Urban and Industrial Habitats: How Important They Are for Ecosystem Services

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http://dx.doi.org/10.5772/intechopen.75723

Abstract

The sustainable management of natural resources can make human survival possible. Sustainable management is based on a deep understanding of the complex mechanisms of the Earth's natural ecosystems and of how those resources can be managed without compromising future benefits and availability. The sustainable management of natural resources becomes much more complicated when there is severe and constant anthropogenic impact, and therefore, an interdisciplinary approach has to be undertaken to improve the understanding, assessment, and maintenance of the natural capital, and the related ecosystem services, in urban-industrial areas. In ecological restoration, the biggest challenge is to find a general consensus of suitable biodiversity indicators and economically viable measures, which will produce multiple socially and ecologically guided environmental benefits. There is difficulty in reaching such consensus because of the complexity, and differing understanding, of the biodiversity concept. In an effort to restore sites disturbed by industrial (mining) activities, restoration projects should involve ecologically based methods and approaches, which will be able to fulfill many stakeholders' expectations for sustainable development and human well-being. The integrated natural and human models for sustainable management can used to understand the dynamics of ecosystems, including biodiversity and trophic levels (including mid-trophic consumer influences), in order to simulate and evaluate different management scenarios in relation to biodiversity and ecosystem services. There is still a need for the increasing understanding of the role of biodiversity and ecosystem service identification as important factors influencing the dynamics of ecosystem and sustainable management scenarios.

Keywords: biodiversity, ecosystem functioning, natural capital, urban-industrial areas, ecosystem services, interdisciplinary approach, sustainable management scenarios

1. Introduction

Human existence is dependent on nature [1]. The sustainable management of natural resources, based on a deep understanding of the complex mechanisms of the Earth's natural ecosystems, can make human survival possible [2]. These mechanisms become much more complicated when there is severe and constant anthropogenic impact, and therefore, an interdisciplinary approach has to be undertaken to improve the understanding, assessment, and maintenance of ecosystem services in urban-industrial areas.

In the twentieth century, it is argued that the Earth has entered the Anthropocene epoch [3]. It is in this epoch that human influence has become the dominant driver of changes to the global Earth systems [3]. The main characteristic of the Anthropocene epoch is that human influences are shifting the natural conditions beyond their limits, and beyond the natural conditions, humans need for their own existence [4]. Everard [5] states that we have to co-create a symbiotic future of natural forces (soil, water, air, and living organisms) with human forces (innovations, development, and human well-being) [6].

When discussing ecosystem services, it is important to consider natural capital as the key provider of natural assets from which ecosystem services are derived. Often the terminology regarding natural capital and ecosystem services is used interchangeably, and this complicates the understanding of this complex subject [7]. Natural capital can be considered as the stock, or natural assets, within an ecosystem or an area. The natural assets can include the biotic elements, such as the ecological communities and the soils (with living organisms and soil organic matter, etc.), and the abiotic elements, such as land, minerals, water, and air. The natural capital can then provide or generate ecosystem services through environmental production and processes over time [7].

The natural capital of any one area or ecosystem can vary according to different parameters, for example [8]:

- the amount of an area covered by vegetation;
- the physical and chemical composition of the environment and biological diversity of the habitats;
- the variety, in space and time, of the mosaic of suitable habitats to provide conditions for the development for species, communities, or functional groups aiding the fulfillment of their roles in the ecosystem (ecosystem service);
- the establishment of the combination of particular species and/or functional groups;
- the abiotic factors that interact with the biotic factors in the above groups.

Ecosystem services that are derived from natural capital through environmental processes and functions can also differ depending on the area or ecosystem involved [8]. It is the processes and functional relationships between natural capital and ecosystem services that directly or indirectly influence human life, which produces human benefit [9–12]. Therefore, the variety of the Earth's ecosystems, including the environmental properties (EvP) and the environmental functioning (EvF), can provide that which is necessary for human existence and human well-being. The natural capital element alone is of value, but the most important is the proper interaction and relationships between the elements that provide the ecosystem services [13, 14]. To some extent, human activity is able to enrich these relationships, particularly in the highly populated urban and industrial areas. However, conversely, habitat degradation and the disturbance of resources associated with natural capital cause the decrease of ecosystem services in some places [15, 16].

As ecosystem services are defined as "the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life" [17], this concept is shaping human-environmental interactions [18] within the environmental and sustainable context and reveals an understanding of the concept of urban populations' dependence on elements of [19–21].

The global increase in human population is leading to the increasing range of land-use activities, including the conversion of natural landscapes for human use or by changing the system of management practices on land that is already human-dominated. For example, large areas of the Earth's land surface have been transformed through intensive agriculture, natural resource excavation, expanding urbanization and industrialization, and so on. Often such human activities are changing the world's ecosystems and landscapes in drastic ways, and intensive research has revealed that the pressure of land use throughout the globe has influenced the environment, ranging from modification in the composition of the atmospheric gases to the extensive modification of the Earth's ecosystems [22]. The Millennium Ecosystem Assessment revealed that 60% of ecosystem services have been put under risk because natural resources have been affected by exploitation and unsustainable use [23].

The environmental processes and functions take place in various ecosystems regardless of the level of the naturalness of that particular ecosystem, including in urban and post-industrial ecosystems, and that in these less natural ecosystems, the type and strength of inter-relations, synergies, and processes that exist may vary widely [12]. As a result, there is an increasing awareness that is leading to the development of more effective management strategies, which consider the challenge of reducing the negative environmental impacts of increased land use and growing demand as well as maintaining the economic and social needs and benefits [24], especially in urban-industrial areas.

The issue of ecosystem services in urban-industrial areas has to be of particular consideration for several reasons:

i. the majority of the world's population lives in urban-industrial areas, and two-thirds of the world's population is expected to be living in urban areas by 2050 [25];

ii. urban-industrial areas comprise a small part of the Earth's terrestrial habitats, but they are responsible for a significant role in global carbon emissions, energy, and resource consumption [26];

iii. the densely populated areas greatly contribute to environmental transformations, causing biodiversity loss, ecosystem degradation, and climatic change on an almost global scale [23, 27, 28].

The application of the concept of ecosystem services to urban and industrial environments has generated an increasing amount of research during the last decade [29–31]. Review papers on ecosystem services in urban and post-industrial environments have considered some specific issues such as water quality and resources [32]. Other studies on "the ecology of cities" [33–35] have considered the environmental balance between natural capital and ecosystem services in urban-industrial areas. Such studies have tended to focus on sustainable development in cities or the links between the urban areas and the rural landscape, with the suggestion that the links between the urban areas and the surrounding rural areas influence each other [35]. Often urban ecosystems include both the "gray" built-up infrastructure and the "green-blue" ecological infrastructure (parks, urban forests and woodlands, cemeteries, gardens, urban allotments, green roofs, wetlands, streams, rivers, lakes, and ponds) [36]. However, it is still a matter of discussion as to what extent peer-reviewed literature is able to currently provide the comprehensive and integrated research, which is capable of covering the diversity and interdisciplinarity of research approaches needed for a fuller understanding of urban-industrial ecosystem services [37].

It can be argued that in the urban-industrial environments, habitats and ecosystems have developed, which would not normally develop outside the urban-industrial areas or would become extinct elsewhere, including ecosystems developing initially on nutrient and mineral poor habitats. It is important to realize that apart from ecosystem services providing direct impact on human health and security, such as urban cooling, noise reduction, air purification, and runoff mitigation, there are also some services that are more difficult to assess. Nevertheless, these are important urban-industrial ecosystems at the initial stage of succession, with their unique microorganism-vascular plant relationships, and provide an important contribution into the overall ecological diversity.

According to the Millennium Ecosystem Assessment (MEA) [23], "Ecosystem services are indispensable to the well-being of all people in all places." Ecosystem services can only be provided by ecosystems, which are functioning effectively. However, there is a good evidence base that outlines the importance of biodiversity to ecosystem functioning, but less research is focused on the direct relationship between biodiversity and ecosystem services. Binner et al. [7] suggest, with reference to urban areas, that there is an evidence gap in the understanding of biodiversity in urban woodlands and the benefits that are accrued. Many of the world ecosystems have been damaged or disturbed by human activity, and those changed ecosystems need to be restored and/or managed accordingly [38, 39]. Knowledge regarding those ecosystems modified, transformed, or created by human influence is very limited. It is important that these changed ecosystems are restored and/or managed, but because of the lack of knowledge about the details of their functioning (**Figure 1**), the restoration practice is very complex and often unsuccessful [40, 41].

Even though there has been a sustained period of study, many of the mechanisms governing ecosystem functioning are still not fully understood. The general rule is that the relationships between the ecosystem elements are complex, and therefore, models have to be simplified, transformed, and translated into more accessible and informative formats for stakeholders and decision makers to incorporate the ecosystem principles into management practice. Improving management practice may facilitate the enhancement of ecosystem services for human well-being in urban-industrial sites.

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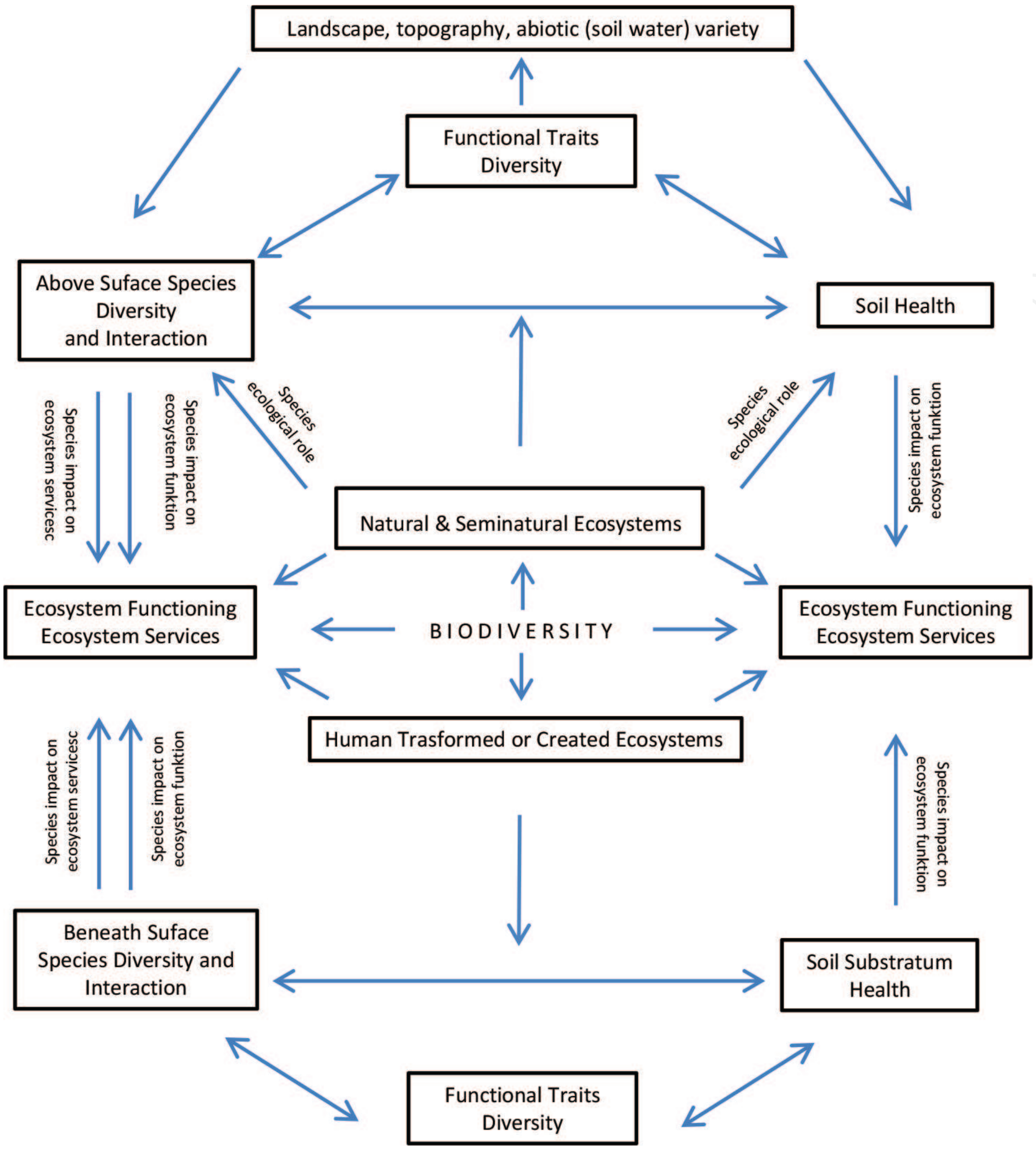

Figure 1. The basic inter-connected relationship between biodiversity and ecosystem functions, including the diversity (species richness, relative abundances of species, genetic diversity, and diversity of functional trait variability of vegetation types), impact, and interaction (species ecological role, species impact on ecosystem function, species impact on ecosystem services, variability of ecosystems, variation at landscape scales, abiotic or non-living diversity, and topography).

One of the relatively well-understood ecosystem principles, which has been substantiated in many studies, is that biodiversity, and in particular functional diversity, strengthens ecosystem stability, ecosystem services, and productivity [42, 43]. In this respect, the worldwide decline in biodiversity, caused mostly by human influence and anthropogenic factors, has to be of global concern [44, 45]. Decline in biodiversity is a global issue that has to be managed by local practice and within the local context [46, 47].

It has also been reported that the mechanisms that regulate biodiversity are complex and incorporate many potential interactions and feedback loops, which may even accelerate the loss of biodiversity, and should not be disregarded. One example of an important unsolved feedback relationship concerns whether producer diversity is related to the presence of consumers (top-down regulation) or related to the availability of resources (bottom-up regulation). The latest study suggests that the two relationships interact with each other [48–50] and seem to be habitat type dependent. However, whether and how biodiversity is related to ecosystem functional processes at higher trophic levels in different human transformed ecosystem types is arguable. It has been suggested [51, 52] that it is necessary to test if, in the complex communities with multiple trophic levels, diversity effects are governed by trophic interactions, including trophic processes, in order to gain a better understanding of functional diversity.

Politicians, business managers, and decision makers are increasingly aware of the need for the sustainable management of natural capital. However, they do not have the tools to evaluate the influence of different decisions [53], and there is a lack of knowledge and understanding of how abiotic and biotic elements of natural capital interrelate in ecosystems to provide different services. In addition, there is a growing concern that human needs are becoming detrimental to biodiversity conservation priorities [54] and that utilizing natural capital resources, required for necessary ecosystem services, are decreasing due to species loss and habitat fragmentation [23]. Therefore, the contemporary task for scientists is to provide the managers and stakeholders, if possible, with manageable protocols to help them understand the very complex links, synergies, and generally nonlinear relationships in ecosystem function. To date, research has shown that one management strategy will not work across all spatial, temporal, or cultural situations.

2. Urban-industrial environments uniqueness and ecosystem potential

Both urban and industrial areas represent complex land-cover mosaics, which are "novel ecosystems" in terms of their ecological component composition [55]. The community composition in urban-industrial areas, i.e., the below and above surface organism relationships developing on soil/soil substratum, is different to non-urban and non-industrial counterparts. In such new environmental situations, such as in habitats under constant human pressure in urban areas or created by human activities in industrial or post-industrial areas, the understanding of which features of particular organisms, communities, vegetation type, or habitat characteristics are most important (the service provider concept) is limited [56]. The most important point for understanding the urban-industrial areas' ecosystem function (ecosystem service providing mechanisms) is the biodiversity-ecosystem function-ecosystem service relationship. In the environment of urban-industrial areas, which are frequently modified, it might be expected that various aspects of the urban biodiversity-ecosystem service relationship are unique. There are many sites in urban-industrial areas that are poor in nutrients (oligotrophic) and are at the initial developmental stage, and these sites are valuable in terms of their potential for biodiversity enhancement (**Figure 1**). This uniqueness implies the urgent need for the study on the biodiversity-ecosystem function-ecosystem service relationship on one hand, and the need for the decision makers and stakeholders to take this uniqueness into account in policy and management recommendations on the other hand. This uniqueness also implies that there is a high potential for the enhancement of those habitats. However, ecosystem dynamics in urban and industrial landscapes are poorly understood [20, 57], especially when it comes to designing, creating, and restoring ecological processes, functions, and services in those areas [57, 58].

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2.1. Urban areas—ecosystem service potential

Urban areas are more often related to high population density and high consumption, and these areas are more likely to be connected with a reduction in resource demand rather than the production of ecosystem services. However, the results in the recent studies indicate that cities, in general, can be important ecosystem service providers [59, 60]. The research of [61] presented unexpected results that indicate that cities are able to store a comparable amount of carbon per unit area as that found to be stored in tropical forests. The high biodiversity stored in the ruderal vegetation of urban sites (**Figure 2**) has been represented by Kompała-Bąba 2013 (modified [62]).

Research has enabled the recognition, quantification, and performance of ecosystem service assessments in urban areas [60, 63–65]. The ecology of urban areas that support ecosystem services is unclear [37], and the biodiversity-ecosystem service relationship should be clarified as to what extent, and how, biodiversity influences ecosystem service provision. The

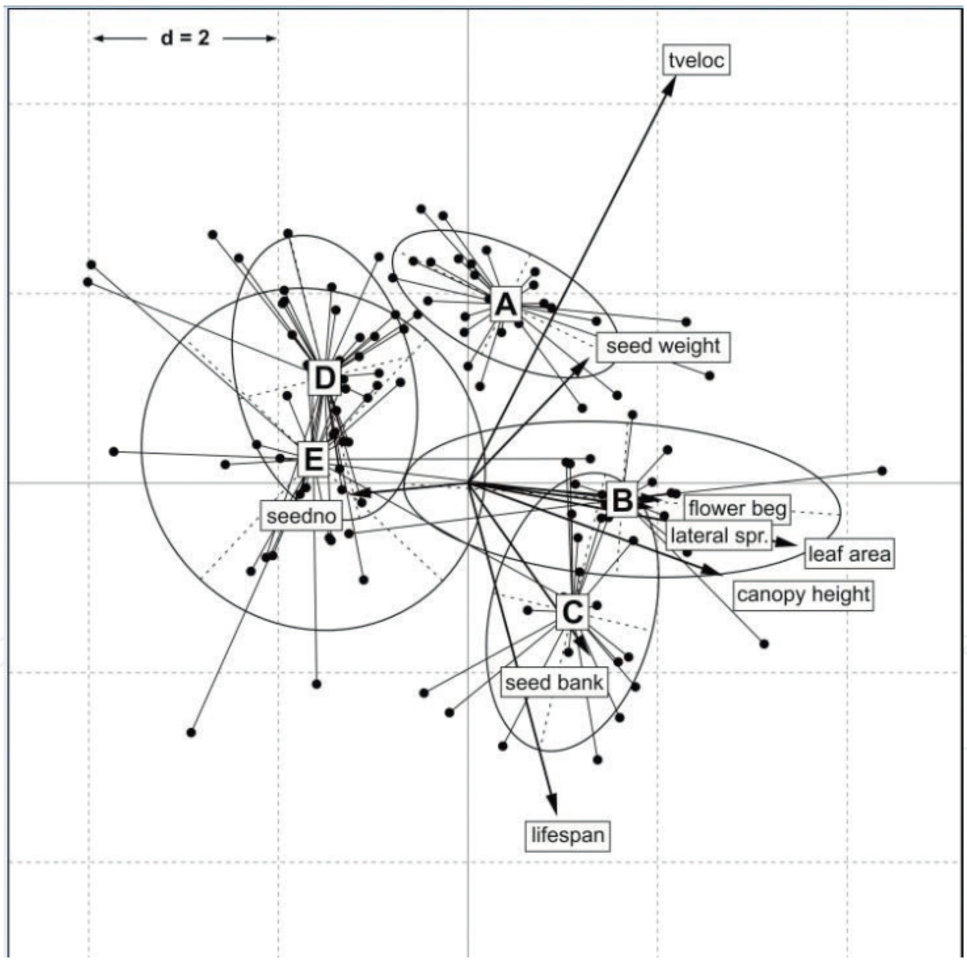

Figure 2. The floristic diversity of vegetation of ruderal habitats expressed through the use of functional traits of species. Five functional groups of species in urban ruderal habitats are distinguished in relation to fertility and disturbance gradients: (A) comprised monocarpic and biennials that had a high seed weight and terminal velocity and that differed in relation to seed bank type and lateral spread; (B) and (C) groups comprised polycarpic species, which had many traits that are connected with competitive ability (high leaf area, canopy height, high seed number, and long-term seed bank), mainly nitrophilous ruderal and meadow species, which differ in relation to lateral spread, seed weight, and terminal velocity; (D) and (E) groups were mainly made up of species that possessed traits that enabled them to adapt to disturbances or other forms of stress that differ in relation to life span (modified [62]).

lack of a precise definition of biodiversity in its biological and ecological sense on one hand and a precise definition of biodiversity as understood by economists and sociologists on the other hand is a real challenge. A commonly used definition [66] (Convention on Biological Diversity) states that "Biological diversity means the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are a part; this includes diversity within species, between species and of ecosystems," and it is sometimes understood that biodiversity can be given a numeric value. In particular, biodiversity in an industrial urban situation suggests that the principle that "more is better" is not working. Biodiversity should be understood as a complex mosaic of different habitats in which the species composition is appropriate for the abiotic site conditions. Such understanding of biodiversity may help to limit or avoid the spread of alien, invasive species, and the spread of expansive, ruderal organisms occurring in large numbers in different habitats. Research has shown that the spread of alien and invasive plant species causes a decrease in the species composition of native habitats [67, 68].

Apart from the serious contemporary constraints in understanding the biodiversity-ecosystem service relationship, there are reports concerning successful Blue-Green City projects. A Blue-Green City is a concept relating to the support or enhancement of natural potential, mostly by plants, and using them, for example, to reduce flood risk or to help improve air, soil, and water quality. When nature (plants or water) is used by people to help manage and enhance urban environments, e.g., in managing storm water, it is often referred to as blue-green infrastructure (**Figure 3**). Green infrastructure as a whole is a larger concept associated with the service provision of an ecological framework for the social, economic, and environmental health of the surrounding environment.

The aim of the Blue-Green City approach is to recreate a water cycle based on natural processes by joining water management with the green infrastructure in urban areas, for example, to manage flood risk by combining the hydrological and ecological potential of the urban landscape. The interaction between blue and green can enrich the urban environment as illustrated in the Blue-Green City project in Newcastle, UK [69]. In terms of ecology and hydrology, the aims of the Newcastle project are:

i. the creation of an urban flood model to simulate the movement of water and sediment through blue-green features;

ii. the improvement of water quality, habitat, and biodiversity by using a system of blue-green features (http://www.bluegreencities.ac.uk). The Newcastle project takes into account both the ecological and hydrological elements, which are both equally important for the urban ecosystem.

The successful blue-green management projects undertaken on a larger scale (landscape scale) in cities are very important as scientific background is still unclear, and greater evidence and evaluation are required. Only 25% of papers deal with the biodiversity-ecosystem service relationship aspect of aquatic habitats in urban areas [37], in part, because it is difficult to set the boundaries of a water flow inside an urban area. A common operational definition of the term "urban area" and its boundary would be beneficial for further studies. At present, an "urban area" is defined either by taking into account the population size of the urban area (population density—population size to area size) or by the administrative boundary.

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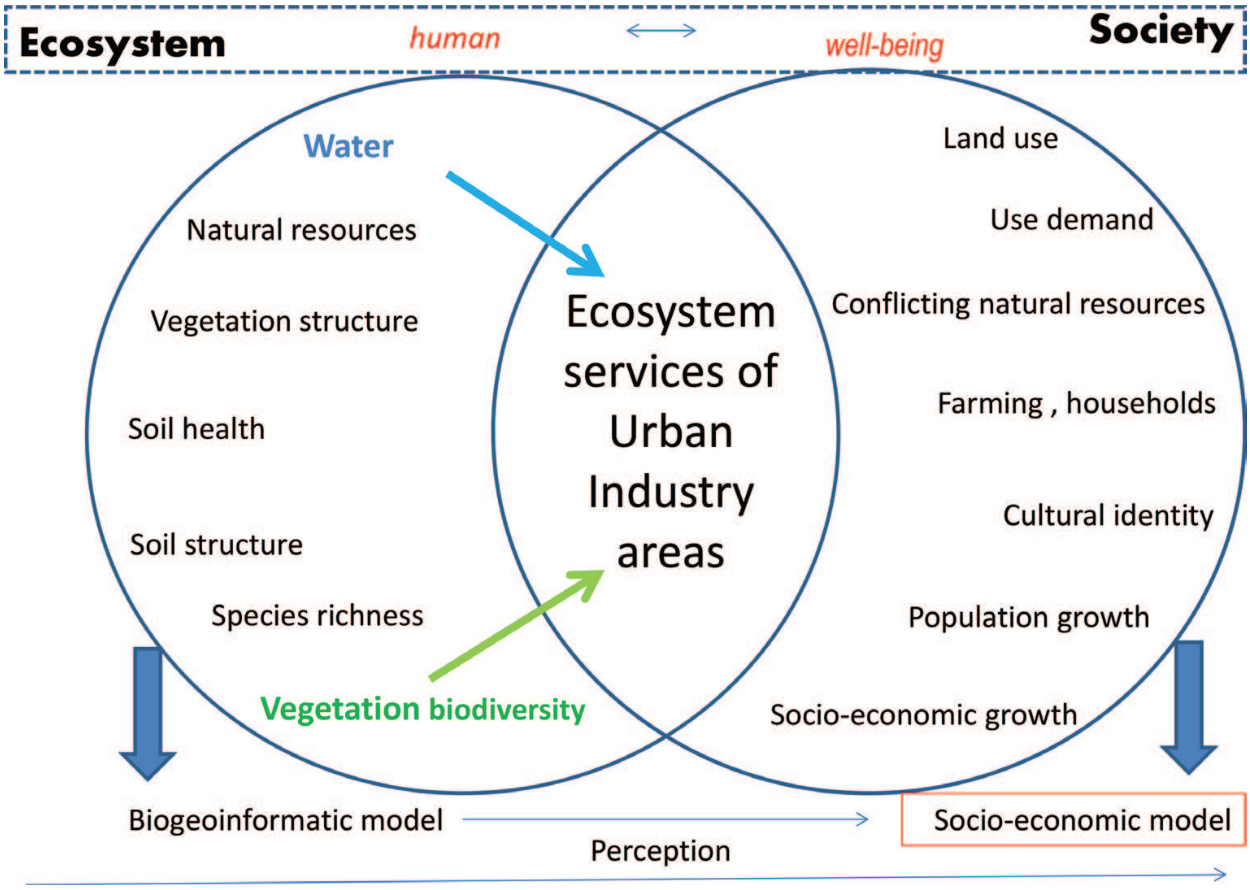

Figure 3. The complexity of the Blue-Green City concept in relation to the special mosaic of urban-industrial sites, land management, land requirements, and demand.

The different definitions are used depending on specificity of a particular county or research purpose [70, 71]. For more comprehensive results, particularly when the hydrological aspect of the natural capital is taken into account, a broader definition for an urban ecosystem service study should be used [6, 72–74]. The most important reason is that administrative boundaries rarely coincide with ecological function "boundaries" [20, 75]. The broader understanding of the target area that is indicated as urban, sub-urban, or peri-urban is required [76].

2.2. Industrial and post-industrial areas—ecosystem service potential

Restoration and regeneration of areas transformed, changed, and/or degraded by industry can be a long and complicated process. Post-industrial sites generally represent heavily affected ecosystems, which have lost their biodiversity and most of their ecosystem functions and services [77].

The wide range of aspects of biodiversity restoration and ecosystem services in post-industrial (particularly post-mining) sites has received wide attention among restoration scientists [78–81]. Although the scientific attention to ecosystem services has been growing, there has been a strong tendency to conduct short-term experimental studies in which biodiversity was experimentally manipulated (in the laboratory or in the field) [28]. However, some studies on vegetation development and spontaneous succession on urban and post coal-mine waste sites were conducted over 10 years providing interesting results about the mechanisms of concerning spontaneous ecosystem development and biodiversity enrichment in a broad spatiotemporal context [62, 82].

Increasing the biodiversity and ecosystem services, which are dependent on ecosystem functions, is the main aim of ecological restoration [83, 84]. In post-mining and post-industrial sites, the biodiversity and ecosystem function restoration and/or enhancement are related to the wider landscape (**Figure 4**), and various local micro-habitats in a broad spatiotemporal context.

The important prerequisites of soil/soil substratum physical features included:

- erosion control;
- water infiltration;
- recognition, assessment, and, when necessary, the improvement of the biotic spoil (spoil substratum) parameters including bacteria, arbuscular mycorrhiza fungi (AMF) diversity, and abundance;
- micro- and meso-climate, etc.

All of which are the prerequisites for the establishment of permanent vegetation [67, 85–88]. The restoration and/or enhancement will be the basis for the re-establishment of primary productivity of post-industrial sites, carbon sequestration, and the increase of the esthetic value of the site and the landscape. Ecologists [78, 89] prefer to emphasize the re-establishment or the increase of biodiversity as a goal of restoration.

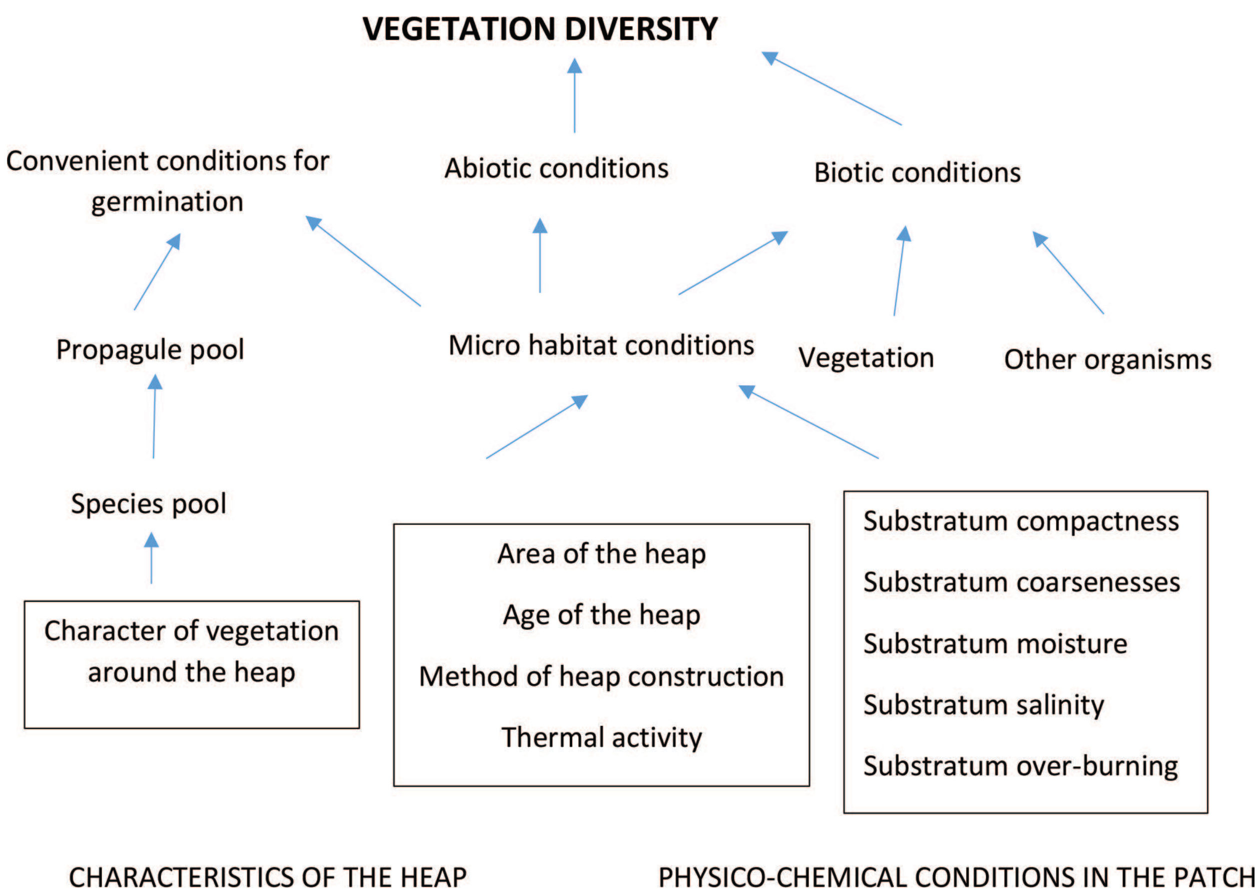

Figure 4. The main landscape factors affecting vegetation diversity during spontaneous ecosystem development on coal-mine heaps in a broad spatiotemporal context (modified [82]).

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Biodiversity is often considered to be closely linked with the increase in ecosystem functions or ecosystem services [90]. Biodiversity is also commonly used as a main driver or as a surrogate of ecosystem functioning and informs the understanding of ecosystem health (understood as overall description of the condition of an ecosystem) [91, 92]. However, society finds difficult to evaluate biodiversity because it is unquantifiable in monetary terms.

Among different definitions of the term biodiversity, including diversity of species, food webs, or genetic structure of populations, particularly meaningful is the definition on the diversity of functional groups [93]. Functional diversity reflects the importance of an ecosystem's diversity as it may occur that many species can fulfill the same role within the ecosystem (**Figure 5**), and so regardless of the number of species, a system may not necessarily function properly. However, species diversity is a useful and often adopted measurement in restoration projects, but unfortunately, it can be insufficiently informative and even misleading, particularly in highly transformed and modified urban and industrial ecosystems.

An understanding of biodiversity measurements of these ecosystems is needed because of the high number of species (species diversity), which may include both species appropriately adjusted to the particular habitat conditions (e.g., grassland species on grassland habitat, wetland species on wetland habitat, i.e., the target species), regardless of whether the sites are of natural or anthropogenic origin [67] and are dominated by competitive generalists, ruderals, and sometimes alien species. Alien, invasive, and expansive species may indicate an unwanted developmental and/or restoration pathway [94]. Selecting biodiversity indicators in restoration projects requires detailed study and understanding of the mechanisms governing spontaneous processes existing on post-industrial sites (**Figures 5** and **6**) [95–97]. The management proposed has implications for choices made based on certain values and focusing on some specific aspects, e.g., restoration or spontaneous succession [82, 98].

Post-industrial sites need to be managed, and the consideration of which restoration method is the most effective in terms of environmental/ecosystem recovery is necessary and site specific. The restoration/reclamation approach presents a type of gradient, or a continuum, of ecological restoration. There are intervention levels that range from technical reclamation (which involves heavy interventions, such as the restructuring of landforms, importing soil, and planting or sowing of plants) on one hand, and on the other hand, the spontaneous succession of the ecosystem that might be expected to recover principally through natural processes [79, 82, 99].

It can be expected that for post-industrial ecosystem development and functioning and the ecosystem services that may be accrued, the primary succession through natural processes is the most appropriate for several reasons:

- the site conditions of post-industrial sites are so different from the natural ones that it is inappropriate to use the experience from natural habitats for reclamation practice;
- the high microsite heterogeneity on post-industrial sites would require low-scale action that is not economically beneficial;
- recognition and increasing understanding of spontaneous succession enable the facilitation of natural processes by assisted restoration, in order to speed up the natural regeneration and the recovery of the ecosystem under adverse environmental conditions [86];

- it should be accepted that the target ecosystem may not always be a replacement of the original ecosystem that was lost by mining or industrial activities, but a system of living organisms that is best adjusted to the new post-industrial conditions;
- factors influencing spontaneous succession of post-industrial sites have to be assessed, through the studies of various measures and approaches, and this should be the basis for the planning of effective ecological restoration [100–103];
- at the beginning of spontaneous succession, the early successional stages create a mosaic of species group composition that is of high-conservation value [47, 96, 104];
- the maintenance of early successional stages should be a goal of restoration projects;
- technical reclamation, when compared with spontaneous succession, can negatively influence the local biodiversity since it decreases the amount of habitats that affect the specialized threatened species [101, 104] or even enhance and maintain the pool of seeded alien species that may spread to the surrounding environment [105];
- spontaneous natural succession on post-industrial and urban areas often leads to the establishment of a self-sustained, well-functioning ecosystem. However, they may be different ecosystems from those that occur in natural and semi-natural habitats;
- the differences caused by the adverse environmental conditions, such as contamination of the surroundings, are also a reason why technical reclamation fails;
- in some post-industrial sites, the conditions are so extreme endemism, and microevolution could be expected—still an issue to be studied;

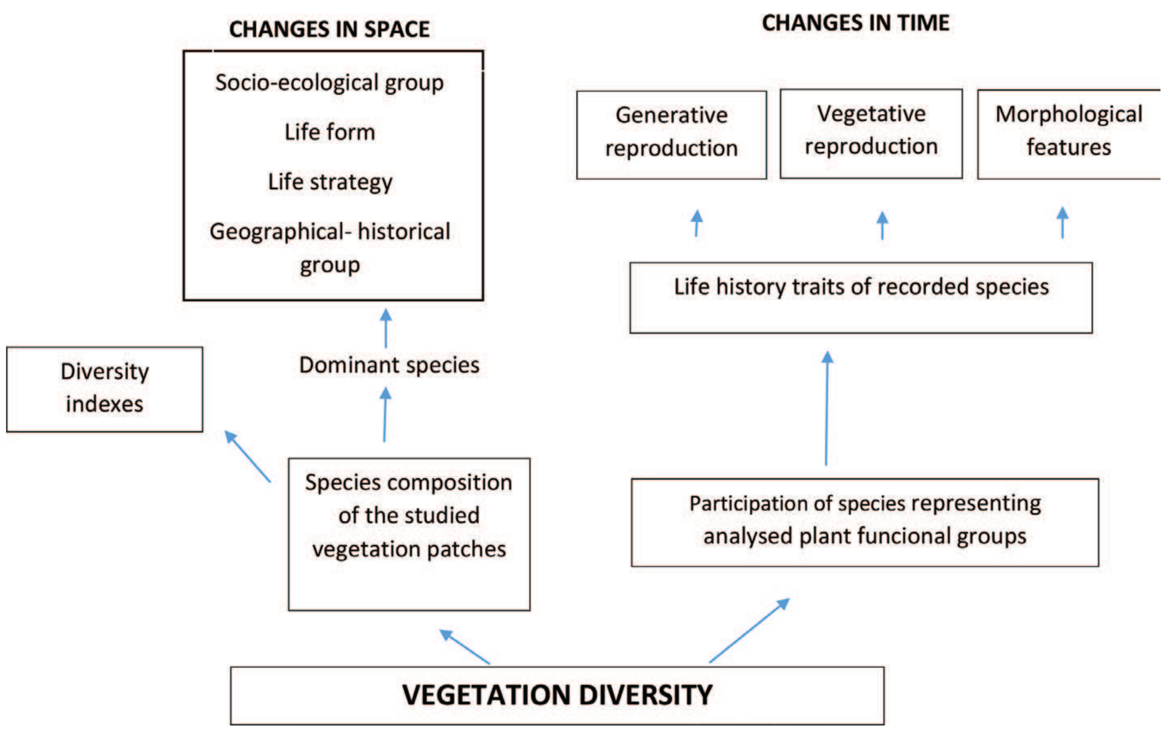

Figure 5. Aspects of functional diversity of vegetation development on post coal-mining heaps (modified [82]).

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- not all parameters are the only the negative products of human disturbances. Some of the post-industrial sites may provide refuges for specialized wildlife [101, 104, 106–111];
- It is possible to use high-resolution remote sensing data and LIDAR scanning; together with the wide range of ecological data (microorganisms including bacteria, arbuscular mycorrhiza fungi, mezofauna, vascular plant species, plant chlorophyll content, photosynthesis potential, vegetation species composition, and biomass production), in order to build a biodiversity model of urban industrial sites, with coal-mine heaps as an example (InfoRevita project) [112].

The above list suggests the need for a detailed study and the analysis of spontaneous development of ecosystems on post-industrial waste sites. Such research could provide scientific information on environmental and plant characteristics that may influence the regeneration and succession for restoration (**Figure 7**) and reclamation practice. These data can be used in developing effective ecological restoration under adverse site conditions resulting from post-industrial sites [100, 103, 107, 113, 114].

Post-industrial subsidence (**Photo 1**) and wetlands (**Photo 2**) have particular environmental, ecosystem function, and ecosystem service potential. These aquatic and wetland habitats of anthropogenic origin can provide opportunities for using ecosystem services to improve

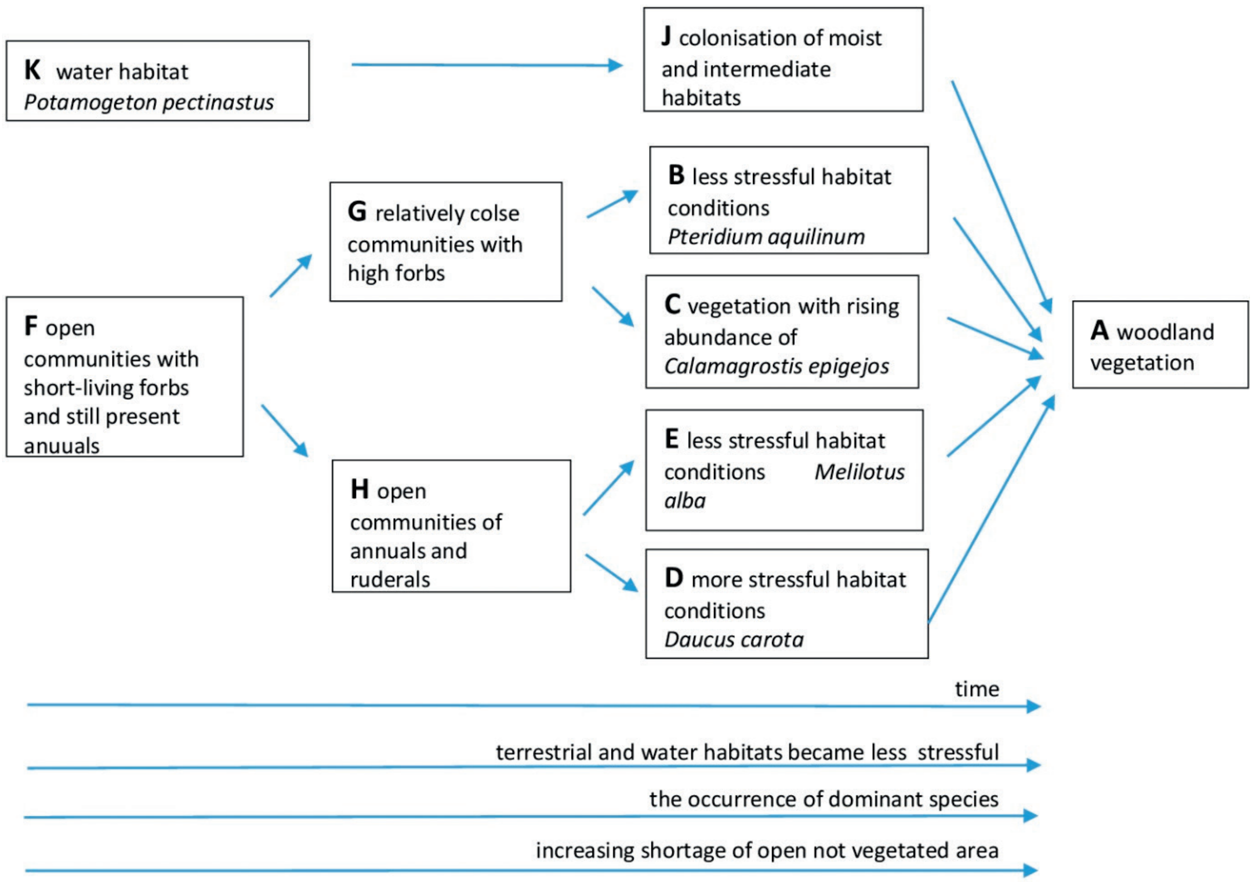

Figure 6. The example of predicted changes in vegetation development on coal-mine heaps depending on the TWINSPAN analysis of 2567 vegetation records performed on unclaimed post coal-mine heaps [82].

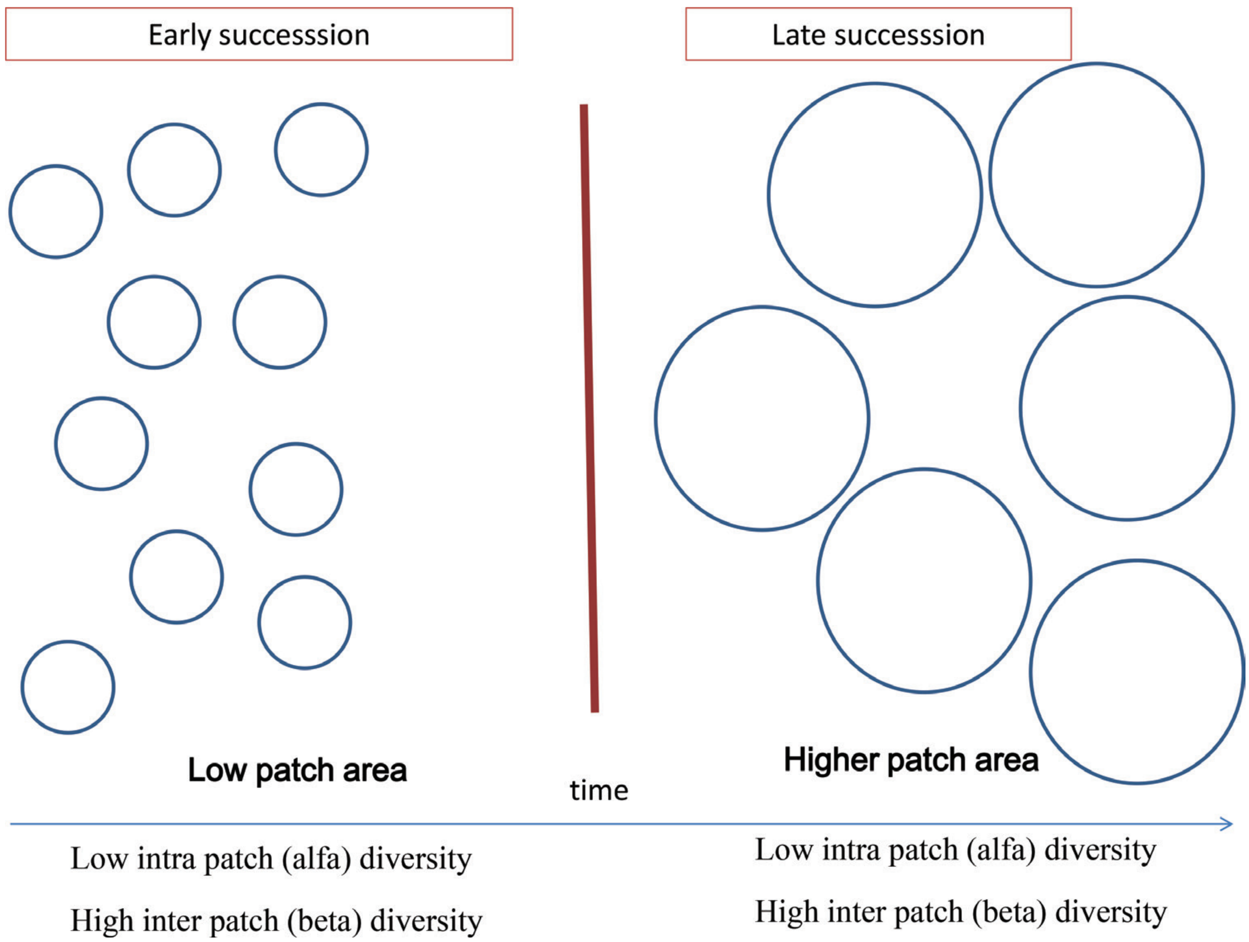

Figure 7. Divergence or convergence of biodiversity/ecosystem function recovery on post-industrial sites. The probable development pathway.

the quality of human life and minimize climatic change in urban-industrial areas. The study [115–117] conducted on the coal-mine subsidence included:

- identification of the ecological status of waters with the use of selected parameters, including biodiversity;
- identification of the potential of photosynthesis of aquatic plants;
- modeling of the functionality of biodiversity;
- identification of habitat conditions including the humidity of the ground and areas of water accumulation, based on high-resolution remote sensing data and LIDAR scanning;
- the role of vegetation diversity in modifying humidity conditions (including the water balance of the area), taking into account the results of modeling the species niche and the digital vegetation model;
- conditions of soil moisture in regeneration and creation of habitats in the revitalization of urban-industrial areas;

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Photo 1. Post coal-mine subsidence. The visual impression is misleading and does not refer to the real biodiversity potential of these anthropogenic habitats (photo: Edyta Sierka).

Photo 2. The peatbog vegetation with many rare and protected plant species developing spontaneously on wetland habitats of anthropogenic origin (photo: A. Błońska).

- the variety of vegetation in terms of functional features of species and their importance in water retention [67];
- diversification of habitat conditions and aquatic properties of anthropogenic peatlands [67];
- creating wetlands habitats and their role in local water retention.

Flooded mine subsidence is one of the effects of underground 'deep' coal mining. The subsidence results from the gradual sinking of the ground over the mine workings and takes the form of shallow (3–4 m deep) basins with gently sloping sides. Subsidence can occur in woodland, farmland, or industrial areas. However, the few studies conducted so far suggest that subsidence basins are unique enclaves, which facilitate the development of new ecological systems, thereby contributing to the biodiversity of such areas [77, 115, 116].

The study conducted on flooded mine subsidence showed that despite similar origins, subsidence pools differ substantially when it comes to the level of plant diversity. In contrast, there is no difference in terms of the average share of various functional groups (FGs). Plant diversity was substantially affected by the size and depth of the subsidence pools and habitat humidity, C/N ratio, concentration of P total in the soil, water, and water clarity. Subsidence pools differ significantly in terms of the number of dominant species. The importance and value of ecosystem services provided by 10 subsidence pools on the post-industrial area in Poland and Czech Republic, and their vicinity was estimated on an average of €521,000 [€ × ha × year^{-1}]. The most important ecosystem service that the pools fulfill is the water supply and habitat creation (**Figure 8**) [75].

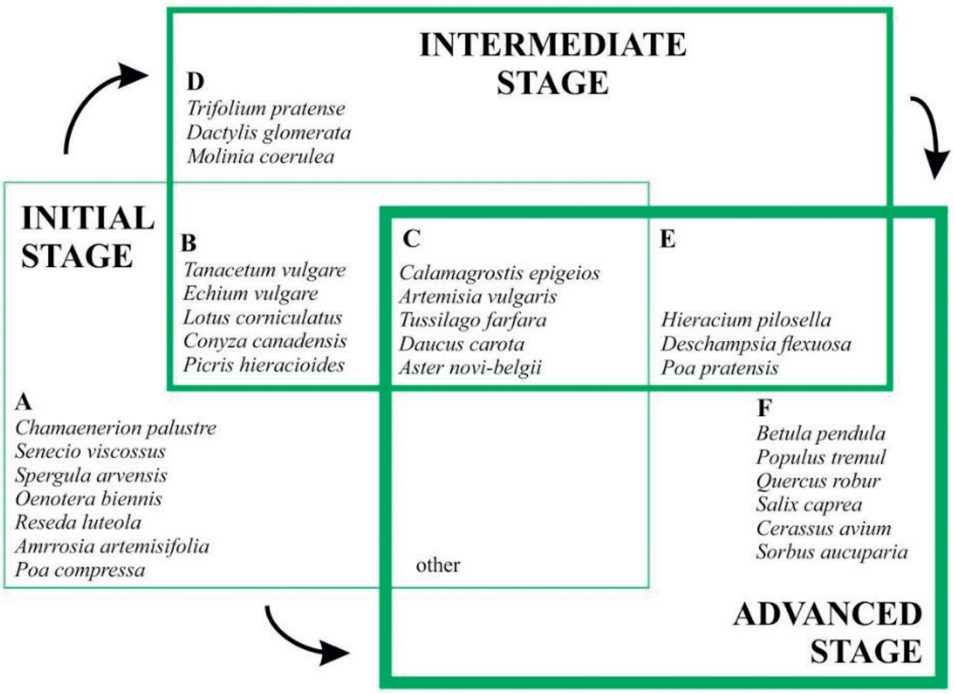

Figure 8. The example of predicted changes in species composition of vegetation developing on coal-mine flooded mine subsidence [75].

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It has been shown that the development of reservoirs in the subsidence troughs within post-mining areas, contributes to the enrichment of environmental potential of these areas, provides new possibilities for their use by living organisms, and improves the quality of human life.

3. Conclusions and perspectives

In ecological restoration, the biggest challenge is to find a general consensus of suitable biodiversity indicators and economically viable measures, which will produce multiple socially and ecologically guided environmental benefits. There is difficulty in reaching such consensus because of the complexity of the biodiversity concept. In an effort to restore sites disturbed by industrial (mining) activities, restoration projects should involve ecologically based methods and approaches, which would be able to fulfill many stakeholders' expectations for sustainable development and human well-being.

In this respect, it would be useful to employ integrated natural and human models to understand the dynamics of ecosystems including most of biodiversity and trophic levels (including such trophic levels like the mid-trophic consumer) in order to simulate management scenarios in relation to biodiversity and ecosystem services. Another crucial point will be the increasing understanding of the role of biodiversity and ecosystem service identification as important factors influencing the relationships between them. Both the models and the knowledge could be used to develop predictive scenarios of system-level impacts under a range of possible management policy scenarios in order to assess and to explore which management policy provides the greatest impact on sustainable ecological, social, and economic aspects.

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