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Modelling ecosystem services – a tool for assessing novel ecosystems functioning in the urban-industrial landscape

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Abstract: The necessary ecosystem services can be effectively provided through the diverse functioning and processes of ecosystems. Apart from services provided by natural and semi-natural ecosystems, the study on ecosystem development on mineral habitats, established as by-products of mining activity, have revealed surprising results. Unrecognised yet crucial ecosystem services can be provided by novel ecosystems that develop spontaneously on mineral sites created due to human activities, such as mineral mining. These mineral habitats and the ecosystems established *de novo* provide a wide range of ecosystem services. Modelling ecosystem functioning can simulate and predict the effects of interventions on ecosystem services provided by novel ecosystems. This approach supports adaptive management strategies that maximise desired services while minimising negative impacts on biodiversity and ecosystem integrity. Understanding the functioning of novel ecosystems and their ecosystem services is crucial for enhancing resilience, promoting restoration efforts, and implementing sustainable land-use practices.

Recognising the importance of ecosystem services provided by novel ecosystems and involving stakeholders in decision-making processes can foster public support for conservation initiatives and promote collaboration among diverse stakeholders. This approach is particularly important given that many activities related to the re-development of post-industrial areas, especially post-mining regions, have fallen short of achieving their objectives.

The essential role of ecosystem services provided by natural, semi-natural, and novel ecosystems highlights the importance of the ecosystem functioning modelling approaches. Such approaches are needed to understand and quantify these services in the context of adhering to sustainable development principles during urban development.

Keywords: biological diversity, modelling ecosystem services, nature-based solutions, post-industrial areas, post-mining novel ecosystems sustainable development, urban development

INTRODUCTION

The concept of ecosystem services was first articulated in the Millennium Ecosystem Assessment (MA) (MEA, 2005a). While biologists and environmental experts have long understood the importance of ecosystem processes such as biodiversity, biomass formation, and decomposition, these processes had not been defined as ecosystem services (MacArthur and Wilson, 1967). These ecosystem processes and functions provide society with a wide range of services, classified into four main groups: provisioning, regulating, supporting, and cultural services. This underscored the need to synthesise information about ecosystem services' development. Therefore, an international initiative led by the United Nations Environment Programme (UNEP), Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), and MA (MEA, 2003) was announced. The initiative aims to highlight emphasise the need for balanced human use of nature's services with the preservation of critical ecological relations in ecosystem processes and functions (Perrings *et al*., 2011).

People depend on ecosystems functioning, regardless of whether the ecosystems are of natural or anthropogenic origin. This dependence underscores the importance of accurately identifying and modelling the mosaic of ecosystem functioning processes with urban-industrial landscapes. "An ecosystem is a dynamic complex of plant, animal, and microorganism communities and the non-living environment interacting as a functional unit" (MEA, 2005b, p. vii). According to Costanza *et al*. (1998; p. 4), ecosystem services translate into "benefits human populations derive, directly or indirectly, from ecosystem functions". Many of these ecosystem services are indirect and essential to sustain the ecosystems functioning (Bolund and Hunhammar, 1999).

Scientists have made effort to classify, quantify, and map ecosystem services (Martínez-Harms and Balvanera, 2012). Urban-industrial landscapes are rapidly expanding due to increased urbanisation and industrial activities, leading to significant alterations of natural ecosystems. These transformations often result in novel ecosystems – ecosystems that are heavily influenced or created by human activities and no longer follow historical environmental patterns. However, the functioning of these ecosystems, especially in terms of the ecosystem services they provide such as air purification, water filtration, and climate regulation, remains poorly understood. With urban planning and environmental management playing pivotal role in sustainable development, there is an urgent need for effective tools to assess and monitor ecosystem services in these novel environments. Traditional approaches often fail to account for the complexity of novel ecosystems, highlighting a gap in current research. Moreover, constructing mathematical models to examine the relationships between ecosystem services and various human life parameters remains relatively uncommon. Therefore, the main research problem addressed is the development of a modelling framework to assess ecosystem services in novel urban-industrial ecosystems.

The primary objective of the study is to analyse how ecosystem services function within these altered environments and propose a method to accurately capture their dynamics. Specifically, the study seeks to consolidate the data needed for modelling the ecosystem services (ecosystem functioning) including: (i) identifying and listing the type of ecosystem services that need to be modelled, (ii) identifying and listing the types of data and information sources used in modelling ecosystem services, (iii) identifying and classifying the methods used in modelling ecosystem services under suboptimal social-ecological pressure. Ecosystem services are goods that are provided exclusively by ecosystem functions and processes, a critical aspect that is frequently underestimated or overlooked. Unfortunately, the provision of ecosystem services is mostly determined by the rate of human society's resource consumption. While these ecosystem services focus on human needs, modelling should prioritise the functioning of wildlife ecosystems. For this reason, it is necessary to shift the focus toward ecosystem functioning processes as the basis for assessing ecosystem services. Currently, the ecosystem function and processes approach for understanding ecosystem services has not yet been developed.

The article aims to review selected studies that deal with the importance of ecosystem services and the possibilities for their modelling in relation to ecosystem functioning processes. It highlights the research area, emphasising an interdisciplinary approach that integrates economic, social, and administrative aspects.

REVIEW OF THE ENVIRONMENT-CENTRIC APPROACH LITERATURE

GENERAL INFORMATION

Scopus, an electronic database, has been screened identifying such terms as "ecosystem services" and "ecosystem services modelling". The following filters were applied:
– the first search: TITLE-ABS-KEY ("ecosystem services") AND PUBYEAR > 1999 AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (DOCTYPE,"ar")) AND (LIMIT-TO (LANGUAGE, "English")) – 39,369 documents were found;
– the second search: TITLE-ABS-KEY ("ecosystem services modelling") – 104 documents found;
– the third search: TITLE-ABS-KEY ("ecosystem services modelling") AND PUBYEAR > 1999 AND (LIMIT-TO (SRCTYPE,"j")) AND (LIMIT-TO (DOCTYPE,"ar")) AND (LIMIT-TO (LANGUAGE,"English")) – 75 were documents found.

Additionally, in the following part of this study, papers related to various methods of modelling ecosystem services were processed. The selected papers were further analysed to promote informed development of a model for identifying, assessing, predicting, and enhancing ecosystem functioning processes related to ecosystem services.

THE CONCEPT OF THE ECOSYSTEM PROCESSES AND FUNCTIONING-BASED APPROACH

The most frequently modelled services are regulating services, followed by provisioning, cultural, and supporting services (Tab. 1). The analysis of selected papers reveals that the most commonly mapped services include carbon storage, water provision, food production, and cultural services.

Individual ecosystem services are difficult to compare, as certain areas may indicate high values across multiple service categories (Tab. 2). This is a significant challenge when making

Table 1. Frequency distribution of ecosystem services (ES) modelling in studies

Group of services	Type of services	Examples of articles related to the different types of ES
Payments for ecosystem services	payments	Martin-Ortega, Ojea and Roux (2013), Sun and Müller (2013), Nuppenau (2014), Smajgl *et al.* (2015)
Cultural services	cultural (general)	Brander, Beukering van and Cesar (2007), Chen *et al.* (2012), Johnson *et al.* (2012), Bagstad, Semmens and Winthrop (2013), Arbault *et al.* (2014), Cordier *et al.* (2014), Larocque, Bhatti and Arsenault (2014), Nuppenau (2014)
Provisioning services	provisioning (general) including: food production, biodiversity	Grêt-Regamey *et al.* (2008), Schlüter, Leslie and Levin (2009), Villa (2009), Johnston *et al.* (2011), Koniak, Noy-Meir and Perevolotsky (2011), Brady *et al.* (2012), Johnson *et al.* (2012), Notter *et al.* (2012), Bagstad, Semmens and Winthrop (2013), Arbault *et al.* (2014), Commelo *et al.* (2014), Cordier *et al.* (2014), Ding and Nunes (2014), Hou *et al.* (2014), Larocque, Bhatti and Arsenault (2014), Nuppenau (2014), Petz *et al.* (2014), Watanabe and Ortega (2014), Zanchi *et al.* (2014), Balbi *et al.* (2015), Connor *et al.* (2015), Guillem *et al.* (2015), Keller, Fournier and Fox (2015), Moor, Hylander and Norberg (2015), Smajgl *et al.* (2015)
Regulating services	regulating (general) including: climate regulation, nutrient retention, carbon storage, soil stability, flood prevention, water provision	Schlüter, Leslie and Levin (2009), Villa (2009), Feng *et al.* (2011), Koniak, Noy-Meir and Perevolotsky (2011), Locatelli *et al.* (2011), Swetnam *et al.* (2011), Johnson *et al.* (2012), Bagstad, Semmens and Winthrop (2013), Bai *et al.* (2013), Delphin *et al.* (2013), Grêt-Regamey *et al.* (2013), Meylan et al. (2013), Arbault *et al.* (2014), Cordier *et al.* (2014), Ding and Nunes (2014), Gebremariam *et al.* (2014), Guerra, Pinto-Correia and Metzger (2014), Larocque, Bhatti and Arsenault (2014), Nuppenau (2014), Petz *et al.* (2014), Poppenborg and Koellner (2014), Watanabe and Ortega (2014), Zanchi *et al.* (2014), Balbi *et al.* (2015), Boumans *et al.* (2015), Connor *et al.* (2015), Harmáčková and Vačkár (2015), Keller, Fournier and Fox (2015), McVittie *et al.* (2015)
Supporting services	supporting (general) including pollination	Johnson *et al.* (2012), Sabatier *et al.* (2013), Arbault *et al.* (2014), Cordier *et al.* (2014), Larocque, Bhatti and Arsenault (2014), Keller, Fournier and Fox (2015)

Source: own elaboration based on the literature review.

Table 2. An example of an area that provides many ecosystem services

Ecosystem services	Percentage share	
	area 1	area 2
Payments	20	40
Cultural	40	70
Provisioning	60	60
Regulating	60	20
Supporting	80	10

Source: own elaboration – the theoretical possibilities of the percentage shares of the potential ecosystem services of a site.

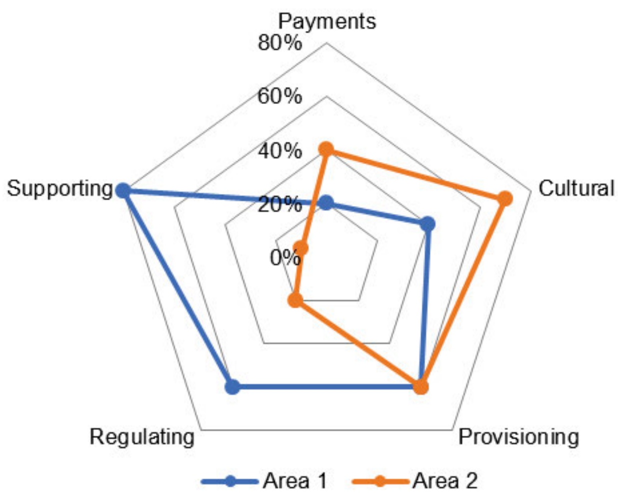

Fig. 1. The visualisation of the relation of percentage shares of the potential list of ecosystem services – an example of a radar chart for an area that provides many ecosystem services; source: own elaboration

decisions about their further development. Currently, there are no dedicated ancillary tools designed specifically for assessing areas that provide a wide range of services. Moreover, the level of the analysis needs to be determined. The pre-parameterisation of seemingly subjective values can be instrumental when transforming many post-mining and post-industrial areas or when addressing regions subject to significant human impact.

The services indicated above are not the only criteria for valuing a specific area, but they constitute a framework that encompasses the full potential of its management.

A radar chart (Fig. 1) is a two-dimensional graphical method for displaying multivariate data. It is useful for comparing the relative strengths and weaknesses of multiple variables or categories. The radar chart consists of several radii (spokes) extending from a central point with each spoke representing a different variable or category. The radar charts effectively identify patterns, strengths, and weaknesses across various categories, making them a powerful tool for visualising and comparing multivariate data across different categories.

The radar chart is effective in presenting the adaptation possibilities of individual areas, facilitating their comparison in a way that is simpler than a multi-field matrix. This analysis is also important as it supports efforts to avoid monoculture during transformations.

ECOSYSTEM SERVICES MODELLING METHODS USED IN THE HUMAN-CENTRIST APPROACH

The methods for modelling ecosystem services, including the acquisition and processing of information and data, have been classified into five categories (Costanza *et al.*, 1998; Martínez-Harms and Balvanera, 2012). The first category, referred to as "mechanistic models", employs state and flow equations to present interactions and relationships between different components of an ecosystem as distinct entities. By focusing on the underlying mechanisms that drive ecosystem processes, mechanistic models provide a detailed understanding of how various factors influence the flow of resources and energy within the system. This approach is particularly useful for capturing the complexity of ecological interactions and for predicting how changes in one part of the system may affect the entire ecosystem.

The second approach involves "probabilistic models", which incorporate cybernetic information to estimate and model ecosystem services. Techniques such as decision trees, Bayesian Belief Networks, and Expert Knowledge frameworks are employed to analyse uncertainties and support decision-making processes. By integrating various sources of information, probabilistic models allow for a more nuanced understanding of ecosystem dynamics and assess the likelihood of different outcomes under various scenarios. This approach is particularly valuable for stakeholders who require informed decisions based on incomplete or uncertain data, thereby enhancing the overall reliability of ecosystem service assessments.

The third category includes "statistical approaches", which employ statistical tests, correlations, and regression analyses to identify relationships and trends within ecosystem data. These methods help quantify connections between ecosystem services and their driving factors, allowing researchers to make predictions based on historical data.

"GIS-based models" (fourth category) leverage geographic information systems to merge and process diverse datasets, providing spatially explicit analyses that support resource management and land-use planning.

Finally, "conceptual models" integrate data from various modelling approaches, employing a heterogeneous modelling to connect different systems and enhance the understanding of ecosystem services across multiple scales. Together, these diverse modelling approaches contribute to a comprehensive assessment of ecosystem services and their relevance in urban-industrial landscapes. The classifying criteria for these modelling approaches were based on the work of Martínez-Harms and Balvanera (2012).

The mechanistic modelling approaches were the most frequently used, followed by GIS-based models. However, except for conceptual models, the four other types of modelling were generally equally represented in the analysed studies. Most ecosystem services analyses in modelling studies were done at the regional scale, including the single ecosystem, local, and national scales, with the global scale following closely (Wu, Sun and Fan, 2022).

THE MODELS OF POTENTIAL ECOSYSTEM FUNCTIONING – ECOSYSTEM SERVICES FOR PLANNING NATURE-BASED SOLUTIONS

Nature-based solutions encompass actions or policies that use natural processes to address societal challenges, such as threats to natural water bodies, regardless of the origin. These solutions involve identifying, protecting, monitoring, restoring, and enhancing ecosystem functioning to increase wildlife ecosystem patches whenever possible. This approach aims in ways that increase the ecosystem mosaic resilience and ability to refer to human social challenges, along with supporting biodiversity and improving the human life conditions (FEMA, 2024) (Fig. 2).

In this respect, the most interesting and crucial examples are wetland ecosystems. The wetland forests along river embankments are fundamental for sustaining fisheries, and for providing protective natural barriers against erosion and flooding. The wetland forest can filter water and provide valuable timber and food supply for animals. What is most crucial, due to anaerobic conditions, the storage of significant amounts of carbon in the waterlogged biomass and organic matter is possible. Protecting and restoring riparian wetland ecosystems along rivers greatly reduces flood risk, as wetland vegetation, including herbs, bushes, and forests, effectively prevents flooding beyond wetland zones along rivers (Keddy, 2010; Nicia *et al.*, 2014; Khan *et al.*, 2022).

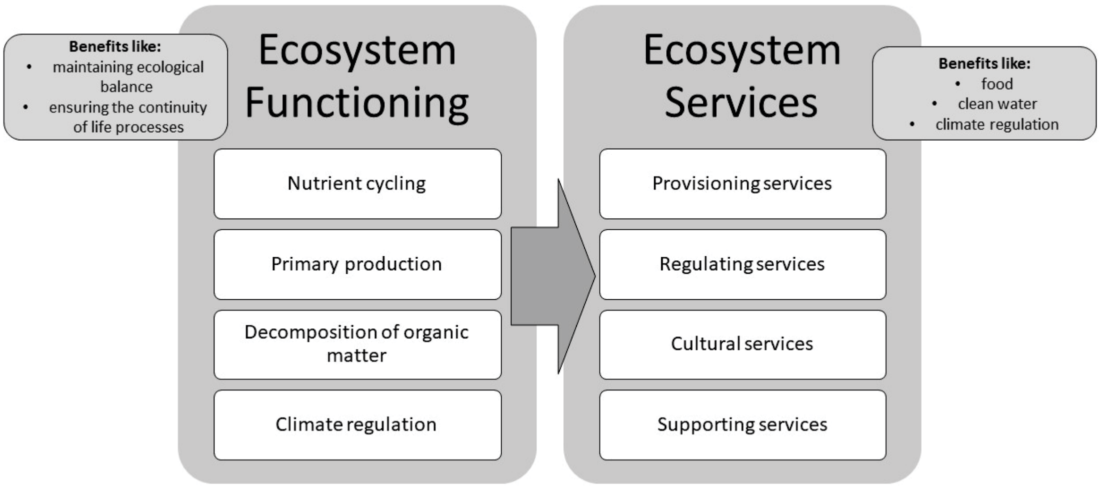

Fig. 2. The dependence of the ecosystem services and the natural processes of ecosystem functioning, within the novel ecosystems; source: own elaboration

THE DIFFERENCE BETWEEN NATURE-BASED SOLUTIONS AND CONSERVATION

Conservation involves protecting and preserving the planet's biological diversity and natural resources to ensure their availability in the future. It includes the protection of plant and animal species, their habitats, ecosystems, and important ecological services against threats. Conservation may involve the protection of parks and reserves, ensuring that all species have habitats they need to survive, and implementing laws to protect endangered plants and animals (Raudsepp-Hearne *et al.*, 2010).

Nature-based solutions, on the other hand, encompass a wide range of approaches – from habitat restoration, water resource management, disaster risk reduction, and green infrastructure – to address societal problems. Nature-based solutions are based on the notion that healthy and well-managed ecosystems provide essential benefits and services to people. These include reducing greenhouse gas emissions, securing access to safe water resources, improving air quality, and providing increased food security (Raudsepp-Hearne *et al.*, 2010).

The conservation potential of novel ecosystems on post-industrial sites represents a shift towards a more inclusive understanding of ecological value, primarily due to the outstanding habitat conditions found in the post-mining mineral environments. By recognising the crucial role mineral habitats play in shaping unique functions and services, conservationists and urban planners can transform disturbed sites into productive and environmentally meaningful landscapes. This transformation is supported by knowledge obtained in the latest biological and environmental research. Managing these sites can help balance nature's potential by supporting biodiversity, enhancing resilience to environmental changes, and offering valuable green spaces. These green spaces form ecosystem mosaics, determined by the habitat patterns characteristic of urban-industrial areas.

THE ECOSYSTEM SERVICES OF POST-MINING NOVEL ECOSYSTEMS

Large areas of the Earth surface have been disrupted by human activities, leading to altered ecosystems and landscapes. Research has revealed that the pressure of land use influences the environment (Wackernagel *et al.*, 2002). Properly functioning ecosystems provide ecosystem services. The Millennium Ecosystem Assessment draws attention to the fact that ecosystem services are essential for maintaining living conditions of all people (MEA, 2005a). The functioning of ecosystems is inextricably linked to biological diversity, whose importance across various ecosystem development stages has been presented in many studies (Binner *et al.*, 2017; Woźniak *et al.*, 2022). For example, this includes post-mineral sites that align with the definitions of novel ecosystems as described by Hobbs (2007) or Raudsepp-Hearne *et al.* (2010). The crucial aspect of understanding the mineral post-mining novel ecosystem functioning lies in the characteristics of the mineral habitat conditions, which depend on the geology of the mined resources and the accompanying geological layers (Shavarskyi *et al.*, 2022; Dyczko, 2023). Biodiversity parameters are fundamental to the functioning of post-mining novel ecosystems and must be considered comprehensively. This includes both the composition of above-ground vegetation composition and the diversity of below-ground organisms, such as soil enzyme activity (Fig. 3) (Błońska *et al.*, 2019, Błaszkowski *et al.*, 2021).

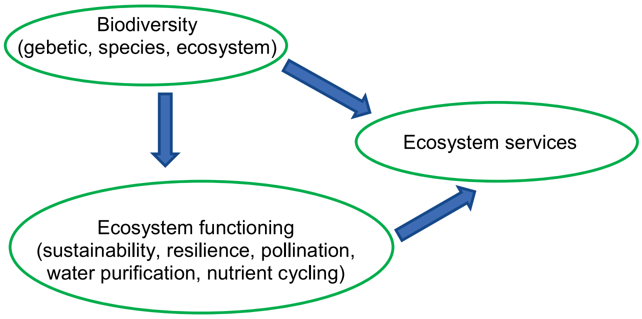

Fig. 3. The scheme explaining the relationships between the biodiversity of the natural, semi-natural and the novel ecosystem functioning; source: own elaboration

The term "ecosystem services" is frequently used interchangeably with "natural capital" (Sen, 1999; Binner *et al.*, 2017). The term "natural capital" is relatively new in the natural sciences. According to Binner *et al.* (2017, p. 70), "natural capital is the stock of physical assets that generate flows of environmental goods and services that benefit people". However, many authors have tried to define this term (e.g. Solon *et al.*, 2017). Barbier (2019) offers an interesting discussion on the concept of natural capital.

A modern approach should include various aspects of ecosystem development and functioning within the urban-industrial landscapes, such as colonisation, the presence of different plant functional groups in spontaneous vegetation patches (Rostański and Woźniak, 2007), and the establishment of late-stage forest novel ecosystems (Woźniak *et al.*, 2022). Spontaneous ecosystem processes must be thoroughly studied and monitored, ranging from molecular level (Talik *et al.*, 2018; Milewska-Hendel *et al.*, 2020), as well as eco-physiological, hyperspectral, and landscape diversity levels (Woźniak *et al.*, 2021b). An important aspect that requires study and analysis is the interaction between soil microorganisms and plants within novel ecosystems (Bąba *et al.*, 2016; Woźniak *et al.*, 2021a).

The modelled solution will often need to be implemented under specific organisational and legal conditions, as described by Ostręga (2013). However, these conditions can sometimes render the modelled solutions unfeasible. Therefore, this aspect must be considered early, during the assessment of individual parameters.

CONCLUSIONS

An increasing number of studies on the modelling of ecosystem services have been observed. Only a few sources devoted to ecosystem services focus on natural sciences, ecosystem functioning processes and biogeochemical relationships, the majority concern the human perspective, covering mainly economic, social and cultural aspects of ecosystem services. This imbalance can introduce a significant bias into the results.

Ecosystem functioning processes, such as carbon storage, biomass accumulation, maintaining biodiversity, food production, and water retention and provision, should be systematically modelled in relation to ecosystem dynamics to support decision-making. Databases, modelling tool, predictions, and scenarios presented on maps would be the most effective way for managing and enhancing ecosystem services. Additionally, some crucial ecosystem functioning processes such as pollination, climate regulation, and flood prevention require more intensive research.

The results of this study have significant policy implications for urban planning and environmental management, highlighting the need to integrate ecosystem services into decision-making processes. By providing the understanding of how novel ecosystems function, policymakers can develop strategies that promote sustainable land use, enhance biodiversity, and improve overall urban resilience. These insights can effectively inform the allocation of resources and investments, ensuring ecosystem restoration and management initiatives that align with both environmental goals and community needs.

The future of ecosystem services modelling should focus on understanding the fundamental processes of ecosystem functioning and identifying the potential of wetland habitats. This is important as these habitats represent a vital source of natural capital and ecosystem services. Special emphasis should be directed towards novel mineral post-mining habitats, as these are often overlooked despite their value in providing ecosystem services. Furthermore, employing an integrated approach that combines various modelling techniques could result in more comprehensive models capable of predicting and quantifying ecosystem services at a broader scale. This is increasingly essential for effective environmental management.

The validation approach should also consider payments for ecosystem services and their impact on the future evolution of service quality and quantity. Assessing monetary value of these services might help bridge the gap between citizens' awareness and the protection of natural capital. Future discussions should also address these aspects and integrated them into predictions for ecosystem services.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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