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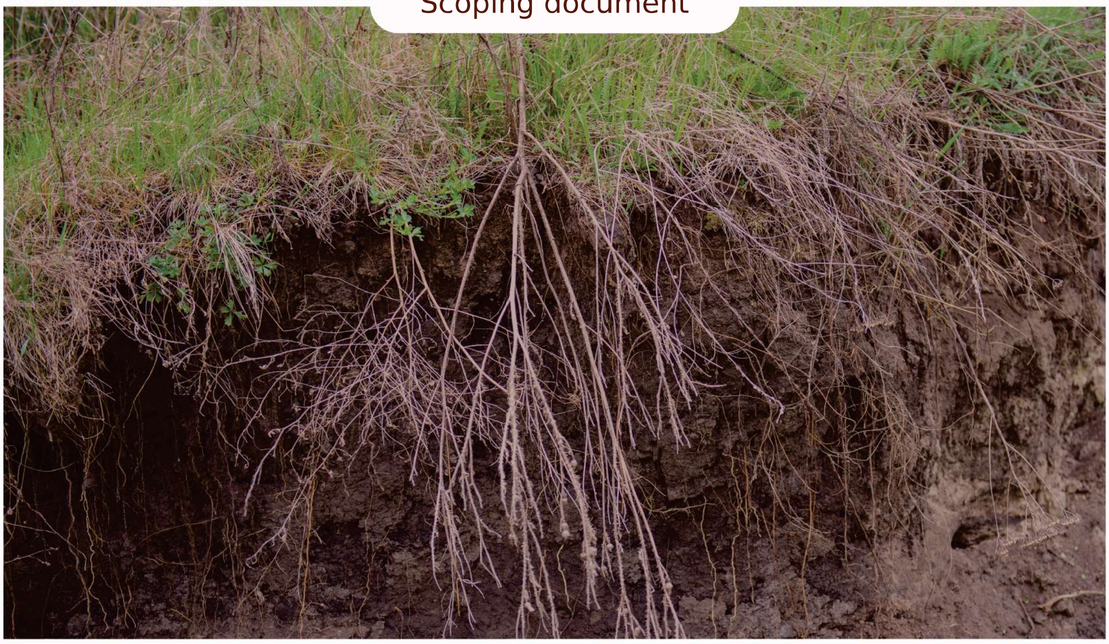

Preliminary assessment of the knowledge gaps to prevent soil erosion

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Preliminary assessment of the knowledge gaps to prevent soil erosion

Mª Helena Guimarães[‡], Martinho Martins[§], Diana Vieira[|], Isabel Brito[¶], Claire Kelly[#], Nuno Guiomar[¤], Nikolaos Stathopoulos[«], Melpomeni Zoka[«], Teresa Nóvoa[‡], Artemi Cerdà[»], Beatriz Faria[˄], João Madeira[˅], Lilia Fidalgo[¦], Panos Panagos[|], Pandi Zdruli[ˀ], Saskia Keesstra[ˁ], Sergio Prats[‡], Pierfrancesco Di Giuseppe[₵], Endre Dobos[ℓ]

‡ MED - Mediterranean Institute for Agriculture, Environment and Development & CHANGE – Global Change and Sustainability Institute, Institute for Advanced Studies and Research, Universidade de Évora, Évora, Portugal, Évora, Portugal
§ Centre for Environmental and Marine Studies (CESAM), Department Environment and Planning, University of Aveiro, Portugal, Aveiro, Portugal
| European Commission, Joint Research Centre (JRC), Ispra, Italy, Ispra, Italy
¶ School of Science and Technology, Universidade de Évora, Évora, Portugal; MED - Mediterranean Institute for Agriculture, Environment and Development & CHANGE – Global Change and Sustainability Institute, Institute for Advanced Studies and Research, Universidade de Évora, Évora, Portugal, Évora, Portugal
# School of Geography, Earth and Environmental Sciences, Faculty of Science and Engineering, University of Plymouth, United Kingdom, Plymouth, United Kingdom
¤ MED - Mediterranean Institute for Agriculture, Environment and Development & CHANGE – Global Change and Sustainability Institute, Évora, Portugal
« Operational Unit “BEYOND Centre for Earth Observation Research and Satellite Remote Sensing”, Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing, National Observatory of Athens, GR-152 36 Athens, Greece, Athens, Greece
» Soil Erosion and Degradation Research Group, Geography Department, Universitat de València, Spain, Valencia, Spain
˄ URZE - Associação Florestal da Encosta da Serra da Estrela, Gouveia, Portugal, Gouveia, Portugal
˅ Sociedade Agrícola Vargas Madeira, Lda., Corte do Gafo de Cima, Mértola, Portugal, Mértola, Portugal
¦ Services Directorate for Territorial Planning, Alentejo’s Commission for Regional Coordination and Development, Évora, Portugal, Évora, Portugal
ˀ International Centre for Advanced Mediterranean Agronomic Studies (CIHEAM) Mediterranean Agronomic Institute of Bari (CIHEAM-Bari), Italy, Bari, Italy
ˁ Resilient and Climate Neutral Regions Cluster, Climate-Kic Holding B.V., Plantage Middenlaan 45, Amsterdam, the Netherlands, Amesterdam, Netherlands
₵ CEO Regrowth s.r.l, Italy, Teramo, Italy
ℓ University of Miskolc, Institute of Geography and Geoinformatics, 3515, Miskolc-Egyetemváros, Hungary, Miskolc, Hungary

Corresponding author: Mª Helena Guimarães (mhguimaraes@uevora.pt)

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Introduction

SOLO project aims to deliver actionable transdisciplinary roadmaps for future soil-related research and innovation activities in the EU, contributing to achieving the objectives of the EU Soil Mission. To achieve this overarching goal, the project employs a transdisciplinary task force known as Think Tanks (TTs). Comprising 10 Think Tanks, SOLO aligns these entities with the objectives set forth by the EU Soil Mission Board. Within our specific TT, we focus on the Soil Mission objective 5, “Prevent erosion”. Broadly, this objective is to reduce “the area of land currently affected by unsustainable erosion from 25% to sustainable levels” (EC, 2021a). Evidence used as background information in the document of the Soil Mission, “A Soil Deal for Europe”, shows that 70% of the land affected by unsustainable erosion rates occurs on agricultural systems, showing a higher severity than on other systems. Within the agriculture area, and according to the EC (2021a), permanent crops are the most affected and notable erosion rates on shrubland and sparse vegetation are also identified. Concluding from the evidence gathered, the EC (2021a) states that, “land failing soil health indicator due to soil erosion equals 23% in cropland and 30% in non-agricultural areas.” According to the Soil Mission, these figures require urgent action, based on contextual knowledge both on soils and on human activity, to halt or revert the erosion process.

The present document thus serves as a platform to underscore the existing knowledge gaps that should be considered in the future research and innovation agenda of the EU to attain the set target.

Why do we need a Think Tank focused on the Prevention of Soil Erosion?

Knowledge on soil erosion is dispersed and fragmented, so we need a TT that can integrate different sources of knowledge not only by systematising it but by exploring its interactions. At first, we are focused on this integration and systemic approach around the prevention of soil erosion. Later, we will develop the same effort considering the interactions between TTs.

In line with the Soil Mission strategy, there is a need to engage non-academic stakeholders in the identification of solutions to the problem of soil erosion and in its prevention and mitigation. Hence, the TT is a platform that allows engagement, collaborative thinking and actions towards prevention and mitigation of soil erosion problems.

Finally, this TT aims to support the challenge of working and linking different scales, so our goal is not to limit the discussion to the European level but to root the work of the TT in local/regional/national contexts where the problems exist.

This Think Tank aims to identify 3 main types of knowledge gaps:

1. **Knowledge** Gaps in existing Research and Innovation priorities related to soil erosion, inclusive of Social Sciences’ and Humanities’ contributions.
2. **Knowledge Transfer** Gaps: This dimension concentrates on the deficient links between available knowledge and its dissemination to stakeholders and the

broader civil society. We emphasise understanding and addressing the gaps hindering the effective transfer of knowledge to key audiences.

3. **Knowledge Implementation** Gaps: This aspect delves into the challenges linked to the practical application of existing and transferred knowledge. This involves navigating issues such as the adaptation of European-level instruments within national or regional contexts, as well as fragmented advisory services. The emphasis is on exploring obstacles to the actual implementation of knowledge in the real-world.

To provide concrete examples of the identified Knowledge gaps, text boxes have been added along the document.

To comprehensively grasp and systematise the three identified types of knowledge gaps, our Think Tank has strategically incorporated three distinct categories of experts:

- Soil-Related Scientists:

Experts in this category bring specialised knowledge in soil-related sciences. Their expertise is crucial for discerning gaps within existing Research and Innovation priorities related to soil erosion which also includes Social Sciences' and Humanities' insights.

- Practitioners:

The inclusion of practitioners is vital for a grounded perspective on the knowledge implementation gaps. These experts bring first-hand experience and practical insights, shedding light on challenges faced during the actual application of existing and transferred knowledge.

- Implementation and Integration Scientists:

This group focuses on the practical aspects of knowledge integration (Hoffmann et al. 2022). Their role is pivotal in bridging the diversity of knowledge types by identifying and addressing the missing links. Moreover, they contribute with insights into overcoming challenges associated with the implementation of knowledge in diverse contexts.

These groups worked in an iterative way to prepare the second version of this live document. Aware that we have failed to involve all necessary experts and to systematise all the available and ongoing effort related to soil erosion, we are eager to receive your revision so that the next version of these documents reflects more accurately and completely the knowledge gaps that need to be tackled in the future Research and Innovation agenda in the EU. We have an important task ahead of us that we take seriously but we are also very aware that we cannot achieve it alone. So, thank you very much for the time you dedicate to the revision of this second version.

State-of-the-Art

Soil erosion is a natural process; however accelerated and important for shaping landforms (Dubey et al. 2023), particularly when it occurs at an unbalanced rate, soil erosion adversely impacts most of the ecosystem services provided by soils, which are the base of the EU soil strategy for the definition of healthy soils (CEC 2006, Beste 2015, EC 2021, Ittner and Naumann 2022). Soil erosion is the detachment and transport of sediments by erosive agents, including rainfall, runoff, wind, tillage and co-extraction on root crops and land-based machinery (Breshears et al. 2003; Panagos et al. 2015, Cerdá et al. 2017; Rickson 2023). Soil is considered a non-renewable resource from the perspective of human lifespan (Di Stefano et al. 2023) and in different settings, related to human interventions into land systems, soil erosion largely surpasses the soil formation rate. While there is no consensus among the scientific community regarding the tolerable rate of soil erosion, it is suggested that the upper limit is around 1.4 t ha^{-1} yr^{-1} (Verheijen et al. 2009). Soil erosion primarily acts on the topsoil, although soil erosion occurring beneath the surface can also occur (e.g., piping and/or subsurface lateral erosion). Soil erosion removes the most valuable fraction of the soil (i.e. organic horizon), which typically contains the highest content of organic matter and nutrients, the most intensive soil life, and possesses the highest capacity to support life (Poesen 2018; Koch et al. 2013; Eekhout and Vente 2022). Therefore, the impact of soil erosion is not only the quantity of removed soil mass, but also the loss of associated soil functions (Lal 2010). Moreover, soil loss can have relevant repercussions in agroecosystems (food and timber production, water regulation, carbon sequestration, nutrient cycling and biodiversity), highlighting the need to increase the inputs to effectively manage agricultural and forestry production (Milazzo et al. 2023). Soil erosion increases the on-site risks of desertification by reducing soil water retention and fertility (O. et al. 2024). This diminishes both potential evapotranspiration and temperature regulation capabilities. Furthermore, eroded soils lose their ability to support life, thus amplifying air temperature increases and ultimately exacerbating climate change.

Soil erosion also accounts for multiple off-site effects (Panagos et al. 2024), such as increasing sediment and nutrient concentrations in water, therefore hindering aquatic life, water quality, or reducing water storage capacity, and increasing water treatment expenditures, as well as the risk of flooding and debris flow during high rainfall and runoff events. It is estimated that sediment accumulation, resulting from soil erosion in the EU's large reservoirs (approximately 5000 in total) exceeds 1 billion m3, with an anticipated cost of ranging from 5 to 8 billion € annually (Panagos et al. 2024a).

The monitoring of soil erosion and its impacts are among the greatest challenges involving erosion studies (Huber et al. 2008). There is a wide variety of soil erosion models (Batista 2019). In essence, both past and recent model applications provide estimates of susceptibility to soil erosion for both natural landscapes, forests and croplands, spanning from at the global scale down to the plot scale, and even incorporating projected climate change scenarios (Borrelli et al. 2023; Vieria et al., 2023). Such a top-down approach, based on consistent methodology, can be very informative. Up to date, the dominant focus in erosion modelling lies on water-induced erosion, accounting for approximately 95% of the studies. Conversely, modelling on wind erosion, tillage and co-extraction on root crops and land-based machinery remains relatively limited (Borrelli et al. 2021). However, models have limitations (Schmaltz et al. 2024), and thus, measured empirical data is essential, as models need validation (Batista et al., 2019) and cannot integrate the complexity of interactions governing the erosion processes, particularly the multi-process modelling approach. Field monitoring capturing high-resolution datasets and conducting thorough long-term periods have been essential to enable models to achieve better calibrations, as well as facilitate effective validations. Moreover, for field studies to be considered suitable in modelling, they must rely on accessible and comparable methodologies. Initiatives such as the EUSEDcollab database (Matthews et al. 2023) may represent a paradigm shift, providing open-access and harmonized catchment data from various European countries, particularly relevant for soil erosion modelling. While such initiatives are scarce, they represent a significant endeavour to leverage inaccessible and potentially unknown data.

Several soil erosion prevention and mitigation measures are recognized, but their adoption among practitioners remains challenging. The effectiveness of these measures depends on the site's specific features such as topography/geomorphology, soil characteristics, climatic conditions, and land management. Nevertheless, the most common practices can be categorized in three broader mechanisms: 1) Providing the soil with a protective cover to avoid direct rain splash and slow down runoff, e.g. planting temporary cover crops, grass, shrubs, and trees, or applying mulch (Girona-García et al., 2021; El-Beltagi et al. 2022); 2) Maintaining or enhancing soil particle stability by adopting no-tillage or reduced tillage practices, or by incorporating organic matter or synthetic amendments and/or industrial by-products (e.g., polyacrylamide, or lignosulfonates) that improve soil structure and resistance to detachment and increase water infiltration (Prats et al. 2014; Vakili et al. 2024); 3) Increasing soil roughness in sloped areas to reduce runoff velocity and enhance water infiltration, e.g., ridge and furrow, contour ploughing, terracing, or vegetative buffer strips (Wei et al. 2016; Mak-Mensah et al. 2022). The use of financial incentives, increased awareness among landowners, participation of innovative farmers and contractors, as well as good advisory and standardized services can revert problematic situations (Prasuhn 2020). Furthermore, education in soil science and ecology is still underrepresented in schools (Charzynski et al. 2022) among practitioners and within the broader society (Cerdà and Rodrigo-Comino 2021). Increasing literacy on soil related issues, particularly by promoting knowledge and awareness of soil erosion challenges, is both desirable and necessary.

Knowledge Gaps

While our current knowledge base is robust, there is a crucial need for a **deeper comprehension of natural and anthropogenic soil erosion processes, and societal impacts, especially focusing on their intricate interactions**, as it is this complexity that determines the real dimensions of the problem (Field et al. 2009, Ravi et al. 2010). Addressing this knowledge gap requires a concentrated effort on interactions operating across diverse spatial and temporal scales, with an emphasis on predicting rates and assessing both onsite and wider off-site impacts, such as socio-economic and cultural impacts.

To comprehensively quantify soil erosion, the assessment must extend beyond merely on-site effects and include the wider repercussions of sediment redistribution. This involves accounting for impacts such as water quality degradation (e.g., turbidity, nutrient and pollutant transport, loss of drinking water quality) and siltation (e.g., reservoirs, lakes, hydropower infrastructure), transcending catchment boundaries, national borders, or even continental scales, as well as its impacts on the weather and atmospheric conditions above the soil surface.

The most recent work by Panagos et al. (2024) on the costs of soil erosion based on sediment removal from water reservoirs is a clear example of the path that science must take to change the paradigm of soil conservation, clearly demonstrating to political and operational decision-makers the costs of their decisions. On an even broader scale, this sediment transport is also fundamental for the stability of coastal areas, and the interruption of the flow through water reservoirs has changed it substantially, leading in many cases to the need for annual replacement of beach sand at enormous costs. **The scale effect in understanding phenomena related to soil erosion, and its implications for multiple ecological processes, must be addressed in the future**.

Furthermore, the **evaluation of soil erosion rates should broaden its scope to encompass a spectrum of erosion processes at various scales – from local to global** (Marzaioli et al. 2010). These include splash, laminar, rill and gully erosion, subsurface erosion (such as piping and tunnelling), wind and/or riverbank erosion. Some human interventions are known to increase soil erosion, such as erosion induced by tillage, land levelling, soil quarrying, termite mound removal, co-extraction on root crops or timber, explosion cratering, and trench digging. There is still a lack of information on the key factors that may trigger soil erosion in each scenario, such as the increase in exposed bare soil but also the increase in soil compaction or a combination of both (Prats et al. 2019). Additionally, the dynamics of factors such as slope gradient and aspect, rainfall and wind intensity, soil type, management practices, and natural events have been individually associated with triggering soil erosion (Poesen et al. 2003; Vieira et al. 2018; Ni et al. 2024). However, **the connectivity of these factors across spatial and temporal scales remains poorly comprehended** (Boix-Fayos et al. 2006; Keesstra et al. 2018b). **Understanding of the interactions of socio-economic and cultural drivers, including policy drivers, leading to tipping points for erosion processes within each scenario is also lacking** (Wynants et al. 2019).

While acknowledging soil erosion's relevance, we currently lack a comprehensive understanding of its role in other critical processes, such as carbon budgeting, transport and fate of contaminants, nutrient loss, climate change and biodiversity (Obalum et al. 2017). It is imperative **to quantitatively, as well as qualitatively, represent the losses of ecosystem services following soil erosion and concurrently occurring soil degradation processes** (Krull et al. 2004; Keesstra et al. 2018a; Jacob et al. 2021). In addition, soil erosion and degradation processes are not experienced equitably across the world. Therefore, **the need of soil erosion risk maps encompassing various types of soil erosion, including potential mitigations and restoration measures, is indispensable for anticipating when and where soil erosion might occur at unsustainable rates** (Parente et al. 2022). Nevertheless, the creation of such maps is either lacking or not uniformly conducted on a standardized and comprehensive scale across Europe. This could greatly benefit decision-makers, not only in identifying vulnerable areas but also in assessing the effectiveness of different mitigation/restoration techniques (Vieira et al. 2023). Soil erosion disproportionately affects vulnerable populations in the most fragile ecosystems, with impacts on health, nutrition, and development opportunities (FAO, 2020; Murage et al. 2024). **Potential solutions to build resilience and prevent soil erosion, including Nature-based solutions (NbS), are being promoted and implemented in many areas but the research evidence to underpin understanding of the potential benefits and to identify context-specific trade-offs has not kept pace.** Qualitative understanding of the trade-offs and benefits considering the wider and dynamic critical process noted above is urgently needed. In this line of thought, **there is a gap in developing tools that seamlessly integrate the aforementioned soil erosion risk maps and potential mitigation or restoration solutions combined with economic and ecological effectiveness analyses**.

Special attention is required in the unique pedo-climatic zones of Europe, necessitating urgent establishment of long-term experimental sites to enhance our understanding of the dimension of soil erosion processes. For example, in arid and semi-arid regions, the analysis of soil erosion demands an expanded perspective, considering triggers related to wind, water, and other non-quantified factors like tillage, crop, and irrigation management.

The effects and trade-offs of land management practices, water management (including irrigation and drainage), and climate change (including greenhouse gas emissions) remain inadequately understood. The emerging relevance of Nature-based solutions to soil conservation poses new challenges to scientists and practitioners, but also reveals relevant knowledge gaps, particularly regarding the effect of soil bioengineering techniques on soil erosion, including the bio-geo-technical properties and the functional traits of plant roots. **Despite the recent efforts on these topics (e.g., Fernandes and Guiomar 2016; Guerrero-Ramírez et al. 2021), current knowledge remains incipient on the effect of these approaches on reducing the erosive potential of rain or wind in different biophysical contexts, especially in drylands.** The need to strengthen knowledge about the effect that other ecological processes have on soil erosion and sediment transport is equally critical. Among these processes, fire is of particular importance, considering the changes observed globally in its regime. Scientific production in this topic has some shortcomings resulting from the lack of collaboration between soil and fire scientists. In fire prone ecosystems/regions, it is counterproductive to compare sample plots in burned and unburned patches. **Comparing soil erosion rates among different types of fires (pastoral, prescribed, wildfires) or along soil burn severity gradients is an increasingly urgent need. Furthermore, results should not be**

disconnected from burning conditions and fire behaviour. Prescribed fires are not always carried out in compliance with the recommended prescriptions (which depends on the objective to be achieved, e.g., fuel load reduction, invasive species control, habitat management), and the results are easily interpreted as a function of the technique itself, and not the decision-making process taken by practitioners in its application. This pathway is critical for the paradigm shift needed in fire management policy and practice (see Moreira et al. 2020). Current knowledge is incomplete and leads to interpretations that increase decision-makers' resistance to fire use (pastoral and prescribed) and to the regulation of management fires (unplanned ignitions that spread under typical conditions for prescribed fires, and that can be managed to reduce fuel load instead of being suppressed immediately).

Bridging these gaps requires comprehensive monitoring data in association with local context-specific socio-economic and cultural knowledge, which is currently the primary knowledge deficit in the soil erosion field. **Establishing a Soil Erosion Monitoring Network at the EU level, incorporating local-scale monitoring and knowledge exchange systems involving local environmental knowledge and citizen science activities is essential** to address this gap (Prats et al. 2022). Integrating multiple scales is paramount for improving future soil erosion assessments.

Investing in more field campaigns and developing platforms that encourage collaboration and data sharing is also imperative. The collected data could facilitate real-scale estimations of soil losses and their correlation with contextual information, such as management practices, land use, soil and ecosystem types, and rainfall regimes. **Aligning monitoring efforts with appropriate spatio-temporal scales is crucial for identifying specific erosion processes occurring at different scales** (Herrick et al. 2016).

Exploring the potential of artificial intelligence and remote sensing is strategic for gaining a more nuanced understanding of soil erosion processes, enhancing data collection systems, and improving modelling capabilities.

Calibration and validation of existing models are required, emphasising the compilation and analysis of data at a meta level. Data mining on existing soil erosion and sediment yield data is necessary to enhance the accuracy of modelling tools. Although current modelling capacity allows consideration of the effects of management practices (such as gully and tillage) and geomorphic processes (such as land sliding and riverbank erosion), **there is a lack of data for the quantification of these effects.** Models also need to be linked to the consequences of soil erosion, especially within the context of climate change (Keesstra et al., 2018b; Borrelli et al., 2023). Furthermore, such efforts on data collection will make it possible to understand patterns associated with overestimations and underestimations and evaluate the existence of factors associated with the errors' dispersion and propagation (e.g., soil types, climate). Still regarding the use of models, it is important to understand the relative effect of the input data on the final result (e.g., the application of [R]USLE depends on a set of metrics, including the LS factor, that implies user choices, from the DEM to the calculation method). Existing erosion models demonstrate improved accuracy when supported by precise auxiliary input parameters such as climate, DEM, soil, vegetation characteristics, among others (Batista et al., 2019; Lopes et al. 2021; Vieira et al., 2023). **Consequently, there is a need to invest effort into constructing high-resolution databases at the EU scale based on local data.**

Finally, recognizing the pivotal role of policy, as well as soil erosion literacy in local decision-making processes, **it is imperative to identify trade-offs between policies and to test strategies to mitigate them** (Petratou et al. 2023). Currently, we have policies that indirectly induce soil erosion while achieving benefits in other dimensions; such trade-offs need to be properly understood and alternative policy designs tested with those directly affected (Kelly et al. 2020; Rodríguez Sousa et al. 2023). This policy matter, combined with a constant lack of perception of soil erosion impacts often leads to the global underestimation of soil erosion as a major problem.

Knowledge Transfer Gaps

While soil erosion control measures (such as the use of cover crops, adoption of reduced or no tillage techniques or contour cropping) already exist, an effective strategy requires systematically organising these measures to fit the specific local environmental and livelihood situations where soil erosion is a problem. T**o ensure sustainable soil use, there is a pressing need to assess and develop current and innovative soil erosion prevention techniques and field strategies with practitioners and those who can act.** Prioritising the utilisation of Nature-based solutions, evidence-led, locally appropriate and targeting soil erosion hotspots and off-site effects should be a primary focus.

Promising results have emerged from testing **soil erosion techniques after fires** (e.g., mulching techniques); however, **transferring this knowledge requires careful consideration as its effectiveness and widespread dissemination have been limited** (Girona-García et al. 2021; Petratou et al., 2023).

Example:

Galicia (NW Spain) is a successful example of post-fire management in EU on what concerns the mitigation of soil erosion impacts. Their operational emergency stabilization targets off-site impacts of runoff and erosion after fire, preventing additional economical losses downstream the burned area (e.g. infrastructures, bivalve mariculture). So far, this is the only region that implemented an operational strategy to tackle post-fire soil erosion, despite the significant extension of annual burned areas in EU.

Urgent steps must be taken to **increase awareness of soil erosion and the potential threats it poses**. Society needs to be more cognizant of the current situation, facts, threats, and the preventive measures required (Chicas et al. 2016; Prats et al., 2022). **Developing a comprehensive guide on the importance of soil, the risks associated with soil erosion, impacts on life on Earth and ecosystem services is essential** (Dazzi and Lo Papa 2022). This guide can serve as a valuable tool for raising awareness and educating individuals, starting from primary school. However, it must be able to address all generations and education levels in society. Concrete and enlightening examples should be used, to create a real impact on the target audience. Involving citizen science activities may help in the recognition of the real scale of the problem and in raising awareness in wider society. Soil erosion prediction scenarios should provide information on the magnitude of consequences, including off-site effects and subsequent risk assessment (Panagos et al. 2020; Parente et al., 2022; Parente et al. 2023). **Developing "risk maps" as policy tools to indicate hotspots requiring immediate action is crucial and should be prioritised for swift development**. Their development must be accompanied by a sound delimitation methodology, as well as by effective norms regarding authorised land use and its monitoring.

Example:

In Portugal, the creation of the National Ecological Reserve (REN) in 1983 has, in an innovative approach, contemplated "abandoned areas due to marked surface erosion". Currently, REN integrates, within the framework of public utility restrictions and territorial management instruments, ecological systems that play a determining role in the functioning of ecosystems. The areas to be included in the REN have land use restrictions that vary depending on the criteria that determined their delimitation. Among these criteria are areas at high risk of soil water erosion. The latest revisions to the legislation in 2019 and 2020, and, in particular, the strategic guidelines, determine that the delimitation of areas at high risk of soil water erosion must be based on the identification of potential soil erosion, through the application of the Revised Universal Loss Equation (RUSLE), which considers the following factors: precipitation erosivity (R), soil erodibility (K) and topography (LS). The Strategic Guidelines indicate the data and methods to be used to map these factors. The threshold above which areas must be part of the REN was established at 25 tons/ha/year. However, the methodology to define their boundaries is non-consensual, and, furthermore, there's a need for effective regulatory guidelines that tackle not only the authorised land use types in these areas, but also their control. The delimitation of the REN is carried out at the municipal level, and there are some constraints that hinder the desired articulation between municipalities, such as the absence of a soil dataset on the same scale for all territories of mainland Portugal. Conceptual inconsistencies were also identified. For example, factors related to land cover and land management were not considered since the objective is to estimate potential soil erosion, but the guidelines to compute LS requires the integration of road networks as a factor in interrupting surface runoff. There is still a gap regarding the method to be followed to generalise the result of applying the RUSLE, since the dispersion of isolated pixels makes the decision-maker's action difficult. Lastly, the criteria that established the soil erosion threshold is not clear, particularly in the geographic context in which it is applied.

Knowledge Implementation Gaps

Effective implementation of knowledge is crucial in preventing soil erosion, and a key aspect of this is **planning monitoring systems in a cost-effective manner**. Only smart and cost-effective systems are likely to endure in the future (Petratou et al., 2023).

While monitoring systems and modelling tools play a pivotal role in supporting and enhancing decision-making processes, **it is equally essential to engage with managers and landowners while co-developing tools that can support (or influence) their decision making.** Understanding their motivations during land management is critical, and collaborative approaches and governance mechanisms need to be developed jointly (EC et al. 2020; Briassoulis, 2011).

The interaction between researchers and practitioners should be approached with a sense of responsibility. **Allocating resources to experts and expertise on integration becomes crucial to secure conditions for collective actions that benefit all parties involved**.

Negative effects arising from **trade-offs between policy instruments** are apparent, particularly in specific land uses such as agriculture, forestry, and agroforestry systems, leading to increased soil erosion. **Urgent measures are needed to mitigate these negative trade-offs**.

The Common Agricultural Policy (CAP), a key policy instrument, has caused many of these challenges. Testing innovative models is imperative. **Results-based models within CAP where soil health becomes a measurable result, and supported by payment when deliverabled, should be tested** (Guimarães et al. 2023). This system needs significant changes in traditional policies, including a focus on achieving results related to ecosystem services, payment for ecosystem services (specifically for preventing soil erosion), and the establishment of a supporting system for knowledge exchange among producers, public administrators, and researchers.

Another model involves **setting benchmarks for soil health**, **where soil health objectives and indicators cut across various policy instruments**. This approach aims to provide a unified framework for addressing soil health across different sectors and policy domains.

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