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Assessment of resilience and recovery potential of regional ecosystems under extreme conditions and sustainable management models

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SUMMARY

The full-scale war has inflicted immense damage on Ukraine's ecosystems, requiring not only monitoring and assessment of losses but also an evaluation of their resilience and potential for recovery based on a systematic approach. This approach must take into account the prospects of post-war reconstruction of the country's territories. The study presents a conceptual framework for assessing the resilience and restoration potential of regional ecosystems, considering the specifics of their degradation, destruction, or annihilation through a value-based approach. An integrated assessment of the state of regional ecosystems as a result of large-scale invasion (2022–2024) has enabled the determination of their resilience and differentiation levels in terms of recovery potential. It has been substantiated that modern ecosystem restoration practices have an interdisciplinary nature and should rely on scientific evidence, appropriate planning, and management methods. These practices must balance the processes of natural regeneration (ecosystem recovery potential) with the goals and objectives of environmental programs (i.e., through human intervention mechanisms and restoration thresholds), while considering limited resources and the aims of post-war sustainable spatial development. A proposal has been made to combine approaches for designing ecosystem services with regard to the restoration potential of regional ecosystems and their local components.



Introduction

Extreme conditions, combined with environmental evolution and global challenges (including climate-related ones), pose serious problems for Ukraine's sustainable development. They increase community vulnerability and lead to extensive social, environmental, and economic losses. Both natural and war-induced extreme conditions can trigger interconnected chains of complex crises. Observations by the State Emergency Service of Ukraine confirm this: in 2020, losses from natural disasters increased more than sixfold compared to 2019 (from \$1.6 billion to nearly \$9.9 billion) (UNDP, 2025). According to The Annual Review «Russia-Ukraine War: Environmental Impact. 2024», environmental damage due to military actions from February 24, 2022, to September 13, 2024, reached \$62.9 billion. Experts suggest these losses have long-term environmental, social, and economic consequences, including irreversible damage to ecosystems (biodiversity and valuable natural sites) and public health. Thus, research into the restoration of degraded, damaged, or destroyed ecosystems under extreme conditions, the assessment of their recovery potential, the justification of sustainable management models, and the development of strategies and investment priorities for post-war sustainable spatial development are of high relevance (Komelina, Kharchenko, 2023). Given the nature of the issue, such research must be interdisciplinary, enabling the design of hybrid regional ecosystem models that incorporate their regenerative potential.

Method and Theory

The consequences of extreme conditions caused by war or natural disasters are complex and multifaceted, typically categorized into economic, social, and environmental indicators. This highlights the necessity of an integrated approach to sustainable planning and strategic goal setting. Current scientific discussions on ecosystem resilience and recovery potential encompass a broad spectrum of issues. Various modern concepts of contaminated ecosystem restoration suggest different approaches to addressing this challenge. One approach focuses on repairing damage inflicted by human activity on biodiversity and local ecosystem dynamics, emphasizing the reversal of negative impacts (Jackson et al., 1995). Another perspective views restoration as a process of facilitating the natural recovery of ecosystems that have been degraded, damaged, or destroyed. A third approach incorporates sustainable development principles, taking into account regional specificities when formulating restoration strategies (Komelina, Komelina, 2022; Ostapchuk et al., 2024). Additionally, some researchers propose designing ecosystem services as a basis for restoration, aligning recovery efforts with future land-use planning and broader territorial rehabilitation strategies (Silliman et al., 2024).

A scientifically grounded methodological approach to the integrated assessment of regional ecosystem recovery potential enables the prioritization of restoration efforts to ensure environmentally safe and sustainable development in Ukraine. This assessment method offers key advantages, including the ability to synthesize the overall impact of various indicators and coefficients examined in the study. Furthermore, it facilitates the conversion of ecosystem recovery potential evaluations into a single quantitative value, making economic interpretation more straightforward and actionable.

Results

Under extreme conditions, a value-based conceptual approach to regional ecosystem restoration is particularly important. This approach considers existing recovery potential and aims to ensure a synergistic effect. In practice, it helps select the most appropriate restoration strategy for a specific (national, regional, or local) ecosystem (Jones, 2017; Komelina, Komelina, 2022).

The primary goal of this approach is to establish a balance between natural regeneration (ecosystem recovery potential), environmental program objectives and priorities (i.e., human intervention



mechanisms and ecosystem restoration thresholds), and limited resources (Yang et al., 2022; Mahmoudi et al., 2018; Horoshkova, 2023).

Implementing an integrated assessment method for regional ecosystem recovery potential has revealed significant differentiation in recovery potential across Ukraine's regions. Higher integral assessment scores indicate better regional ecosystem recovery potential. Based on 2022–2024 data (State Statistics Service of Ukraine; Decentralization in Ukraine Platform; The Annual Review “Russia-Ukraine War: Environmental Impact. 2024”), an integral regional rating score was calculated, assessing ecosystem resilience and recovery potential. The calculations followed an improved methodology (Bohoslovska et al., 2018).

Regional comparisons of ecosystem resilience and recovery potential were conducted in two stages. The first stage involved creating a database based on eighteen key indicators for all regions. The second stage focused on expert evaluation of the integral assessment results, selecting appropriate quantitative and qualitative characteristics of the research object. Key indicators were categorized into stimulating and destimulating factors. Stimulating indicators promote positive changes and sustainable ecosystem development, enhancing recovery potential. These include the total area of nature reserves and national parks, the number of unexploded ordnance neutralized since the full-scale war, state budget subsidies for local projects under the Ukraine Recovery Program, growth in local budget revenues over nine months in 2024 compared to 2021, and capital investments in environmental protection. Destimulating indicators negatively affect ecosystem recovery. These include environmental damage caused by the war, the volume of waste generated, carbon dioxide (CO₂) emissions from stationary sources, water withdrawal from natural bodies, and the area of forest loss. These indicators enabled the ranking of regions by their integral assessment and the formation of clusters based on ecosystem recovery potential (Figure 1).

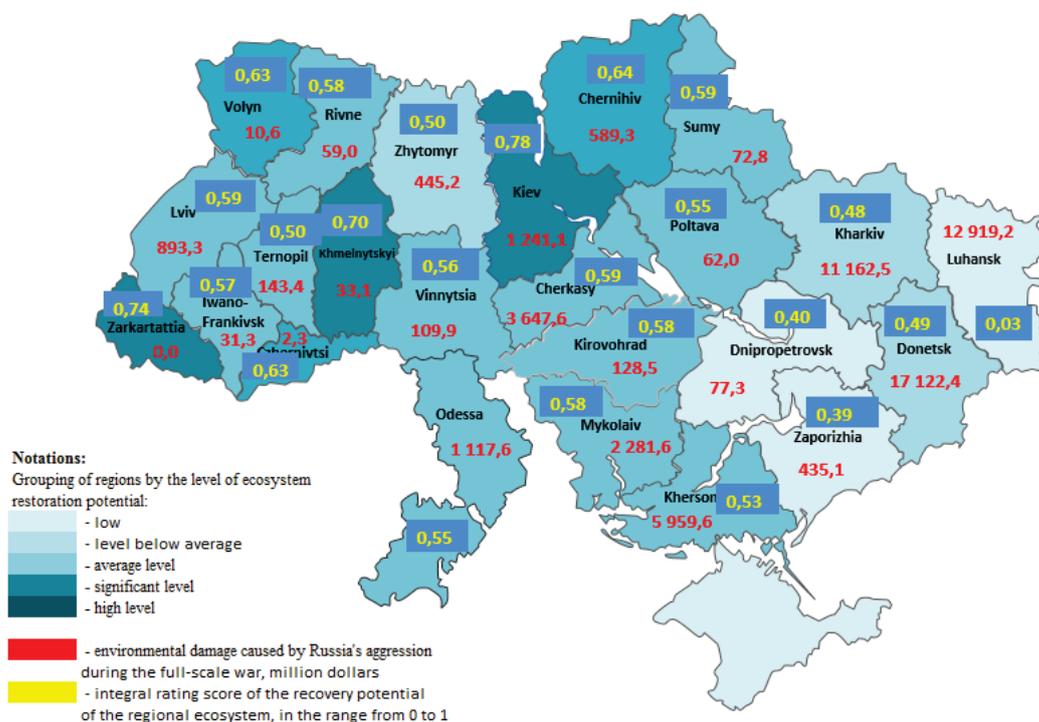


Figure 1 Differentiation of regional ecosystems of Ukraine according to their sustainability and restoration potential (2022-2024).



The assessment results present an objective picture of ecosystem destruction across Ukraine during 2022–2024. Most regions have moderate recovery potential, requiring active environmental restoration efforts. Donetsk (0.49), Kharkiv (0.48), Dnipropetrovsk (0.40), and Zaporizhzhia (0.39) regions have low indicators, reflecting severe environmental problems due to intense warfare, industrial destruction, and environmental pollution. These regions require significant restoration efforts and resources.

According to the authors, the methodological approach to integrated ecosystem restoration under the influence of global challenges and extreme conditions may include the following research components: (1) analysis of changes in ecosystem services, (2) assessment and forecasting of the dynamics of ecosystem services as a result of the integrated impact of climate change and land use interactions, (3) modeling of medium- and long-term effects from the implementation of various environmental programs, (4) identification of threshold values for ecological restoration, (5) evaluation of the socio-economic and environmental effectiveness of the ecosystem restoration management system, (6) assessment of the quality of management of ecosystem service restoration programs and projects.

The research results presented by him provide a comprehensive basis for assessing the resilience and recovery potential of regional ecosystems, as well as choosing a model of sustainable management under extreme conditions. The results provide a systematic identification of the processes of degradation and recovery of regional ecosystems; economic, ecological and social assessment of such losses due to large-scale damage caused by the war; management of these processes in accordance with the goals of sustainable development of Ukraine.

The effectiveness of the sustainable management system in ensuring the resilience and restoration of regional ecosystems should account for the impact of extreme conditions, the existing potential, and future directions for restoring ecosystems that have been damaged or destroyed. This must be done with consideration of their uniqueness, the sustainable development goals of territories based on projected changes, and the scope of investments in strategically significant national, regional, and local priorities.

Conclusions

Given the significant scale of environmental challenges, further research should focus on identifying key factors influencing ecosystems, assessing the effectiveness of restoration measures, and forecasting the dynamics of ecological processes. The value-based approach, which underlies the selection of regional ecosystem restoration concepts under extreme conditions, is highly universal and aims to achieve a balance between self-recovery processes, the goals and objectives of regional environmental programs, and the priorities of post-war sustainable spatial development. In particular, it is necessary to expand the analysis of ecosystem services, assess the long-term effects of implementing environmental programs, and determine threshold values for ecological restoration across different regions.

Thus, the findings of this study contribute to the development of a scientifically grounded framework for decision-making regarding regional ecosystem restoration, which is a critically important task amid current environmental and socio-economic challenges. The application of the proposed concepts and management tools for regional ecosystem restoration provides a foundation for avoiding pitfalls and achieving advantages through early integration.



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