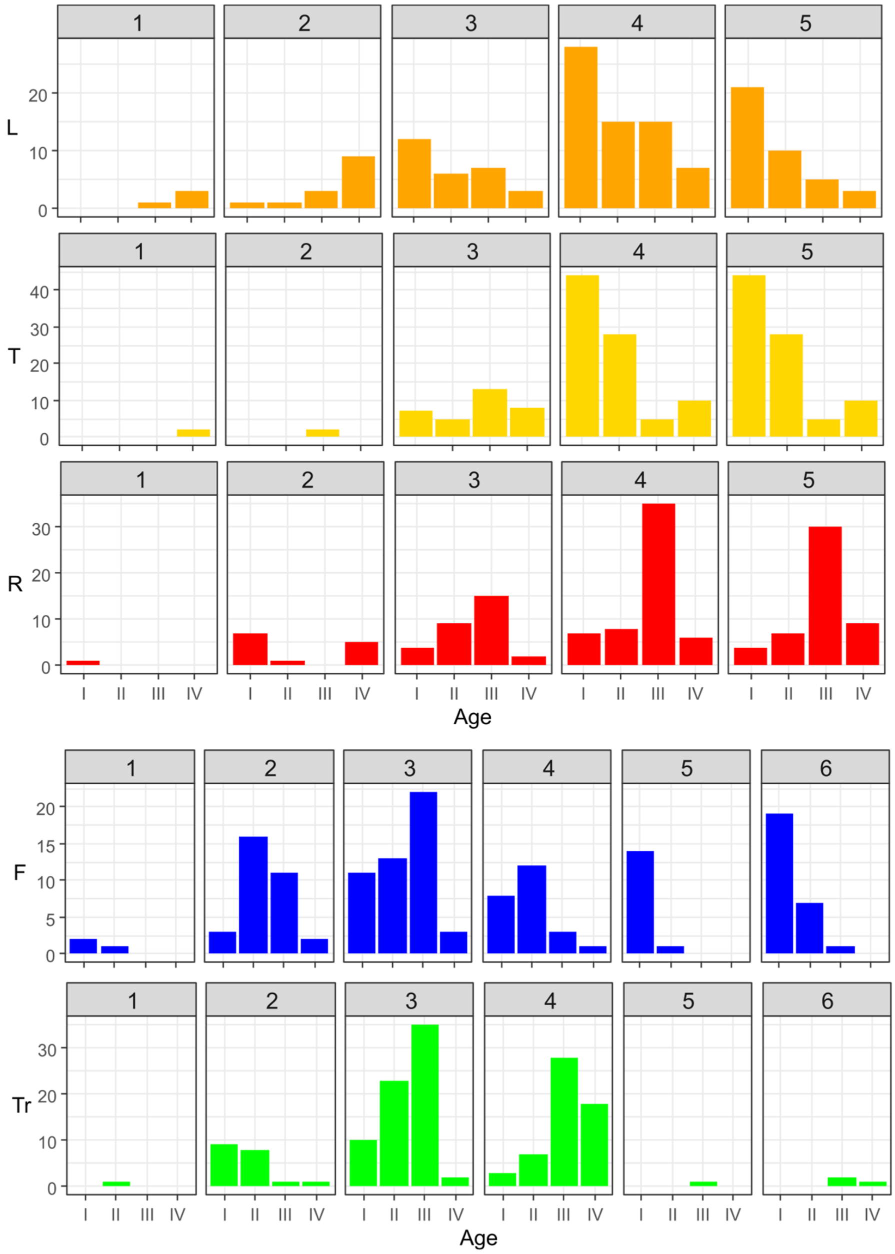

Figure 4. The participation of rare, endangered, and protected species recorded on post-coal mining heaps in relation to the values (1–6) of selected ecological indicators (L—light, T—temperature, R—soil reaction, F—moisture, and Tr—trophy) and the age class of the heap (I–IV) they were found on.

Considering the light index (L), it was found that moderate light and full light species predominate on the post-coal mining sites (aged up to 10 years). On these heaps, it is not possible to observe deep shade plants at all. On the older sites (aged up to 60 years and older), there is a greater variety of plants representative of a wide spectrum of the light index (1–5). In relation to the thermal index (T), in plants found in each age group of heaps, most species represent habitats with moderately cold and moderately warm climatic conditions. Only on older heaps are there fewer species associated with colder areas. For the moisture index (F), on the studied post-extraction sites, the numerous groups of species are representative of habitats with moderately moist conditions. In terms of the trophism index (Tr) of plants found in each age group of heaps, soils are mostly moderately rich and rich (with the occurrence of mesophrophic and eutrophic species). The differentiation of the soil acidity index (R) has shown a wider spectrum of this index in the case of plants on younger heaps. On heaps aged up to 60 years, there is a greater dominance of species on sub-neutral to neutral and alkaline soils. Only heaps of the first age category have shown species that represent each value of this index.

Explanations:

- Differences in participation are significant according to G-test for L ($G = 21.122$, $p = 0.006829$), T ($G = 33.496$, $p < 0.001$), R ($G = 21.964$, $p = 0.004983$) and Tr ($G = 41.935$, $p < 0.0001$), and non-significant for F ($G = 16.406$, $p = 0.08858$).
- The age of heaps: I—up to 10 years, II—up to 30 years, III—up to 60 years, IV—more than 60 years.
- Light index (L): 1—deep shade, 2—moderate shade, 3—half shade, 4—moderate light, 5—full light.
- Thermal index (T): 1—coldest areas in the country, mainly alpine and subnivean zones, 2—moderately cold areas, mainly subalpine and upper mountain zones, 3—moderately cold climatic conditions, lower mountain zone, northern division in lowlands and special microhabitats—raised bogs, 4—moderately warm climatic conditions, most of the lowland and colline region, 5—warmest regions and microhabitats.
- Soil acidity index (R): 1—highly acidic soils ($pH < 4$), 2—acidic soils ($4 \leq pH < 5$), 3—moderately acidic ($5 \leq pH < 6$), 4—neutral soils ($6 \leq pH < 7$), 5—alkaline ($pH > 7$).
- Moisture index (F): 1—very dry habitats, 2—dry habitats, 3—fresh habitats, 4—moist habitats, 5—wet habitats, 6—aquatic.
- Trophism index (Tr): 1—extremely poor (extremely oligotrophic) soils (water)—raised bogs, loose sand, dry coniferous forest, 2—poor (oligotrophic) soils (water)—fresh coniferous forest, 3—moderately poor (mesotrophic) soils (water)—mixed forest, acidophilous oak and beech forests, 4—rich (eutrophic) soils (water)—lowland, fertile beech forests, 5—very rich (extremely fertile) soils (water), 6—over-fertilized soils (water).

4. Discussion

4.1. Novel Habitats, Diversity of Plant Species and Vegetation

The feedback relations between various assemblages of organisms and abiotic elements of ecosystems are assessed based on our current scientific knowledge about natural and semi-natural ecosystems. There are many publications relating to relationships between novel ecosystems, habitat variability, biodiversity, ecosystem functioning, and ecosystem services. These subjects are still discussed and studied in the scientific literature [9,57,58]. Biodiversity is a multilevel, hierarchical system of increasing complexity of all levels of biological organization (genes, individual organisms, species populations, communities, and ecosystem mosaics). The role of individuals of single species in providing specific ecosystem services is difficult to estimate [59]. It is easier when the role of the keystone species is considered. The assemblages of living organisms, not individuals of separate species, directly interact with the abiotic habitat patch conditions. Diversity of the species composition of the diverse community patches reflects the complexity and plays a crucial role in enhancing resistance to habitat disturbances and biotic transformation such as by invasion of alien species [60]. In natural or semi-natural ecosystems, living organisms such as plants are assembled and persist in dynamic equilibrium with the habitat conditions. Species abundance and composition varies temporally and spatially within particular natural and semi-natural ecosystems. The gradients of abiotic parameters are the factors of spatial heterogeneity [61], and the dynamics of species populations lead to temporal heterogeneity in natural and semi-natural ecosystems [62]. Some studies have shown that vegetation species composition and their associated functional diversity underpin higher stability and resistance (resilience) of the ecosystem. It is known that ecosystem processes and functioning enhance the ability to provide a wider range of ecosystem services [9,42,63].

Modifications in biodiversity cause changes in ecosystem functioning. One gene altering the tolerance of a plant to stress can significantly increase the amount of biomass in a particular ecosystem. The differences in species composition and abundance of Fabaceae in vegetation patches can influence the nitrogen cycle [64]. The wide range of adaptive abilities of living organisms allows them to grow in de novo established habitats. The adaptive and evolutionary basis of biodiversity are responses to habitat constraints. The challenging conditions of post-mineral extraction sites and some other urban-industrial habitats created de novo and novel ecosystem habitats play a vitally important role in stimulating the adaptive and evolving processes of living organisms [65,66].

Vegetation, and its associated species diversity, is influencing the stimulation of soil-forming processes, atmosphere regulation, prevention of erosion, and the abundance of pollinators [57,67]. Scientific research confirms that enhancing biodiversity, particularly rare, protected, and endangered plant species, and vegetation, significantly influences ecosystem services and the functioning of entire ecosystems [4,21,68–71].

In the post-industrial landscape of Silesia (Silesian Upland), Bacler-Żbikowska and Nowak [30] distinguished 7.4% of notable rare, protected, and endangered species in the flora of the Silesia Region. The presence of rare, protected, and endangered species in the Silesian urban-industrial sites provides evidence that the conditions of some urban-industrial areas, particularly those of post-mineral extraction, are appropriate as refuges and secondary habitats for these species. The open post-mineral extraction poor oligotrophic areas enable the growth, spontaneous colonization, spread, establishment, persistence, and survival of rare, protected, and endangered plant species [30,72].

The importance of the diversity of the species composition of the spontaneous vegetation within novel ecosystem habitats for enhancing and maintaining biodiversity should be understood by decision makers and practitioners. The management of these sites in urban-industrial landscapes must be carried out based on the newest scientific environmental knowledge, particularly in respect to their provision of ecosystem services in densely populated urban-industrial areas.

4.2. Energy and Matter Flow

In natural and semi-natural habitats, an ecosystem is defined as a system of biotic and abiotic elements linked by processes due to which the flow of energy and matter takes place. Likewise, for novel ecosystems, the relationship between biodiversity and the functioning of ecosystems should not be based on studies of ecological groups of living organisms by looking only at species composition. The aspect of dynamics should not be overlooked. The research focused on the flux of energy absorbed by the autotrophic organisms, mostly plants, and matter flow through the system can be a key feature.

For novel ecosystems, indicators measuring different aspects of biodiversity along environmental and development gradients may prove helpful. The complexity of biodiversity at a certain scale, such as the richness of species in a landscape, may be important [73]. Among ecosystem processes, the measures of biomass or acquisition of nutrients can be utilized. Both are crucial in the assessment of ecosystem services.

Apart from measuring the dynamic ecosystem processes, it is important to predict the relationship between biodiversity change and the diversity of ecosystem processes and functioning. There is a need to measure the influence of biodiversity increase, or decrease, over a range of changes in environmental conditions. Similarly, it is important to be able to assess the influence of biodiversity change after anthropogenic and environmental stresses of socio-economic systems without loss of their value [74,75]. Analysis of the relationships between biodiversity change, ecological and ecosystem processes, and functioning (provision of services) is very important. Changes in climate are also very important [76]. A scientific understanding of the environmental processes can help to protect and enhance the maintenance of an ecosystem mosaic and to support the resilience of complex systems in urban-industrial landscapes. The need for models that reflect links between plant species composition of vegetation, biodiversity, and ecosystem processes is undeniable as the prerequisite for the provision of ecosystem services [77].

4.3. The Results of the Study in a Broader Context

The scope of the presented study limits the area that could be considered. The rare, endangered, and protected species can be analyzed only in accordance with a particular area under specific circumstances. In the broader sense, the scientific issues related to post-mineral extraction and some post-industrial habitat conditions enhance the adaptation process at a species, community, and ecosystem scale. In this respect, post-extraction and post-industrial sites should be considered in terms of the capability of individuals of selected plant species to tolerate challenging habitat conditions [78–81]. The role of some post-extraction and post-industrial sites in enhancing the local biodiversity and ecological processes, such as succession, is presented by Mota et al. [82,83] and Musarella et al. [84]. Woźniak et al. [85] pay particular attention to the functional diversity on such habitats. Such aspects affect the adaptation processes of living organisms and the increase of biodiversity on post-extraction and post-industrial sites should be reflected in the management decisions for these sites [86,87].

5. Conclusions

5.1. The Diversity of Plant Species and Vegetation of Novel Habitats

This research shows how important novel ecosystems on post-mineral extraction sites are at supporting plant and vegetation diversity within the urban-industrial landscape. The studied sites are vitally important for many interesting plant species (e.g., rare, endangered, and protected species). Ecological analysis of these species has shown that plants from a wide ecological spectrum appear in this type of habitat. Their occurrence is connected with the variety of habitat conditions provided by the environment of post-mineral extraction and of some post-industrial areas (giving rise to novel ecosystems). Thus, the habitat conditions of post-industrial areas help many living organisms to survive, particularly plants, in the urban-industrial landscape after the constraints caused by the massive eutrophication of terrestrial wetland and water habitats. An inter-related variety of natural processes are maintaining these urban ecosystems. Environmental function is of crucial importance in these mosaics of novel ecosystems within the urban-industrial landscape.

5.2. The Importance of Novel Ecosystems in Urban Post-Industrial Sites

The nutrient-poor, oligotrophic, post-mineral extraction sites enable the colonization and establishment of not only common but also rare, endangered, and protected plant species. Along with the occurrence of these plant species in the patches of recently assembled vegetation, natural processes enhance the diversity of above- and below-ground living organisms. The species composition of the vegetation is ruling the above- and below-ground ecosystem processes. This shows the close relationship between vascular plant species diversity, as the primary producers which promote energy and biomass during ecosystem functioning, and the provision of ecosystem services.

5.3. Novel Ecosystem Habitats—The Need for Good Environmental Decisions and the Possibilities of Management Projects

The occurrence of high species diversity within the recorded patches of spontaneous vegetation growing on post-extraction sites must be recognized during the environmental management of the legacy of these industrial sites. The management of novel ecosystem habitats also needs to be taken into account when making decisions about the long-term future of these post-industrial sites.

5.4. The Potential of Novel Ecosystems

In the future, these studies can be used for comparative purposes with other novel ecosystem habitats from other regions of Poland or with those of another country. Furthermore, this type of research could help in increasing our understanding of the potential of novel ecosystems and the role they play in the provision of ecosystem services.

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