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SOIL DEGRADATION IN THE WORLD, SERBIA AND MONTENEGRO: CAUSES, CONSEQUENCES, AND POSSIBLE SOLUTIONS

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Abstract: This study investigates the primary causes of soil degradation globally, but also in Serbia and Montenegro, as well as their ecological and socio-economic consequences, with a particular emphasis on potential mitigation and remediation strategies. Soil degradation is analysed because of its substantial impact on biodiversity, sustainable development, and agricultural productivity. The research aims to assess the extent to which natural and anthropogenic factors contribute to soil quality decline. The methodology involves a review of relevant scientific and professional literature and the analysis of statistical data from international and national institutions, with a focus on the past two decades and on agricultural and erosion-prone regions. Findings indicate that erosion, unsustainable farming practices, urbanisation, and climate change are principal drivers of soil degradation both globally and in Serbia and Montenegro. The study concludes that adopting sustainable soil management practices, strengthening the legal framework, and enhancing public awareness could substantially mitigate the negative effects of soil degradation. The main limitations concern the availability and timeliness of data for certain regions.

Keywords: Soil degradation, Erosion, Sustainable management, Climate change, Serbia, Montenegro

INTRODUCTION

Soil degradation is a key constraint on sustainable development, food security and ecosystem stability at the global scale. Driven by the combined effects of land-use change, inappropriate agricultural practices, pollution and accelerating climate change, the loss of soil quantity and quality is now documented across all continents and a wide range of agro-ecological zones. In the Western Balkans, and particularly in Serbia and Montenegro, this process is further conditioned by pronounced relief, mountain karst geomorphology, and the limited extent of high-quality agricultural land, which together make soils highly vulnerable to erosion and structural decline. Despite growing international attention, there remains a need to synthesise global knowledge with region-specific evidence to understand better how natural and anthropogenic factors interact to shape degradation patterns and their ecological and socio-economic impacts. This paper therefore analyses the main drivers, consequences and potential mitigation and remediation options for soil degradation at the global level and in Serbia and Montenegro, with comparative reference from the Global to the local level.

MATERIAL AND METHODS

The study is based on a desk-based synthesis of scientific and professional literature, supported by data from international (FAO, UNCCD, FAOSTAT, etc.) and national institutions in Montenegro and Serbia. Priority was given to sources from the last two decades and to studies focused on agricultural and erosion-prone areas. The analysis proceeded in three steps: (i) identification and classification of the main drivers and forms of soil degradation at the global scale and in Montenegro and Serbia; (ii) comparative assessment of ecological and socio-economic consequences, with particular emphasis on erosion, loss of soil organic carbon and climate-related stress; and (iii) evaluation of proposed mitigation and remediation measures, structured through a comparative matrix and SWOT framework. The approach is qualitative and integrative, aiming to link global findings with region-specific evidence rather than to develop new quantitative models or field measurements.

RESULTS AND DISCUSSION

Leading Causes of Soil Degradation Worldwide

The literature consistently identifies soil degradation as a globally pervasive process driven by human-induced land-use change, unsustainable agricultural practices and climate-related stressors. The Status of the World's Soil Resources report (FAO and ITPS, 2015) indicates that most global soils are in fair to poor condition, with accelerated erosion, organic-matter decline, nutrient imbalance, salinisation, acidification, contamination and biodiversity loss among the dominant threats to soil and ecosystem services (FAO and ITPS, 2015; JRC, 2024).

A leading global driver of erosion is accelerated erosion by water and wind, which removes fertile topsoil, reduces soil depth and productivity, and produces major off-site impacts through sedimentation and water-quality deterioration (Pimentel, 2006; Billi and Spalevic 2022). Erosion is especially severe on sloping terrain, on sparsely covered soils, and on intensively cultivated land, and in many regions, it proceeds far faster than natural soil formation (FAO and ITPS, 2015; Pimentel, 2006; Spalevic, 2011; Spalevic et al., 2014). Recent global modelling also shows that cropland expansion and land-use change in the 21st century have further intensified erosion risks in several world regions.

Closely linked to erosion is the decline in soil organic carbon (SOC). Converting natural ecosystems to cropland, removing residues and practising intensive tillage reduce organic inputs and accelerate mineralisation, leading to losses of soil structure, fertility and biological activity. SOC depletion is widely recognised as a key indicator of land degradation, with major implications for agricultural productivity and the global carbon cycle (Lal, 2015). Many agrarian systems also face nutrient depletion and elemental imbalance, where nutrient export through harvesting and erosion is not compensated for by replenishment. This long-term nutrient mining lowers crop productivity and reduces soil resilience, particularly in marginal and smallholder systems (FAO and ITPS, 2015).

In mechanised production zones, degradation is manifested as soil compaction and structural decline caused by heavy machinery and repeated tillage, which restrict rooting, reduce infiltration and reinforce cycles of low biomass return. In irrigated and arid regions, salinisation is a widespread problem resulting from inadequate drainage and poorly managed irrigation, leading to altered soil structure, reduced plant growth and significant productivity losses (Shokri et al., 2024). In other areas, acidification arising from inappropriate fertiliser use and land-use transitions decreases nutrient availability, increases metal toxicity, and limits soil biota functioning and crop performance.

Further degradation pressures arise from pollution and contamination associated with industry, mining, waste disposal, pesticides and heavy metals, creating localised but severe hotspots with long-term ecological and health risks. Multiple studies also document losses of soil biodiversity and biological functioning, linked to erosion, SOC decline (Lal, 2015), pollution and land-use intensification, which weaken nutrient cycling and reduce ecosystem resilience.

Finally, land-use change and deforestation act as cross-cutting drivers that amplify erosion, SOC loss and hydrological instability, while climate-change-related stressors, such as warming, extreme rainfall, droughts and increasing aridity, accelerate ongoing degradation and increase the risk of desertification (JRC, 2024). Taken together, the evidence shows that global soil degradation results from the cumulative interaction of biophysical processes and human pressures, with regional variability but broadly convergent trends towards erosion-driven topsoil loss, organic-matter decline, structural degradation, and growing vulnerability under climate change (FAO and ITPS, 2015).

Leading Causes of Soil Degradation in Montenegro

Soil degradation in Montenegro is largely shaped by its mountainous and karst geomorphology, where shallow, erosion-prone soils dominate steep terrain with discontinuous cover. Many soils formed on limestone and dolomite have shallow rooting depth, are drought-sensitive and have limited production potential. Across mountain regions, water erosion is a leading driver, intensified by steep relief, seasonal heavy rainfall and sparse vegetation, resulting in soil thinning, bedrock exposure and fragmentation of arable land (Spalevic, 2024).

A considerable part of the territory comprises land with low or limited agricultural fertility (VII-VIII capability classes), while deeper, more productive soils are largely restricted to river valleys, terraces and karst poljes. In upland rural regions, overgrazing and grazing pressure on natural grasslands and pastures contribute to vegetation degradation, reduced ground cover and accelerated erosion. At the same time, demographic decline and the abandonment of marginal agricultural land increase exposure to erosion and slope instability on already fragile soils. Degradation is intensified where unsuitable cultivation is practised on shallow or steep terrain, including mechanised tillage on discontinuous soils and former terrace systems, which disturb soil structure, reduce organic-matter inputs and increase susceptibility to runoff and topsoil loss (Spalevic, 2024; Hamza and Anderson, 2005).

In contrast, the limited areas of deeper, more fertile soils in valley and coastal plains are increasingly exposed to urbanisation and infrastructure expansion, causing fragmentation and the permanent loss of high-value agricultural land. Climate stress further accelerates degradation: drought reduces vegetation cover, while intense rainfall increases runoff and erosion on steep, shallow soils. Overall, soil degradation in Montenegro arises from the interaction of natural constraints (relief, karst and shallow soils) with human and climate-induced pressures, with erosion and soil shallowing as the dominant outcomes.

Leading causes of soil degradation in Serbia

Evidence from national assessments indicates that soil degradation in Serbia is driven by the combined effects of hydrometeorological extremes, erosion, land-use transitions, agricultural management practices and climate-related stressors (UNDP and MEP, 2022). Among all forms of degradation, water erosion is the most widespread and severe driver, strongly intensified by recent increases in extreme precipitation, high-intensity rainfall and flood events. These processes enhance surface runoff, soil detachment and downslope sediment transport, particularly in hilly and mountainous terrain and in river catchments exposed to torrential flows.

A major accompanying degradation pathway is the decline in soil organic carbon (SOC), driven by land-use change, residue removal, intensive tillage and insufficient organic-matter return to soil. SOC depletion weakens soil structure, increases erodibility, reduces infiltration and lowers resilience to climatic stresses, thereby amplifying erosion and productivity loss (Hamza and Anderson, 2005). Degradation risk is further increased by the overexploitation and mismanagement of agricultural soils, including intensive mechanisation, repeated soil disturbance and inadequate nutrient restoration, which lead to structural deterioration, compaction and reduced soil functionality (Hamza and Anderson, 2005; Vidojević, 2024).

In marginal rural areas, the abandonment of agricultural land leads to vegetation loss and disrupted ground cover, increasing exposure to erosion and slope instability in already vulnerable landscapes. Land-use change and conversion also transform previously stable soil systems, increasing their sensitivity to hydrological extremes and climate pressures, particularly when interventions are unplanned or inappropriate.

Climate change globally acts as a cross-cutting degradation accelerator through rising temperatures, increased aridity during the vegetation period, more frequent and prolonged droughts, and intensified extreme-rainfall events (UNDP and MEP, 2022; JRC, 2024). These changes collectively increase the risk of both erosional degradation and desertification-type processes, with projections indicating that a substantial part of the territory of Serbia may shift into moderate-to-high degradation-risk classes by mid-century.

In the northern lowland region of Vojvodina, degradation is also evident through wind erosion on open agricultural fields, especially during dry periods and bare-soil stages, when the combination of drought, strong winds and reduced ground cover leads to significant loss of topsoil and nutrients, with documented implications for productivity and air quality. Finally, local industrial and urban pollution contributes to degradation in specific zones, adding contamination pressures to soils already affected by structural decline, erosion and organic-matter loss.

Taken together, these processes indicate that soil degradation in Serbia is shaped by the interaction of erosion, SOC decline, land-use change, inadequate soil management and climate-driven stress, with water and wind erosion emerging as the dominant and mutually reinforcing drivers.

Ecological Consequences of Soil Degradation, World

Evidence from global assessments indicates that soil degradation has profound ecological consequences, primarily through the loss and impairment of key ecosystem services: food provision, water regulation and climate buffering. Degraded soils show reduced fertility, diminished biological productivity and disrupted regulation of water and nutrient cycles, which collectively undermine crop yields, increase food-insecurity risk and weaken ecosystems' capacity to support biodiversity and climate-regulating functions. A central demonstration of these changes is the decline in soil organic carbon (SOC), which reduces the soil's carbon-sink capacity, increases CO_2 emissions, weakens soil structure, lowers water-retention capacity and increases erodibility and vulnerability to drought and extreme rainfall.

Soil degradation is also closely linked to biodiversity loss in soil biota and terrestrial habitats, as declines in microbial, faunal and plant diversity disrupt soil food webs, reduce functional redundancy and diminish ecosystem resilience and recovery potential under environmental stress (Bardgett and van der Putten, 2014). In general, these processes are directly linked to alterations in nutrient and biogeochemical cycles (nitrogen, phosphorus and carbon), affecting vegetation productivity, water quality and greenhouse-gas exchange (Bardgett and van der Putten, 2014). Hydrological functioning is reduced: compaction, structural decline and organic-matter loss reduce infiltration, increase surface runoff and flood risk, and limit groundwater recharge and the water-regulating capacity of landscapes. Intensified erosion results in greater sediment delivery to rivers, coastal systems, degrading habitats, increasing turbidity and contributing to eutrophication and downstream ecological stress.

In dryland regions, degradation often manifests as desertification and land aridification, characterised by vegetation decline, soil crusting, loss of biological productivity, and the expansion of sparsely vegetated or barren areas. These transformations reduce ecosystem resilience and increase exposure to drought, wind erosion, and dust emissions. Across many landscapes, soil loss, vegetation decline, and nutrient depletion create positive feedback loops of degradation, in which reduced plant cover accelerates erosion, which in turn depletes soil resources and weakens ecosystem recovery capacity.

Taken together, global evidence demonstrates that soil degradation drives a systemic decline in ecological services, from food provision, biodiversity support and climate regulation to hydrological stability and landscape resilience, with cascading impacts across terrestrial and aquatic ecosystems at local, regional and global scales (Bardgett and van der Putten, 2014).

Ecological Consequences of Soil Degradation in Montenegro

Closely linked to the country's predominantly mountainous and karst relief, where steep slopes, shallow soils and discontinuous vegetation cover create conditions for rapid, cumulative environmental impacts. On steep karst and mountain slopes, accelerated erosion progressively removes and thins the already shallow soils, exposing bedrock and reducing effective rooting depth. This, in turn, diminishes vegetation productivity, reduces landscape stability, and weakens ecosystem functioning. These effects are particularly pronounced in low- or limited-agricultural-fertility land (VII-VIII capability classes), where additional soil loss further reduces biological productivity and reinforces long-term ecological constraints.

In upland rural areas affected by depopulation and land abandonment, the disruption of traditional land management leads to landscape instability and secondary erosion, especially where vegetation regrowth is insufficient to protect fragile slopes. In karst environments, soil thinning and limited water-retention capacity contribute to the degradation of karst ecosystems, altering microhabitats, reducing moisture availability, and limiting the ability of soils and vegetation to buffer hydrological fluctuations. Overgrazing on pastures and grasslands accelerates the loss of pasture productivity and grassland biodiversity, as reduced ground cover increases erosion susceptibility and simplifies plant communities.

Soil degradation also increases the sensitivity of Montenegrin ecosystems to climate variability: episodes of extreme rainfall intensify runoff and slope instability, while periods of drought reduce vegetation cover and biological activity, further amplifying erosion risks on shallow and skeletal soils. At the same time, fertile valley soils and karst poljes are exposed to urbanisation and infrastructure pressure, resulting in the loss of natural and semi-natural land and the permanent loss of ecologically valuable soil resources in the most productive parts of the landscape.

Taken together, these processes demonstrate that in Montenegro's fragile mountain and karst environments, even relatively small soil losses can translate into disproportionately large ecological impacts, affecting vegetation structure, habitat continuity, hydrological functioning, and long-term landscape resilience.

Ecological Consequences of Soil Degradation in Serbia

Arise primarily from the widespread impacts of erosional processes, organic-matter decline and increased exposure to climate-related extremes. The most prevalent effects are associated with water erosion, which leads to progressive soil loss, sedimentation and disturbance of river channels, floodplains and associated wetland ecosystems, thereby reducing their hydro morphological and ecological functioning. Closely linked to these processes is the decline in soil organic carbon, which weakens soil structure, reduces biological productivity and lowers the capacity of soils to retain water and nutrients, diminishing ecosystem performance and resilience.

Reduced infiltration capacity, combined with more frequent extreme precipitation events, increases surface runoff, raises flood risk, accelerates erosion, and limits groundwater recharge and the water-regulating functions of soils. Under climatic warming, parts of Serbia face an intensified risk of aridity and desertification-type processes, particularly in regions exposed to prolonged drought and increasing moisture deficits. In the northern lowland areas, especially in Vojvodina, degradation is further manifested through wind erosion, which leads to dust emissions, loss of fine particles and nutrients, and adverse effects on air quality and agro-ecosystem stability during dry, bare-soil periods.

These processes collectively result in a loss of agricultural ecosystem resilience, as evidenced by lower drought tolerance, greater yield variability, and reduced capacity of production systems to absorb climatic shocks. The decline of organic matter and soil biological activity contributes to the degradation of soil biodiversity, weakening nutrient cycling and ecosystem functioning. In addition, localised contamination hotspots near industrial and urban areas introduce further ecological and health risks in already vulnerable environments. Overall, national assessments emphasise that climate change acts as a key intensifying factor, intensifying nearly all degradation-linked ecological impacts by reinforcing erosion dynamics, accelerating organic-matter decline and increasing the frequency and severity of hydrometeorological extremes across Serbia’s landscapes (UNDP and MEP, 2022).

Socio-economic Consequences of Soil Degradation, World

Global evidence indicates that soil degradation has substantial socioeconomic implications that extend beyond the agricultural sector, affecting livelihoods, rural development, public finances, and broader economic stability. One of the most direct impacts is a reduction in farm productivity and food security, reflected in declining yields, higher crop-failure risk and rising production costs, which lead to lower farmer incomes and increased vulnerability of rural incomes, particularly among smallholders and communities in developing regions. As soil fertility declines and structural degradation intensifies, farmers increasingly depend on higher levels of fertilisers, irrigation and other land inputs to compensate for fertility loss, raising financial burdens and widening inequality between capital-intensive and resource-poor farming.

At the macro scale, soil degradation contributes to the loss of natural capital and ecosystem service value, including diminished water regulation, climate buffering, erosion control, and flood protection, functions that support both rural and urban societies. Degraded landscapes also experience greater exposure to disasters such as floods, landslides and drought-related losses, as reduced infiltration, slope instability and weakened ground cover increase the frequency and severity of damaging events. In many regions, these processes are associated with rural poverty, land abandonment and migration pressures, particularly in marginal environments where declining productivity and repeated economic stress lead to depopulation and social restructuring.

For governments, soil degradation increases public expenditure on land restoration programmes, the rehabilitation of damaged infrastructure, disaster recovery measures, and environmental protection initiatives. Taken together, the cumulative impacts of soil degradation create a negative feedback loop within national economies, undermining agricultural GDP, weakening food-system stability, and constraining long-term development potential. Overall, the literature indicates that soil degradation is not only an environmental challenge but also a systemic socio-economic risk with far-reaching implications for public welfare and sustainable economic growth at the global scale.

Socio-economic Consequences of Soil Degradation: Montenegro

Strongly conditioned by the country's fragile mountain and karst environments and by the limited extent of productive soils. Reduced productivity on already shallow, low-fertility soils lower agricultural output and farm profitability, particularly in marginal upland areas where production potential is inherently constrained. On steep, erosion-prone terrain, continued soil loss reduces usable land, limiting opportunities for rural development and narrowing land-use options for local communities. These processes are closely linked to depopulation and the abandonment of marginal rural areas, where low economic returns and declining land productivity contribute to out-migration and ageing settlements.

At the same time, erosion, slope instability and surface runoff increase maintenance and protection costs for rural infrastructure, affecting roads, terraces, retaining structures and other assets that require frequent repair or stabilisation. Because fertile valley soils and karst poljes are scarce and highly valuable resources, they are increasingly exposed to urbanisation and land-use competition between agriculture, tourism and construction, leading to permanent loss of high-quality soils and constraining future agricultural development. In upland pastoral systems, soil degradation and erosion reduce pasture quality and livestock carrying capacity, resulting in economic losses for households dependent on grazing-based production.

These vulnerabilities are further intensified during climate extremes, when droughts and episodes of intense rainfall increase economic damage to land, production systems and infrastructure. Despite the relatively small absolute area of degraded land, the combination of fragile terrain, limited agricultural resources and the concentration of fertile soils means that soil degradation in Montenegro exerts disproportionately high socio-economic impacts on rural livelihoods and regional development.

Socio-economic Consequences of Soil Degradation: Serbia

The socio-economic consequences of soil degradation in Serbia are closely linked to the combined effects of erosion, declines in soil organic carbon and intensifying climate stress. The most direct outcomes are yield reduction and a loss of agricultural income, as declining soil fertility, structural degradation, and recurrent hydrometeorological extremes reduce productivity and increase production variability. In response, farmers face higher costs for soil rehabilitation, irrigation and nutrient inputs as they attempt to compensate for deteriorating soil quality and maintain acceptable yield levels. Frequent episodes of flooding, runoff and extreme precipitation cause additional damage to farmland, settlements and rural infrastructure, generating repeated recovery costs and increasing economic vulnerability. In climatically sensitive regions, degradation increase the risk of desertification and land-use restrictions, thereby limiting economic use, investment, and long-term development opportunities.

In Vojvodina's northern lowland region, soil degradation is evident through wind erosion, including the loss of fine soil particles, nutrient leaching, dust events, and reduced crop value, as well as negative impacts on air quality and agroecosystem stability. At a broader scale, these interacting pressures weaken the resilience of rural economies to climate shocks, resulting in greater production instability and greater household vulnerability. For the public sector, soil degradation involves increasing expenditures on monitoring, land restoration, disaster response, and adaptation planning, particularly in erosion-prone and flood-affected catchments. National assessments emphasise that climate change multiplies socio-economic risks by accelerating existing degradation trends and increasing the frequency and severity of damaging events across rural systems in Serbia.

Potential Mitigation and Remediation Measures: World

The global literature highlights a broad range of mitigation and remediation measures that can slow, halt, or reverse soil degradation while restoring ecosystem services and production capacity (Lal, 2015). A central pillar of sustainable land management is the implementation of conservation and regenerative agriculture, including reduced- or no-tillage systems, permanent soil cover through mulching, crop residues or cover crops, and diversified crop rotations and intercropping, which enhance soil structure, increase organic matter inputs, reduce erosion, and improve water-use efficiency. A key pathway for improving long-term soil quality is the restoration of the soil organic carbon (SOC) pool, supported by residue retention, the application of manure and compost, the targeted use of biochar in degraded or sandy soils, and the expansion of agroforestry and agro production systems, which strengthen soil fertility, biological activity, and structural stability.

Complementary measures should focus on erosion control, including contour farming, strip cropping and terracing, together with vegetative buffer zones, riparian belts, and the stabilisation and revegetation of gullies, thereby reducing sediment loss and protecting downstream ecosystems. Improved soil performance also depends on balanced and integrated nutrient management, combining soil testing and site-specific fertilisation strategies with the integration of organic and mineral nutrient sources to maintain positive nutrient balances and prevent depletion and pollution. In areas affected by chemical degradation, targeted actions for salinity and acidity management, such as improved drainage and leaching management, gypsum application where appropriate, and liming of acid soils, contribute to the recovery of soil functionality and plant growth (FAO and ITPS, 2015).

Mitigating contamination requires strengthening pollution-prevention and remediation frameworks, including stricter industrial and mining controls, as well as site-specific measures such as phytoremediation and the removal of contaminated soil in critical hotspots (Lal, 2015). At broader spatial scales, landscape-level restoration, through reforestation and afforestation of fragile slopes, rangeland rehabilitation and controlled grazing regimes, supports erosion reduction, biodiversity recovery and hydrological regulation. Finally, long-term progress depends on effective monitoring and governance mechanisms, including integrated soil-monitoring systems, early-warning tools and incentive schemes such as payments for ecosystem services and soil stewardship programmes, which promote the adoption of sustainable management practices and support progress towards land-degradation neutrality at the global scale (JRC, 2024).

Potential Mitigation and Remediation Measures: Montenegro

Potential mitigation and remediation measures in Montenegro are shaped by the predominance of steep mountain and karst terrain, the shallow, erosion-prone nature of many soils, and the limited spatial extent of highly productive land. A key priority is erosion prevention on steep and karst landscapes, particularly in hilly agricultural zones, through contour planting and terracing, re-vegetation of bare and shallow soils, and targeted stabilisation of erosion hotspots, which help to reduce runoff, protect fragile slopes and prevent further soil thinning. In upland pastoral regions, sustainable pasture and grazing management, including rotating or controlled grazing and reseeding of degraded grasslands, supports the recovery of plant cover, improves pasture productivity and enhances the long-term ecological stability of upland landscapes.

Given the scarcity of productive soils, protecting fertile valley soils and karst poljes is a strategic measure, implemented through zoning to reduce urbanisation pressure and safeguard high-value agricultural land from irreversible loss and fragmentation. In areas of abandoned agricultural land, restoration approaches include natural succession or assisted afforestation, as well as transitions towards perennial or agroforestry systems that increase vegetation cover, improve soil structure and enhance organic-matter accumulation. On shallow, low-fertility soils, soil-fertility improvement measures, such as organic amendments, mulching and low-input conservation farming, strengthen soil resilience and reduce erosion susceptibility.

Montenegro is exposed to hydrometeorological extremes, climate-resilience actions are also essential. This includes introducing drought-tolerant crops in drier regions and improving drainage and runoff-control measures in areas affected by intense rainfall. Finally, the effective targeting of mitigation actions depends on regional land monitoring and erosion modelling, which support the identification and prioritisation of high-risk mountain catchments and enable evidence-based planning of restoration and protection measures.

Potential Mitigation and Remediation Measures for Soil Degradation in Serbia

Focus should be on reducing erosion, restoring soil organic matter, improving farm management and boosting climate resilience. Priority measures include preventing water and wind erosion in hilly areas and Vojvodina's lowlands through contour and strip cropping, winter cover on fields, and shelterbelts and windbreaks to reduce runoff and soil loss. Restoring soil organic matter and soil organic carbon (SOC) plays a central role in improving soil structure, fertility, and climate resilience. Retaining crop residues, applying organic amendments and green manures, and adopting reduced-tillage systems support the build-up of organic matter and reduce erosion susceptibility. These practices are complemented by improved agricultural soil management, including avoiding over-exploitation and excessive residue removal, and diversifying crop rotations to stabilise yields and enhance soil biological activity (Borrelli et al., 2017; Khaledi Darvishan et al., 2019).

At the territorial level, risk-based land-use planning is essential for limiting the conversion of relatively stable soils to more vulnerable land uses and for guiding development away from flood- and slope-prone areas (Borrelli et al., 2017; Spalevic et al., 2013; Spalevic et al., 2014). Erosion-risk zoning enables prioritisation of protection and adaptation measures in landscapes exposed to accelerated runoff and geomorphological instability. Climate-related risks are addressed through drought-mitigation practices (mulching, conservation tillage) and runoff and flood-control measures in areas affected by extreme rainfall. Effective mitigation further requires stronger monitoring and early-warning systems, supported by integrated soil-degradation assessments that identify priority intervention areas and enable timely decision-making (Spalevic et al., 1999). Restoration of degraded land through assisted re-vegetation, agroforestry, and perennial cover supports the long-term recovery of soil functions, reduces erosion, and strengthens landscape resilience in Serbia. Table 1 summarises the dominant drivers, ecological and socio-economic consequences, and priority mitigation and remediation measures related to soil degradation at the global level and in Montenegro and Serbia.

Table 1. Comparison of Soil Degradation: Drivers, Consequences and Mitigation

Dimension	World	Montenegro	Serbia
Dominant drivers	Land-use change, unsustainable agriculture, erosion by water & wind, SOC decline, compaction, salinisation, acidification, pollution; climate stress as accelerator	Mountainous & karst relief, shallow soils, steep slopes, water erosion, overgrazing, land abandonment, unsuitable cultivation on fragile soils; urbanisation pressure in valleys; climate extremes	Water erosion (extreme rainfall & floods), SOC decline, intensive tillage & residue removal, land-use change & abandonment, wind erosion in Vojvodina; climate-driven aridity
Ecological consequences	Loss of ecosystem services; reduced fertility and productivity; SOC decline and increased CO_2; biodiversity loss; disturbed nutrient and hydrological cycles; desertification and sedimentation; weakening of ecosystem resilience	Thinning of soil and loss; habitat fragmentation; degradation of karst ecosystems & poor water retention; pasture & biodiversity degradation; sensitivity to droughts & intense rainfall; loss of land in valleys	Soil loss & sedimentation; weakened soil structure & productivity; increased runoff & flood risk; aridity / desertification risk; wind-erosion dust & nutrient loss in Vojvodina; decline of soil biota & resilience
Socio-economic consequences	decreased yields and food security; increased production costs; lower farm income; disaster exposure; rural poverty, abandonment and migration; rising public restoration costs; negative feedback on GDP and food-system stability	decreased farm profitability; loss of usable land on steep slopes; rural depopulation & ageing; higher infrastructure maintenance costs; competition for scarce fertile valleys; decreased pasture capacity; climate-amplified damages	Yield & income losses; increased costs of irrigation & nutrients; flood damage to land & infrastructure; land-use limits in vulnerable regions; wind-erosion losses in Vojvodina; decreased rural economic resilience; increased costs

Priority mitigation / remediation	Conservation / regenerative agriculture; SOC restoration; contouring, terracing & buffers; integrated nutrient management; salinity / acidity treatment; pollution control; landscape-scale restoration; monitoring & governance incentives	Erosion prevention on steep & karst terrain; re-vegetation & hotspot stabilisation; sustainable grazing; protection of limited fertile valley soils; restoration of abandoned land; organic amendments & low-input farming; climate-resilience & catchment prioritisation	Prevention of water & wind erosion (contour / strip cropping, winter cover, windbreaks); SOC restoration (residues, organics, reduced tillage); diversified rotations; risk-based land-use planning; drought & runoff control; monitoring & re-vegetation / agroforestry

The SWOT comparison presented in Table 2 synthesises key strengths, weaknesses, opportunities and threats related to soil degradation and its management in the global context and in the specific environmental and socio-economic conditions of Montenegro and Serbia.

The results of the comparative and SWOT analyses indicate that, although the dominant drivers of degradation are broadly similar across scales, their impacts are considerably amplified in Montenegro and Serbia, particularly in fragile terrain, under land-use pressure, and amid intensifying climate extremes.

Table 2. Comparative SWOT Framework for Soil Degradation Drivers, Impacts and Responses

Strengths		
World	**Montenegro**	**Serbia**
Extensive scientific evidence base & global soil assessment frameworks	Clearly identified natural specificities (mountain-karst relief, shallow and erosion-prone soils)	Strong scientific and professional tradition in erosion and land degradation studies
Developed concepts for sustainable and regenerative soil management	Small territory enables targeted pilot restoration and management actions	Institutional network and experience with monitoring programmes
International initiatives and funding mechanisms (FAO, UNCCD, EU)	Recognised need to protect scarce fertile valley soils and karst fields	Presence of agronomic and planning measures for erosion reduction
Weaknesses		
World	**Montenegro**	**Serbia**
Large regional inequalities in data quality and management capacity	Limited extent of productive soils and dependence on mountain areas	Intensive agriculture with SOC decline and structural degradation
Slow implementation of sustainable land management policies	Rural depopulation & abandonment increase erosion exposure	Excessive tillage, residue removal and weak crop-rotation diversity
Expansion of land degradation faster than the mitigation capacity	Limited institutional and financial capacity for long-term monitoring	High exposure to floods and erosion in hilly and river-basin areas

Opportunities		
World	**Montenegro**	**Serbia**
Global shift toward *land-degradation neutrality* and climate-finance mechanisms	Strengthening protection of fertile valley soils through spatial planning and zoning	Scaling-up conservation agriculture and agroforestry practices
Expansion of regenerative farming and carbon-smart soil management	Pilot restoration of erosion hotspots and abandoned land	SOC recovery through organic amendments and reduced tillage
Rapid development of monitoring, modelling & remote sensing tools	Incentive schemes and PES mechanisms for farmers	Access to EU and regional funds for restoration of degraded land
Threats		
World	**Montenegro**	**Serbia**
Accelerating climate change leads to more droughts, extreme rainfall and degradation pressure	Urbanisation of valleys and karst fields leads to permanent loss of the most fertile soils	Extreme rainfall, flash floods and runoff intensify erosion damage
Expansion of intensive agriculture and pressure on marginal lands	Continued depopulation and abandonment of upland rural areas	Increasing aridity and desertification risk in vulnerable regions
Rising global food demand increases pressure on soil resources	Limited resources for large-scale restoration and monitoring	Industrial-urban contamination hotspots add to existing degradation

CONCLUSION

This study confirms that soil degradation is a pervasive and accelerating global and Western Balkans problem, driven primarily by erosion, loss of soil organic carbon, inappropriate agricultural practices, land-use change and intensifying climate stress. While the dominant processes are broadly similar at the global scale and in Montenegro and Serbia, their impacts are particularly severe in fragile mountain-karst and erosion-prone environments with limited reserves of high-quality agricultural land. The ecological consequences include the loss of ecosystem services, reduced fertility and productivity, biodiversity decline and increased hydrological instability. At the same time, socio-economic impacts are expressed through yield and income losses, rural depopulation, rising infrastructure and restoration costs, and heightened vulnerability to climate extremes (JRC, 2024). Comparative and SWOT analyses show that both countries have significant opportunities to reduce degradation through conservation and regenerative agriculture, protection of scarce fertile soils, restoration of abandoned and degraded land, and improved risk-based land-use planning (JRC, 2024). To be effective, these technical measures must be supported by stronger legal and institutional frameworks, systematic monitoring and targeted incentives for sustainable soil management, so that soil resources can continue to support biodiversity, food security and rural development under changing climatic conditions (JRC, 2024).

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