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ON THE IMPORTANCE OF ENVIRONMENTAL FACTOR PROTECTION IN KEY AREAS OF THE BORDER ZONE. CASE STUDY ROMANIA-UCRAINA, MARAMUREȘ MOUNTAINS

Maria ȘEVERA[1], Mirela COMAN[2]

[1]University of Agricultural Sciences and Veterinary Medicine of Cluj-Napoca, 3-5 Mănăștur, Cluj-Napoca, Romania
[2]Technical University of Cluj-Napoca, 62 A V. Babeș Street, Baia Mare, Romania

Corresponding author email: maria.severa@student.usamvcluj.ro

Abstract

Key areas located in the northernmost part of Romania, within the Maramureș Mountains along the northern border with Ukraine, represent agro-mountain ecosystems of high value for environmental stability and regional ecological security. This cross-border area is exposed to increased anthropogenic pressures in the context of the armed conflict in Ukraine, which amplifies the vulnerability of environmental components, biodiversity, and ecosystem functionality. The study addresses the assessment of environmental impacts on soil, water resources, biodiversity, and habitat fragmentation through an integrated approach specific to environmental science and engineering. The methodology is based on environmental quality indicators, pedological and hydrological analyses, ecosystem condition assessment, multi-criteria evaluation methods, and GIS tools for the spatial analysis of pressures and impacts. The results highlight the need to implement preventive-oriented environmental protection measures aimed at biodiversity conservation and the reduction of ecological degradation risks in border regions. Romania–Ukraine cooperation is essential for the sustainable management of environmental impacts in transboundary areas affected by conflict-induced regional instability.

Key words*: environmental impact, key-areas, transboundary area.*

INTRODUCTION

The Maramureș Mountains constitute a fundamental pillar of ecological stability in the northern part of Romania, representing a transboundary agro-montane ecosystem with a biodiversity of European importance. The importance of protecting environmental factors in this key area is emphasized by the status of a protected area (Maramureș Mountains Natural Park) and by the need to maintain the ecological security of the border with Ukraine (Ilieș et al., 2010). In the context of 2026, anthropogenic pressures on this ecosystem have diversified, being amplified by regional instability that generates additional risks for soil, water and habitats (Ukraine conflict environmental briefing: Nature, 2024). The degradation of environmental factors in border areas is not only a regional problem, but a systemic one, because habitat fragmentation and transboundary pollution can affect ecological connectivity across the entire Carpathian chain (Kuemmerle et al., 2011). The use of modern technologies, such as Geographic Information Systems (GIS) and remote sensing, has become imperative for monitoring these hard-to-reach areas, providing precise data on land use dynamics and ecosystem health (McGarigal, 2015; ESA, 2026). This paper analyzes these vulnerabilities and proposes preventive measures based on a multi-criteria environmental impact assessment.
The hydrographic structure of the Vișeu basin is defined by a series of lotic systems with sources in the Maramureș Mountains, among which the right tributaries Ruscova (39 km), Socolău (13 km) and Bardi (11 km) stand out (Curtean-Bănăduc et al., 2008; Bănăduc et al., 2011a, Curtean-Bănăduc et al., 2017). There are three administrative-territorial units (Poienile de Sub Munte, Repedea, Ruscova) with approximately 19,343 inhabitants in 2021 (National Institute of Statistics, 2023). As can be seen in Figure 1, this cross-border area is exposed to increased anthropogenic pressures, which amplifies the vulnerability of soil and water resources (Kucsicsa & Popovici, 2016), biodiversity and ecosystem functionality.
Among the monitored taxonomic units, fish present a heightened vulnerability to pressures

exerted by human activities, being directly affected by habitat changes and anthropogenic stressors (Năvodaru & Năstase, 2006; Bănăduc et al., 2011b; Florea, 2017; Khoshnood, 2017).

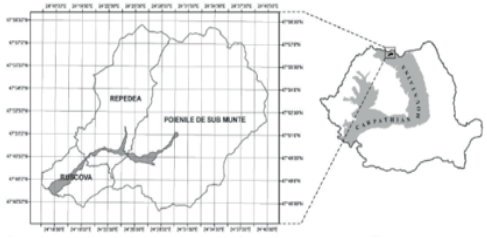


Figure 1. Valea Ruscova Depression (processing after) (Kucsicsa & Popovici, 2016)

MATERIALS AND METHODS

The methodology uses GIS tools for spatial analysis of pressures (Kłapyta et al., 2024) and quality indicators related to environmental standards (Ministry of Water, Forests and Environmental Protection, 1997). The assessment of anthropogenic pressures on the ichthyofauna in the Vișeu basin must be carried out in accordance with national environmental quality standards (Ministry of Water, Forests and Environmental Protection, 1997). At the same time, given the transboundary nature of the watercourses in the region, their management is subject to international agreements for the protection of common water resources (Parliament of Romania, 1995), within the broader framework of environmental protection legislation (Parliament of Romania, 2005). The current configuration of the agro-montane landscape and the state of habitats in the Poienile de Sub Munte sector, observed during the field monitoring stages, are presented in Figure 2.
Spatial analyses carried out in the watersheds of the Maramureș Mountains (e.g. Ruscovei Valley) indicate a high vulnerability of water quality to anthropogenic influences, especially through increased nitrate concentrations from agricultural and domestic activities (Kucsicsa & Popovici, 2016). The use of Geographic Information Systems (GIS) allows the identification of critical areas where environmental factors and population density converge, generating risks of pollution of water resources essential for local biodiversity (Kucsicsa & Popovici, 2016).



Figure 2. Panoramic view of the study area in the Poienile de Sub Munte administrative unit; the mosaic of forest and agricultural habitats is observed (Source: Author's personal archive, 2024)

Monitoring environmental factors involves the use of status indicators that reflect the degree of anthropization and the risk of ecological degradation of protected areas (Coman, 2010). Mountain ecosystems are highly vulnerable to human interventions, degradation processes often being irreversible in the absence of well-structured conservation measures (Coman, 2010). Natural resource management in the Ruscova Corridor must align with the principles of sustainable development specific to Maramureș County, where the protection of fragile ecosystems is inextricably linked to the economic viability of local communities (Coman, 2006).
Digitalization of the management of resources involved in environmental protection facilitates superior team coordination in difficult areas, such as the Ruscova Corridor, ensuring clear traceability of field activities and interventions in vulnerable areas (Thira et al., 2025). This digital infrastructure allows for rigorous data collection necessary for the assessment of ecological security, which must take into account the transfer capacity of pollutants from soil to vegetation. The use of transfer indices similar to those analyzed in recent studies in the Maramureș region is essential to prevent risks of bioaccumulation in the food chain and to ensure food security for local communities (Filip & Coman, 2024; 2025).

RESULTS AND DISCUSSIONS

The forests of Maramureș are under double pressure: on the one hand human activity/conflict, on the other hand drought and increasing temperatures in recent years, which

limit tree growth (Popa et al., 2024). The forests of Maramureș not only produce wood, but also provide ecosystem services (soil protection, water regulation, biodiversity) valued at impressive amounts. The study shows that the "conservation" scenario offers a much higher total value in the long term than intensive timber exploitation (Popa et al., 2016).

Sustainable management of mountain ecosystems must recognize soil not only as an agricultural resource, but as a strategic asset capable of providing vital ecosystem services (carbon storage, water filtration, biodiversity), fundamental for the ecological security of the region (Cioruta & Coman, 2022). Early studies on ciliates in the Tisza basin (Kovalchuk, 1997) established a baseline state of aquatic biodiversity. Comparing these data with recent monitoring (e.g. Bitušík et al., 2025) allows identifying the cumulative impact of pollution and climate change on the mountain lotic ecosystems of the Maramureș Mountains.

The sustainable management of the Ruscova Corridor must take into account the adaptability of forest species to climate change, given the high sensitivity of spruce and fir to thermal and water stress identified in the region (Popa et al., 2024). The protection of juniper habitats in the subalpine floor of the Maramureș Mountains is critical, given their role in stabilizing slopes and the presence of specific insect communities, such as Retinia rosinella, which require undisturbed habitats to maintain biological balance (Olenici & Semeniuc Fecioru, 2021).

It is not just a matter of visible pollution, but of a biological collapse: soil fauna can no longer mediate litter decomposition (Dou & Lin, 2026), while the main forest species are already at the limit of resilience due to thermal stress (Popa et al., 2024). Regional ecological security can be supported by integrating varieties improved for productivity and resistance into the local agricultural circuit, thus ensuring a stable fodder base, without resorting to excessive chemical fertilization, protecting biodiversity and water resources (Schitea, 2010).

Environmental protection in the Ruscova Corridor can be supported by encouraging local entrepreneurship in rural tourism. Digitalization of services and promotion of authentic cultural heritage reduce pressure on natural resources by offering a sustainable economic alternative to intensive forestry (Ciolac et al., 2022). Environmental protection in Maramureș must go hand in hand with the preservation of the historical and cultural testimonies of the communities, as these form the local identity that underpins any sustainable regional development initiative (Cioruță et al., 2023).

Climate change in the Eastern Carpathians is leading to earlier snowmelt, a process that, while initially increasing carbon sequestration capacity, drastically alters ecosystem dynamics throughout the growing season (Vought et al., 2025). Deforestation in the Ruscova Corridor not only reduces woody mass, but also destroys the ecosystem's ability to moderate maximum temperatures. This phenomenon, combined with earlier snowmelt (Vought et al., 2025) and the sensitivity of spruce to heat (Popa et al., 2024), creates a "cascade" effect that threatens regional ecological security (Abera et al., 2025).

The ecological security of the Pop Ivan transboundary area depends on the integrity of its peatlands, which function as critical carbon reservoirs. Retrospective studies (Deyl et al., 2023) establish a historical purity standard (pH 3.8-5.5 and conductivity below 40 µS/cm), any deviation from these values being indisputable evidence of anthropogenic or military pollution at the border. Alteration of this bio-chemical balance, corroborated with early snowmelt (Vought et al., 2025), risks transforming these bogs from carbon stores into massive sources of greenhouse gas emissions, accelerating the degradation of the mountain ecosystem.

Although current genetic diversity is robust, habitat fragmentation through massive logging or border infrastructure can isolate conifer populations. Curtu et al. (2009) emphasize the importance of maintaining gene flow; the isolation of these forest 'islands' would lead to a decrease in genetic resilience precisely at the moment when climatic stress (Popa et al., 2024) is at its highest. Given the unique genetic structure identified in Maramureș (Curtu et al., 2009), any ecological reconstruction effort must use exclusively local genetic material in order not to alter the evolutionary adaptability of these transboundary ecosystems.

Sustainable management is not a luxury, but an economic necessity. The loss of water regulation services through excessive logging in the border area will generate flood repair costs much higher

than the profit obtained from the sale of logs (Popa et al., 2016). Knowledge of the spatio-temporal evolution trends of forest resorts in the Maramureș Mountains is essential for local authorities. Herman et al. (2026) emphasize that tourism development is discontinuous and uneven, which requires specific ecological security policies for sensitive areas such as the Ruscova Corridor, to avoid landscape degradation that constitutes the very basis of tourist attractiveness.

The discovery of new species for the Romanian fauna in the Maramureș Mountains (Bitušík et al., 2025) imposes a more severe restriction of tourist activities near glacial lakes, in order to maintain the chemical and biological balance of these fragile ecosystems. Monitoring populations of endemic earthworms (e.g. Octodrilus species) is essential for assessing the health of alpine ecosystems. Soil degradation through intensive grazing or transboundary pollution (metallic or chemical) directly threatens these endemic species, endangering decomposition processes and nutrient cycling in the Pop Ivan meadows (Csuzdi & Pop, 2008).

International experience suggests that the success of conserving alpine landscapes, such as those on Pop Ivan, depends on increasing the resilience of local communities. The integrated development model proposed for Asian mountain regions can be adapted in Maramureș through green financing mechanisms and cross-border ecological education programs (Nasrullah, 2024). As Cioruta & Coman (2022) point out, any anthropogenic intervention in the Ruscova Corridor must be preceded by an analysis of soil functions correlated with meteorological factors. Soil degradation through mining or forestry activities (previously studied by Cioruță in a philatelic/historical context) irreparably alters water storage capacity, amplifying flood risks downstream.

The literary and spiritual heritage described in particular by Pop (2009) provides a solid basis for cross-border collaboration. In this context, protecting biodiversity on Pop Ivan Peak and in the Ruscova Basin should be a joint effort, based on the shared cultural heritage that unites the two banks of the Tisza. The protection of natural heritage, such as the Beech Forest (included in the UNESCO heritage), must overcome political barriers. Academic cooperation, as exemplified by the collaboration between the "Ștefan cel Mare" University of Suceava and Ukrainian partners (Coșofreț, 2017), represents the "keystone" for the ecological security of the entire Maramures area.

Recent studies conducted in the cross-border region of Ukraine emphasize the importance of constant monitoring of chemical elements in soil and plants, using vegetation as an indicator of nutritional conditions and the presence of toxic substances (Karbivska et al., 2025). Ecological reconstruction in the Maramureș Mountains highlights the importance of cross-border collaboration in monitoring high mountain ecosystems sensitive to climate change (Kłapyta et al., 2024). The Maramureș Mountains represent the northernmost area of the Romanian Carpathians that preserves traces of glaciation, offering unique habitats formed by complex geomorphological processes on the border between Romania and Ukraine (Kłapyta et al., 2024).

In Romania, the correlation between investments in environmental protection and the perception of quality of life is significant, highlighting the fact that a healthy ecosystem is the foundation of social well-being (Gheorghe, 2024b). The integration of digital solutions in the monitoring of environmental indicators facilitates a more efficient management of natural resources and allows a rapid assessment of the impact of anthropogenic activities on vulnerable habitats (Gheorghe, 2024b).

The harmonization of legislation and the increase in the number of operators in organic agriculture reflect a growing concern for sustainability in Romania, providing a favorable framework for the protection of protected natural areas (Gheorghe, 2023). The assessment of the pressure exerted by human consumption on the biosphere through the ecological footprint reveals the need for immediate measures to reduce the negative impact on natural resources and maintain the balance of ecosystems (Gheorghe, 2024a).

The rural region of the Maramureș Mountains possesses a vast natural and cultural heritage, the exploitation of which through the concept of Smart Tourist Village can ensure balanced development, while protecting local ecosystems from uncontrolled anthropogenic pressure (Ciolac et al., 2022). In order to ensure the conservation of habitats on the Ruscova

Corridor, we consider, based on the analyzed data, that it would be necessary to transition to a Smart Village development model, which would integrate sustainable tourism and organic agriculture, protecting the natural resources of the localities of Poienile de sub Munte, Repedea and Ruscova (Ciolac et al., 2022; Gheorghe, 2023).

According to the regulations of Order 756/1997, the area of the localities of Poienile de sub Munte, Repedea and Ruscova is classified as a sensitive use area, which imposes strict environmental quality standards to protect the health of the population and the integrity of the ecosystems. Even in the absence of large industrial centers, domestic activities and the historical use of fungicides can lead to local increases in Zn and Cu concentrations in the soil, a phenomenon that needs to be carefully monitored in the Ruscova Corridor to protect both terrestrial and aquatic ecosystems (Bošković-Rakočević et al., 2014; Kucsicsa & Popovici, 2016).

Combating the high-intensity anthropogenic pressure in the Ruscova Corridor requires an approach based on sustainable solutions, where landscape architecture plays a crucial role in the regeneration of degraded ecosystems and in the creation of natural barriers against pollutants (Ciobanu & Cebotari, 2025). The implementation of sustainable landscape projects in border areas can reduce the vulnerability of these agro-montane ecosystems, contributing to regional ecological security by utilizing the environmental cleaning function of selected vegetation (Ciobanu & Cebotari, 2025).

The continuous transformations of trade flows and the adaptation of customs legislation in the context of regional instability (Bahnă, 2026) also require increased vigilance in terms of monitoring environmental factors, in order to prevent the degradation of agro-mountain ecosystems on Romania's northern border. Although the economic development of the Ruscova Corridor is based on the exploitation of mountain potential, the relationship between tourism and environmental law remains tense (Bocancea & Braşoveanu, 2026). It is imperative that tourism activities do not ignore ecological regulations, in order to avoid transforming this natural refuge into an area degraded by excessive and unregulated tourism.

CONCLUSIONS

Transboundary ecosystems in the Maramureș Mountains face heightened risks due to pressures induced by the armed conflict in Ukraine, requiring immediate preventive protection measures for soil, water and biodiversity. GIS and multi-criteria analyses reveal critical vulnerabilities in habitat fragmentation and pollution, underlining the economic superiority of conservation over ruthless resource exploitation.

Romania-Ukraine cooperation, based on shared cultural heritage and international agreements, is vital for sustainable management and regional ecological security. In this sense, the strategic framework provided by the joint operational programs (Ministry of Development, 2021) constitutes the necessary administrative pillar for the implementation of these measures.

Digital tools and local genetic resources must guide reconstruction efforts to maintain evolutionary adaptability and in the face of climate stress.

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