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Identifying and understanding novel ecosystem functions: a scientific approach to nature restoration law

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Abstract: Human activity causes changes in habitat conditions. Where habitat conditions have been significantly altered by human activities, novel ecosystems emerge. This paper aims to analyse novel ecosystem parameters, particularly in relation to biodiversity and restoration law. It presents the role of novel ecosystems in ecosystem functioning and their significance within urban-industrial landscapes. Based on extensive literature reviews, that these ecosystems have been a subject of scientific interest for many years. However, comprehensive knowledge of these ecosystems still needs to be broadened. An interdisciplinary approach to their management is essential. The European Union (EU) has implemented various legislative and policy measures aimed at restoring and conserving natural ecosystems and biodiversity across different members states. Key initiatives include the EU Biodiversity Strategy for 2030, EU Habitats Directive, and EU Funding Programs, all of which promote sustainable development and strengthen restoration laws. Only a proper identification and understanding of novel ecosystems and their ecological processes can contribute to implementing relevant legal actions.

In the urban industry landscape, the poor mineral post-mining habitat sites have the unique potential to harbor and develop biodiversity hot spots in densely populated areas. Many of these sites with very harsh habitat conditions that have been left to spontaneous processes going on have become protected sites with outstanding biodiversity established (e.g., Bytom city). Such examples in Silesia (S Poland) provide proof that such solutions should be a constant element of the post-mining site management plans.

Keywords: biodiversity, ecosystem's functioning, mineral resources mining, nature restoration law, novel ecosystems, novelty, spontaneous process

INTRODUCTION

Human activity, driven by the pursuit of economic development, has altered, modified, and sometimes fundamentally transformed the biophysical and biochemical conditions of habitats. As habitat conditions change, so does the composition of plant species, reshaping entire ecosystems and their processes. Most ecosystem processes and functions depend on biodiversity (Hawksworth and Bull, 2008; Sahney, Benton and Ferry, 2010; Wuebbles, Fahey and Hibbard, 2017). However, direct and indirect effects of human activities result in biodiversity loss as well as habitat and ecosystem fragmentation (e.g. Jones *et al.*, 2018; Cepic, Bechtold and Wilfing, 2022). The Intergovernmental Panel on Climate Change (IPCC), The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), the Aichi Targets Progress Report, and The Economics of Biodiversity: The Dasgupta Review, paid attention to the biodiversity and one of the frequently observed influences of human activity which is the change of landscapes.The vegetation cover is removed, and then large areas become open abandoned land. In terms of ecosystem re-establishment, the question still stands: What should be done with the large surface area changed as a result of human activity? Sometimes such areas are established *de novo*, providing new, previously unknown severe habitat conditions. Traditionally, restoration environmentalists have focused on reversing the effects of human-induced disturbances. Attempts to reverse changes and restore disturbed ecosystems to their previous states has largely been unsuccessful. Similarly, the restoration strategies based on the agricultural approach have proven ineffective. Observing biological patterns and understanding ecosystem functioning is often complex and rarely successful (Tropek *et al.*, 2012).

The frequent failure of restoration activities has led some researchers, like Hobbs, to consider that in the case of natural ecosystems that have been altered significantly cannot return to their original conditions. Moreover, sites that have been significantly modified or those that are established *de novo* present conditions that are unprecedented in natural and semi-natural ecosystems. While recognising these challenges, scientists developed the concept of novel ecosystems (Hobbs *et al.*, 2006; Hobbs, Higgs and Hall, 2013; Morse *et al.*, 2014).

Novel ecosystems developed through the emergence of non-analogous vegetation assemblages in habitat conditions that have been significantly altered by human activities, to the extent that they no longer resemble historical or natural ecosystems (Hobbs, Higgs and Hall, 2013). These ecosystems often arise from the interplay of human activities such as urbanization, agriculture, and habitat fragmentation. The biodiversity of novel ecosystems can vary widely, depending on the specific environmental conditions, human interventions, and particular species that become established. The plant species composition of novel ecosystems differs from that of natural ecosystems. Their biodiversity includes mainly native plant species (Bąba *et al.*, 2016; Błońska *et al.*, 2019a; Błońska *et al.*, 2019b; Dychkovskyi, Dyczko and Borojević Šoštarić, 2024) that have persisted or adapted to the changed habitat conditions. These species often display traits that allow them to thrive in disturbed or human-modified environments. Additionally, the habitat conditions of novel ecosystems often support rare and protected plant species, particularly those associated with nutrient-poor oligotrophic sites (Bacler-Żbikowska and Nowak, 2022; Woźniak *et al.*, 2022). Some novel ecosystems have even been designated as protected sites (Woźniak, Hutniczak and Dettmar, 2022).

The research aims to analyse the parameters of the novel ecosystem functioning process, focusing on their role in enhancing biodiversity and alignment with EU restoration law. By examining the various factors that influence ecosystem dynamics, the review will assess how these processes contribute to biodiversity conservation and ecological stability.

THE ROLE OF NOVEL ECOSYSTEMS IN THE ECOSYSTEM FUNCTIONING

In novel ecosystems, taxonomic, functional, and species diversity are recorded as key components of biodiversity. Functional diversity refers to the variety of ecological functions performed by different species within an ecosystem. In the development and establishment of novel ecosystems, plant species functional traits fulfil crucial roles in nutrient cycling, pest control, and overall ecosystem stability. Together with plant diversity, biomass establishment and microbial diversity supports the flow of matter and energy, which forms the basis of ecosystem functioning. Microbial diversity (Bierza *et al.*, 2023a; Bierza *et al.*, 2023b; Likus-Cieślik *et al.*, 2023; Malicka *et al.*, 2024) plays an essential role in novel ecosystems by supporting nutrient cycling, decomposition, and soil health (Kompała-Bąba, 2013). The maintenance of genetic diversity is vital for the long-term resilience and adaptive capacity of species in changing environments (Hoban *et al.*, 2021). In novel ecosystems, it can be expected that harsh habitat conditions may increase genetic diversity (Milewska-Hendel *et al.*, 2020). The latest studies show that the adaptation of plants to new habitat conditions is reflected in modifications to the chemical composition of cell walls (Milewska-Hendel *et al.*, 2017; Milewska-Hendel *et al.*, 2020). Milewska-Hendel *et al.* (2020) reveal that levels of pectins and arabinogalactan proteins increased in post-industrial habitats in comparison to control sites. Overall, the biodiversity of novel ecosystems significantly enhance the diversity of urban-industrial landscapes, fostering complex interactions and adaptations of species to human-modified, challenging conditions (Woźniak *et al.*, 2022).

While novel ecosystems offer opportunities for restoration, they also present risks that must be carefully managed within the framework of nature restoration law. Invasive species can thrive in these altered environments, outcompeting native flora and fauna, leading to biodiversity loss and further ecological imbalance (Sala and Bieda, 2022; Woźniak *et al.*, 2022). Additionally, ecosystem degradation may occur if novel ecosystems fail to deliver essential functions, such as water filtration or carbon sequestration, undermining restoration goals (Bierza *et al.*, 2023a; Richert, Dudek and Sala, 2024). Social conflicts may arise from competing land uses, divergent community priorities, or perceptions of environmental changes, particularly when local stakeholders are not adequately involved in decision-making processes (Milewska-Hendel *et al.*, 2020; Woźniak *et al.*, 2022; Richert, Dudek and Sala, 2024). Addressing these challenges requires a comprehensive understanding of novel ecosystem functioning, supported by adaptive legal frameworks that balance ecological integrity with socio-economic needs.

Understanding and managing biodiversity in novel ecosystems is essential for conserving ecosystem services, supporting ecosystem resilience, and mitigating the impacts of global environmental change. The above findings suggest that novel ecosystems play a significant role in the mosaic of the urban-industrial landscapes. Moreover, some environmentalists regard particular types of novel ecosystems as potential reservoirs for ecosystem services (Chapin *et al.*, 2006; Perring, Standish and Hobbs, 2013; Fedoreiko, 2024). These ecosystems provide services that benefit humans and the natural environment, including food production and security, clean water, carbon sequestration, and natural protection against environmental disasters. Undoubtedly, novel ecosystems should be recognised as 'healthy ecosystems' (defined by Lu *et al.* (2015)). These ecosystems are essential for our long-term survival, well-being, prosperity, and security, forming the basis for overall resilience.

THE SPECIFIC ROLE OF NOVEL ECOSYSTEMS IN THE URBAN-INDUSTRIAL LANDSCAPE

According to some studies, novel ecosystems represent a new category of ecological entities that can be identified and understood based on their own unique biological and environmental rules (Morse *et al.*, 2014; Evers *et al.*, 2018). Morse *et al.* (2014) suggested that novel ecosystems are exceptional assemblages established due to human-induced alterations. These environmental alterations must be sufficient to surpass an ecological threshold. Such alterations set a new ecosystem development trajectory, preventing the return to the previous stage, even in the absence of further human intervention or disturbance. According to Morse *et al.* (2014), novel ecosystems must meet specific criteria: they should be intentional, optimally adapted to habitat conditions, as well as self-sustaining in ecosystem functioning. This includes the establishment of well-adapted species, stable feedback relationships, balanced biogeochemistry, and continued ecosystem functioning (ecosystem services).

Among novel ecosystems, mineral post-excavation sites, such as opencast sandpits, coal-mine heaps, lead-zinc heaps, quarries, and coal-mine sedimentations pools, as well as unused railway areas, have been relatively well studied (e.g. Hutniczak, Urbisz and Wilczek (2020), Hutniczak *et al.* (2022), Woźniak *et al.* (2022), Kompała-Bąba *et al.* (2023), Radosz *et al.* (2023), Szuba *et al.* (2023), Malicka *et al.* (2024)). Additionally, online platforms providing information about disturbed areas are available, e.g. the OPI-TPP 2.0 system. This system is crucial for ensuring transparency and replicability in research on novel ecosystems. It helps track and monitor the spread of invasive species, assess ecosystem health, and analyse potential risks to ecological stability. By identifying patterns of ecosystem degradation and their impact on biodiversity, this resource is essential for effective restoration planning. Additionally, the OPI-TPP 2.0 system facilitates the integration of socio-economic data, enabling a more comprehensive understanding of social conflicts related to ecosystem changes. A well-structured methodology enhances scientific research reliability, supporting the development of evidence-based nature restoration laws that address both ecological and social dimensions. The database specifically focuses on post-mining and post-industrial areas located in the Silesia Province, Poland, offering detailed site characteristics supplemented with photographic documentation, 3D models, and informative reports. The database also contains maps of these areas with a search and comparison tool. Moreover, the implemented CoalHeap portal is a production-ready system based on a trained model, enabling modelling of parameters for estimating the amount of CO_2 bound in biomass, particularly spontaneously developing vegetation in post-industrial areas, such as coal-mine spoil heaps. This is based on multispectral imaging, LIDAR imagery, and field and laboratory investigations.

Social, cultural, and institutional contexts of the interrelated processes complicate the estimation and proper assessment of ecological thresholds, as well as the most effective ways to enhance novel ecosystems and assess their value for the landscape. Decision-makers and managers' thinking is limited by the concept of utility and financial benefits (Woźniak, 2010; Hallett *et al.*, 2013), limiting their openness to the idea that natural processes can provide significant economic savings. A prime example of this is the role of riparian forests along river embankments and mangrove forests along coastlines. They are priceless, cost-free, and very efficient defences against floods and tsunamis. Moreover, many natural processes remain underestimated, including the increasingly apparent plant trait adaptations, some of which are caused by human-induced rapid environmental change (HIREC). Human-induced plant adaptation processes in response to severe conditions expand the spectrum of unknown biological processes (Kueffer and Daehler, 2009; Jackson, 2013; Perring, Standish and Hobbs, 2013). Direct and indirect human impacts can alter plant species composition and disrupt ecosystem functioning, reducing ecological resistance (Williams and Jackson, 2007; Chen *et al.*, 2011; Yamano, Sugihara and Nomura, 2011; Grimm *et al.*, 2013). Remarkably, many plants species exhibit rapid adaptation to new, harsh environmental conditions. These dynamic responses of living organisms to human-induced rapid environmental change (HIREC) factors support the idea that novel ecosystems, with their autonomous functioning, may serve as a form of natural support for human societies facing global environmental changes (Hobbs, Higgs and Harris, 2009; Belnap *et al.*, 2012; Hallett *et al.*, 2013; Hobbs, Higgs and Hall, 2013; Woźniak, Sierka and Wheeler, 2018). The drivers of novelty are linked to human activity, which causes inevitable disturbances and strong interactions between novel ecosystem components and socio-ecological systems (Collier and Devitt, 2016). Additionally, novel ecosystems can also play an essential role in climate change mitigation (Zedler, Doherty and Miller, 2012; Moyle, 2014; Trueman, Standish and Hobbs, 2014).

NOVEL ECOSYSTEMS IN THE NEWEST RESEARCH

Novel ecosystems emerge in areas where planned or unplanned human activities have led to the establishment of ecosystems with distinct natural values. The accidental or deliberate introduction of new species compositions is a sign of novelty (Hobbs, Higgs and Harris, 2009; Hobbs, Higgs and Hall, 2013). These newly formed species assemblages are characterised by unique above- and below-ground traits, interactions, and processes (Kompała-Bąba *et al.*, 2019; Milewska-Hendel *et al.*, 2020).

Novel ecosystems have been of interest to scientists for many years, with ongoing new scientific research focusing on their taxonomic and functional plant diversity, as well as analyses of ecosystem processes and functioning in these habitats (Chmura *et al.*, 2022; Woźniak *et al.*, 2022; Bierza *et al.*, 2023a; Bierza *et al.*, 2023b). Additionally, they are examined in terms of their socio-economic importance, particularly as sources of ecosystem services (Hutniczak, Urbisz and Watoła, 2023). However, novel ecosystems in the urban-industrial landscapes remain very interesting for further exploration. Broadening knowledge in the field necessitates an interdisciplinary approach.

Nevertheless, comparing novel ecosystem functional parameters remains challenging due to the absence of analogous reference points. Doley and Audet (2013) studied effects of disturbance on post-mining sites as a prerequisite of novel ecosystem development in urban-industrial landscapes. Their research demonstrated that spontaneously developed new ecosystems on post-industrial habitats maintain dynamic balances in the functional development of ecosystems and could provide crucial ecosystem goods for local communities. Novel ecosystems are always composed of non-analogous species composition (Woźniak, 2010). The introduction of new species composition, serving as important primary producers, leads to changes in below-ground microorganism communities, as well as vegetation and ecosystem function and structure (Martínez *et al.*, 2010). Novel ecosystems develop as independent ecological self-sustaining entities. Such new systems of organisms assembled in response to challenging habitat conditions and can take over the ecosystem and environmental functions of lost ecosystems. The *de novo* established environmental systems have not been previously identified and quantified, and the potentially available new ecosystem services of novel ecosystems are not yet recognised or understood.

A key factor in understanding the functioning of mineral post-mining novel ecosystems is the characteristics of their mineral habitat conditions. These conditions are largely dependent on the geology of the mined resources and the composition of the accompanying geological layers (Shavarskyi *et al.*, 2022; Dyczko, 2023; Galica *et al.*, 2024; Kosenko *et al.*, 2024). As the land available for novel ecosystem establishment continues to expand, it is crucial to enhance our understanding of their functioning and services (Lin and Petersen, 2013).

Novel ecosystem examples, concepts, and theory require a redefinition of traditional human interactions with natural resources. Rethinking how society is informed and how practitioners deal with the management of transformed land, restoration actions, and conservation strategies is essential (Marris, 2011; Yung *et al.*, 2013). Unfortunately, a lack of knowledge of the latest scientific achievements has led to mistakes and additional biodiversity losses in urban-industrial landscapes (Bacler-Żbikowska and Nowak, 2022; Kolar *et al.*, 2023). A comprehensive scientific approach must be effectively communicated to the public, ensuring that disturbed sites, particularly post-mineral excavation areas, are thoroughly studied before any management decisions are made. Interdisciplinary research conducted on post-mineral excavation sites has focused on the identification of adaptation processes, and evolutionary and functional implications of how novel ecosystems develop. In the longer term, this enables better understanding and more appropriate management strategies (Belnap *et al.*, 2012).

The socio-economic, legal, and ecological dimensions are deeply interwoven in the identification and understanding of novel ecosystem functioning as a tool for nature restoration law. Socio-economic considerations include the costs, benefits, and community impacts of restoring degraded lands into functional ecosystems that can support livelihoods and local economies (Beshta *et al.*, 2014; Chmura *et al.*, 2022). Legal frameworks provide the basis for defining, protecting, and managing novel ecosystems, ensuring compliance with environmental policies and regulations. The ecological dimension focuses on the scientific assessment of biodiversity, ecosystem services, and resilience, all of which are critical for effective restoration (Woźniak, Sierka and Wheeler, 2018; Polyanska *et al.*, 2022). These aspects are deeply interconnected, as legal mandates often shape socio-economic incentives for restoration, while ecological research findings inform policy and regulatory decisions. Sustainable development policies rely on this integration to balance environmental restoration with economic feasibility and social equity. By addressing these dimensions holistically, novel ecosystems can become a viable tool for advancing nature restoration and legal innovation.

Interdisciplinary, comprehensive environmental knowledge is crucial for identifying and understanding the functioning of novel ecosystems, particularly in response to the growing demand for ecosystem services in densely populated urban-industrial areas (Seastedt, Hobbs and Suding, 2008; Belnap *et al.*, 2012; Woźniak, Sierka and Wheeler, 2018; Woźniak, Hutniczak and Dettmar, 2022). Such an approach requires more appropriate management strategies (Hobbs *et al.*, 2006; Seastedt, Hobbs and Suding, 2008; Bridgewater and Yung, 2013; Hallett *et al.*, 2013; Perring, Standish and Hobbs, 2013). Novel ecosystems are elements of the urban-industrial landscapes, offering new possibilities and potentials to create a mosaic of habitats and ecosystems with new environmental qualities. Designers and planners must identify and understand these emerging systems (Dooling, 2015). The concept and examples of novel ecosystems have inspired a debate on the environmental meaning of new biotic and abiotic interactions that support ecosystem functioning (Bridgewater and Yung, 2013; Collier and Devitt, 2016). A novel ecosystem approach can help ensure long-term protection of oligotrophic habitats and ecosystems generated in the Anthropocene (Waltert *et al.*, 2011). Studies to improve understanding of novel ecosystems functioning and the enhancement of their recognised natural values should be intensified to compensate for environmentally harmful human activities and related environmental transformations (Chapin *et al.*, 2006; Hobbs, Higgs and Hall, 2013; Perring, Standish and Hobbs, 2013; Rotherham, 2017).

THE IMPORTANCE OF KNOWLEDGE ABOUT NOVEL ECOSYSTEMS IN RELATION TO THE EUROPEAN UNION ENVIRONMENTAL REGULATIONS

The European Union (EU) has been actively working on legislative and policy measures aimed at restoring and conserving natural ecosystems and biodiversity across its member states. Key initiatives and legislative actions include the following:
- The EU Biodiversity Strategy for 2030 sets ambitious targets to halt biodiversity loss and restore ecosystems. It includes a commitment to restore at least 30% of degraded ecosystems across the EU by 2030, 60% by 2040, and 90% by 2050, covering

a wide range of habitats, including forests, wetlands, grasslands, and marine ecosystems (European Parliament, 2024.
- The EU Habitats Directive is a base of EU nature conservation policy. It establishes a network of protected areas known as Natura 2000, which aims to conserve habitats and species of European importance. Restoration measures may be implemented within Natura 2000 sites to improve habitat quality and ecosystem functionality (EC, no date d).
- The EU Funding Programmes provide financial support for nature restoration projects, including the LIFE program (EC, no date c), the European Regional Development Fund (ERDF) (EC, no date b), and the Common Agricultural Policy (CAP) (EC, no date b). These funds can be used to support restoration activities, habitat conservation projects, and biodiversity enhancement measures.

Overall, while there is no single "EU Nature Restoration Law", the EU has developed a comprehensive set of policies, directives, and strategies. These initiatives reflect the EU's commitment to addressing environmental challenges and promoting sustainable development in all member states.

FINAL REMARKS AND FUTURE PERSPECTIVES

Understanding novel ecosystem functioning is vital to fulfil the requirements of EU nature restoration laws. In urban-industrial landscapes, post-mineral excavation habitats are the best sites for ecosystem restoration, as well as for spontaneous re-establishment of ecosystems and vegetation patches mosaic.

Habitat identifiers in the EU Habitats Directive are based on phytosociological units. The phytosociological units provide a precise characterisation of primary producers, which, from a biological and ecological perspectives, form the basis of ecosystems processes.

Under the EU nature restoration law, the European Parliament has adopted laws to restore 20% of the EU's land and sea, with the overall EU target. Based on this regulation, member states are required to restore at least 30% of habitats from poor to good condition by 2030. According to the EU assessment, over 80% of European habitats are in poor conditions (European Parliament, 2024). However, EU documents do not provide a clear definition of what habitat improvement means. The phrase "improvement", therefore, requires further clarification.

A proposed concept and clear definition of habitat improvement characteristics are outlined below, consisting of a list of parameters and their interrelations. This proposed definition includes an approach in which the characteristics of "habitat state" (or ecosystem state) are measured.

I – In order to fulfil the obligation of improving the condition of 30% of habitats, a thorough assessment of habitat (ecosystem) parameters must first be conducted. Assessing the habitat condition requires consideration of the following key factors: 1) vegetation plant species composition (mainly plants, bryophytes), their diversity, and compliance of species composition with habitat conditions; 2) amount of biomass (matter) created as a result of primary production (photosynthesis). Both plants and animals become organic matter that must be transformed into inorganic compounds. The course and nature of organic matter transformations are important but underexamined aspect of ecosystem functioning.

II – An algorithm must be developed to assess the condition of habitats (ecosystems) at a given moment and allow for comparisons across a wide range of ecosystem functioning parameters. This will make it possible to indicate places where improvement has occurred and where small measures, e.g. halting drainage, can support natural processes and facilitate the restoration of ecosystems.

Indicator values and a database of basic recordings can provide data for machine learning based on direct monitoring, including:
- percentage of land covered by different ecosystems understood as elements of landscape units with high biodiversity: biodiversity parameters are assessed at several levels of organization, including: (i) organismal level – condition of key plant and animal species for the ecosystem habitat, (ii) population level – number of species of vascular plants, bryophytes, insects, birds, stratification, share of various key groups of species, coverage of bryophyte and vascular plant species, etc. (iii) ecosystem level – plants and other organism compositions in ecosystems vegetation patches,
- numbers of common landscape animals including insects, e.g. butterflies – machine learning based on data on avifauna and entomofauna and their relationships with the parameters of a given habitat; these can be assessed based on hyperspectral imaging: (i) – organismal level – condition of key bird species and butterflies; (ii) biocenotic level – systematic diversity of avifauna and butterflies (share of various taxonomic groups),
- reconstruction/ restoration of organic soils (also used for agriculture) through, for instance, rehydration of drained peat bogs – effectiveness of actions by assessing the condition of peat ecosystems: (i) organismal level – condition of key species for peat bogs in good/bad condition, (ii) population level – potential of bryophytes and vascular plants to retain water; species structure indicating the state of preservation of peat bogs, which are among the most crucial ecosystems which functioning re-establishment.

III – Analysis of a large number of parameters and identification of connections between them, including the indication of highly correlated parameters, will allow for the assessment of habitat (ecosystem) condition as listed in the regulation based on a small package of the best identifiers habitat condition (functioning of ecosystems). We will indicate which parameters are the best indicators of habitat condition.

IV – Changes in conditions of habitats will result from taking or ceasing certain actions. Designing activities aimed at improving condition of habitats, required by the regulation, will also be possible based on historical analyses conducted for the model area. This will enable forecasting effects of specific decisions and actions taken and will allow for selection of the most effective methods to restore good condition of habitats.

Data described above, and those from advanced analytical systems, such as machine learning and hyperspectral images, will be helpful in classifying sites that are optimal for habitat and ecosystem re-establishment according to the EU restoration law.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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