SOLO
Soils for Europe 1: e150281
doi: 10.3897/soils4europe.e150281

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Scoping document

Outlook on the knowledge gaps to reduce soil erosion

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Funded by the European Union

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OPEN ACCESS

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Outlook on the knowledge gaps to reduce soil erosion

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Academic editor: Carlos Guerra

Received: 14 Feb 2025 | Accepted: 01 Jul 2025 | Published: 19 Sep 2025

Citation: Guimarães H, Martins M, Guiomar N, Kelly C, Vieira D, Nóvoa T, Brito I, Zoka M, Prats S, Cerdà A, Zdruli P, Stathopoulos N, Madeira J, Fidalgo L, Di Giuseppe P, Keesstra S, Dobos E (2025) Outlook on the knowledge gaps to reduce soil erosion. Soils for Europe 1: e150281.
https://doi.org/10.3897/soils4europe.e150281

Introduction

SOLO project aims to deliver actionable transdisciplinary roadmaps for future soil-related research and innovation activities in the EU, contributing to 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 specific objectives established by the EU Mission Soil Deal for Europe.

Within the Soil Erosion TT, this outlook focuses on the Soil Mission objective 5, “Prevent erosion”, which seeks to reduce “the area of land currently affected by unsustainable erosion from 25% to sustainable levels” (European Commission 2021). Evidence presented in the Soil Mission document, indicates that the majority of the land affected by unsustainable erosion rates is found in agricultural systems, where the severity is higher compared to other systems (European Commission 2021). Within agricultural areas, according to the EC (European Commission 2021), permanent crops are the most affected, and notable erosion rates were identified in the non-agricultural cover types of shrubland and sparse vegetation. Based on the evidence gathered, the EC (European Commission 2021) concludes that “land failing soil health indicators due to soil erosion equals 23% in cropland and 30% in non-agricultural areas”. According to the Soil Mission, these figures call for urgent action, based on contextual knowledge of both soils and human activity, in order to halt or reverse the erosion process.

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

Knowledge on soil erosion is dispersed and fragmented, requiring a TT to integrate various sources of knowledge, not only by systematizing it but also by exploring its interactions. At first, we focused on this integration and systemic approach around the prevention of soil erosion. Currently, we have extended this effort considering the interactions between TTs and priorities.

Aligned with the Soil Mission strategy, we engaged non-academic stakeholders in the identification of solutions to the problem of soil erosion and its prevention and mitigation. Hence, the TT serves as 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 across and linking different scales. Our goal is not to confine the discussion to the European level but to root the work of the TT in local/regional/national contexts where the problems arise. The SOLO TTs have identified 2 main types of knowledge gaps (KGs):

1. **Knowledge Development Gap**: a knowledge gap that requires generating new information or understanding by research or innovation, inclusive of both natural and social sciences and humanities' contributions.
2. **Knowledge Application Gap**: a knowledge gap that requires research or innovation to find and test new mechanisms that allow the effective implementation of already existing information or understanding. This knowledge gap hence concentrates on the deficient links between available knowledge and its application.

Note that these two concepts, Knowledge Development Gap and Knowledge Application Gap, are central in the entire project and, therefore, key concepts in the development and outcomes of the SOLO project. To support the identification, integration and prioritization process, our TT has strategically incorporated three distinct categories of experts:

- Soil-Related Scientists:

Experts in this category bring specialized 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. Producers, advisors, civil society organisations and policy makers are considered in this category. 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.

Collectively, the above category of expert worked in an iterative way to prepare this outlook document. Based on previous work (see the 2024 Scoping Document by a large team: Guimarães et al. 2024), the current outlook describes the prioritization process for the 24 KGs previously identified while providing further arguments about priorities. Aware that we have not yet involved all necessary experts or fully systematized the available and ongoing efforts related to soil erosion, we appreciate the time and effort to revise the current version. We are confident that your contribution will enhance this document, ensuring a more accurate reflection of the knowledge gaps that need to be addressed in the future EU Research and Innovation agenda.

State-of-the-Art

Current state of the knowledge on Soil Erosion

Soil erosion is a natural process important for shaping landforms (Dubey et al. 2023). However, when it occurs at rates that exceed soil formation, it adversely impacts most of the ecosystem services provided by soils, which are the basis of the EU soil strategy for defining healthy soils (European Commission 2006; European Commission 2021; Beste 2015; 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; Cerdà 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 a range between 0.3 and 1.4 t ha^{-1} yr^{-1}, based on soil formation rates (Verheijen et al. 2009). Soil erosion primarily acts on the topsoil and can range from sheet and rill erosion to gully erosion, which extends into deeper soil layers. It can also impact the subsurface through processes such as piping and/or lateral subsurface 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 de 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 may increase the on-site desertification risk through two mechanisms: by reducing soil water retention capacity and by reducing soil fertility, which is driven by soil organic carbon losses (González-Pelayo et al. 2024). This diminishes both evapotranspiration and temperature regulation capabilities. Furthermore, eroded soils lose their ability to support life, thus amplifying air temperature increases and indirectly exacerbating climate change. Soil erosion can also create deep and fertile soils in deltas and fluvial terraces under natural or geological soil erosion rates. However, an accelerated soil erosion rate can contribute to the degradation of the soils developed in lowlands as a consequence of the excessive sedimentation. This watershed and basin scale process can be found also at field and slope scale when soil erosion is accelerated as a consequence of tillage such as the increase in connectivity of sediments and water (Rodrigo Comino et al. 2018).

Soil erosion also accounts for multiple off-site effects (Panagos et al. 2024b), such as increasing sediment, nutrient and pollutant 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 m^3, with an anticipated cost of ranging from 5 to 8 billion € annually (Panagos et al. 2024a). Fig. 1 exemplifies soil erosion effects.

Figure 1. doi

Social, economic and environmental impacts of soil erosion

The monitoring of soil erosion and its impacts are among the greatest challenges involving erosion studies (Huber et al. 2009). Besides field monitoring, there is a wide variety of soil erosion models (Batista et al. 2019; Karydas et al. 2015; Zdruli et al. 2016) making use of diverse spatio-temporal scales (Borrelli et al. 2021). In essence, both past and recent model applications provide estimates of susceptibility to soil erosion for natural landscapes, forests and croplands, spanning from the global scale down to the plot scale, and even incorporating projected climate change scenarios (Borrelli et al. 2023; Borrelli et al. 2022; Vieira et al. 2025). 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). While modeling efforts have advanced, it is important to recognize that models have limitations (Schmaltz and Johannsen 2024), and thus, measured empirical data is essential, as models need validation (Batista et al. 2019) and cannot integrate the complexity of interactions governing all 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 (Alexiou et al. 2023). 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 endeavor to leverage inaccessible and potentially unknown data (Panagos et al. 2022).

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 aligned with the contour, 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 contribute to solving problematic situations (Prasuhn 2020). Furthermore, education in soil science and ecology remains critically underrepresented across multiple levels - from school curricula to professional practitioners and broader society, including citizens, policymakers and even technical experts (Charzyński et al. 2022;Cerdà and Rodrigo-Comino 2021; Katikas et al. 2024; Petratou et al. 2023; CURIOSOIL 2024). Increasing soil literacy, with particular emphasis on soil erosion, represents both an urgent and valuable opportunity for sustainable land management and healthier soils.

Missing knowledge concerning Erosion Prevention is primarily centered on the need for data and evidence on natural processes; and knowledge application gaps that encompass socio-cultural and economic barriers and challenges, as well as governance, society and cultural barriers. Consequently, our Think Tank has necessarily adopted an interdisciplinary and systems thinking approach to address the issue at hand. From this effort, a total of 24 knowledge gaps (Suppl. material 1, Table 2, see supplementary files) were identified and detailed in Guimarães et al. 2024. In the next section, we present the top 10 knowledge gaps. They were ranked through a prioritization exercise conducted over the past few months by SOLO partners and and members of all Think Tanks.

Knowledge Gaps

Prioritization of knowledge gaps

Fig. 2 illustrates the structure and organization of the Think Tank in addressing various knowledge gaps, beginning with those related to the drivers of soil erosion. This outlook then delves into the details of the soil erosion process and its quantification, progressing toward an understanding of its impacts. Building on this, the analysis explores knowledge gaps concerning actions for prevention, mitigation, and recovery, while also examining the costs and benefits of proactive and reactive approaches.

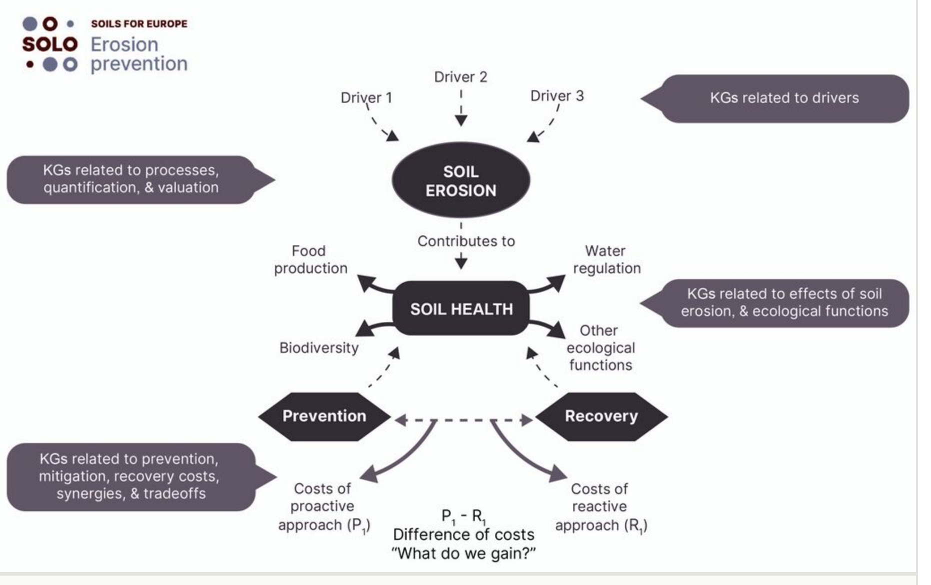

Figure 2. doi

Think Tank's approach to the identification of Knowledge Gaps (developed by the authors)

Table 1 presents the top 10 knowledge gaps identified. In the following section, we focus on the top three gaps, providing arguments for their importance and prioritization. The two primary knowledge gaps selected highlight the need for a co-construction approach that transcends disciplinary collaboration, emphasizing a transdisciplinary effort that actively involves practitioners. It is important to note that this selection does not diminish the critical value of the remaining knowledge gaps identified, as all are important. Our prioritization is justified by two main arguments: first, adopting a transdisciplinary approach can accelerate the generation and application of knowledge along an urgent pathway to mitigate soil erosion. Second, developing effective techniques and tools to support practical applications requires high-quality data and the parallel fostering of robust disciplinary and interdisciplinary collaboration. It is also important to highlight that many of the knowledge gaps identified imply the interaction between researchers and practitioners. The quality of this interaction is paramount and should be approached with a sense of responsibility and respect towards the social relationships that are created. As such, we also take the opportunity to highlight the importance of allocating resources to experts and expertise on integration (Hoffmann et al. 2022) to secure the conditions for collective actions that benefit all parties involved.

Table 1.

Ranking of the top 10 knowledge gaps identified by the Prevention of Soil Erosion Think Tank

Rank	Knowledge gap	Type of knowledge gap
1	Co-construction of soil erosion prevention techniques and field strategies with practitioners	Knowledge Application Gap
2	Co-developing tools that can support managers' and landowners' decision making	Knowledge Application Gap
3	Representation of ecosystem services' losses following soil erosion	Knowledge Development Gap
4	Soil erosion risk maps	Knowledge Application Gap
5	Interactions between natural and anthropogenic soil erosion processes, and societal impacts	Knowledge Development Gap
6	Establishing a Soil Erosion Monitoring Network at the EU level, including long-term experimental sites	Knowledge Development Gap
7	Raise awareness about soil erosion and its impacts	Knowledge Application Gap
8	Setting benchmarks for soil health	Knowledge Development Gap
9	Scientific evidence of potential benefits and context-specific trade-offs of Nature-based solutions	Knowledge Development Gap
10	Soil erosion rates inclusive of erosion processes at various scales	Knowledge Development Gap

Roadmap

Key knowledge gaps

- **1st Key Knowledge Gap: There is a need to co-construct soil erosion prevention techniques and field strategies with practitioners**

To ensure sustainable soil use, there is a pressing need to assess and further develop both current and innovative soil erosion prevention techniques and field strategies in collaboration with practitioners and those in a position to act. While soil erosion control measures — such as cover crops, reduced or no-tillage techniques, and contour cropping — are already available, an effective strategy requires systematically tailoring and integrating these measures to fit the specific local environmental and livelihood contexts where soil erosion is a concern. In this regard, regenerative agriculture (along with conservation agriculture), which comprises farming principles and practices that prioritize soil health, biodiversity, and the resilience of natural ecosystems, holds significant potential. Regenerative agriculture looks to restore soil health through the reinvigoration of the natural interactions between plants, animals and organisms on which crop growth relies (Kearnes and Rickards 2020), and to reduce inputs of agricultural pesticides and fertilizers. Using regenerative techniques can significantly benefit soils at risk of erosion by maintaining vegetation cover during Winter, promoting deeper-rooting and more diverse plant species. Combined with the support to reduced tillage, these practices enhance crop quality while stabilizing and improving soil microbial and invertebrate health.

A primary focus should be on implementing evidence-led, locally appropriate Nature-based Solutions (NbS) or soil-improving cropping systems (Oenema et al. 2018), which specifically target soil erosion hotspots and their off-site effects (e.g., cover crops, contour traffic, minimum tillage). To effectively reduce soil loss, NbS must be clearly classified, and existing projects should be identified, characterized, and assessed (e.g., Rodrigo-Comino et al. 2019; Cerdà et al. 2022). This initial diagnosis is critical for identifying contexts (geographical, land use, and NbS types) that are not yet covered by any or a particular type of NbS but are relevant to increase evidence of their effectiveness in reducing soil erosion (e.g., Olinic et al. 2024). It is important to establish monitoring protocols to assess ongoing NbS projects and practices, as well as those that may be implemented in the future, based on a system of Key Performance Indicators that allows for the assessment of the quality of technical application, benefits and trade-offs, and costs (e.g., Gonzalez-Ollauri et al. 2021). Such an assessment will also highlight front-runners, that is, all NbS initiatives that are likely to stand out as examples that can be replicated in similar socio-ecological contexts. However, the effectiveness and out-scaling of NbS and, consequently, the achievement of objectives aimed at soil conservation, will only be realized if the key-stakeholders actively participate in the co-construction of those solutions, thus owning them and fully understanding the benefits resulting from their application. Participatory monitoring and assessment of impacts are critical to enable social learning and speed up the implementation of effective disturbance-smart and regenerative land use and NbS targeted to reduce soil erosion (e.g., Luján Soto et al. 2021).

Polyakov et al. (2023) highlights the importance of collaborative approaches to collect accurate, spatially distributed data on soil erosion, which is essential for co-developing effective prevention techniques tailored to local conditions. Similarly, Lima et al. (2017) underline the value of iterative design and practical application in soil erosion prevention, emphasizing the need for co-construction with practitioners to ensure strategies are workable, effective, and context specific. The ongoing demand for data validation (Polyakov et al. 2023) further highlights the critical role of practitioners in ensuring that soil erosion prevention measures are grounded in the complexities of real-world applications. However, such data remains scarce and difficult to obtain (Wang et al. 2024), not least because of the time and resources needed for key actors to participate and contribute with data, and often requires a stepwise approach to ensure systematic collection and integration. While we can suggest conservative and regenerative measures, without dedicated demonstration sites and financial support for practitioners, acceptance may remain limited. To address this issue, Soil Mission Lighthouses serve as an important interface and demonstration platform, showcasing the best management practices to prevent soil erosion under local conditions. This fosters knowledge exchange between scientists, policymakers, and land users, building trust and encouraging the adoption of innovative soil protection measures. Furthermore, productivity and financial support guarantees are essential for farmers, foresters, and other land managers to take the risk of implementing alternative measures instead of conventional ones. Within the framework of Soil Mission Lighthouses and their inherently transdisciplinary nature, establishing a strong governance structure is essential. This requires partnerships that include not only researchers and practitioners but also implementation and integration experts who are responsible for ensuring integration and overseeing the process (Hoffmann et al. 2022).

Lastly, data scarcity and the recurring arguments justifying information gaps are not new. Initiatives such as EUSEDcollab, an open-access database which compiles data on runoff, soil loss by water erosion and sediment delivery (Matthews et al. 2023), are positive and should be continually supported, but gaps in data representativeness persist, leading to datasets that do not adequately represent the wide range of geographical, environmental, and land management contexts where soil erosion occurs. Overcoming these issues requires testing new measurement approaches through the integration of remote sensing-based innovation and technology that allows for upscaled estimates (e.g., Manić et al. 2022; Alexiou et al. 2023;Alexiou et al. 2024). This integration must be done step by step: from field-based measurements to terrestrial scanning (e.g., Terrestrial Laser Scanning, t-LiDAR), from these to aircraft systems (equipped with high-resolution LiDAR, Radar, and hyperspectral sensors), and finally from aircraft systems to satellite imagery.

- **2nd Key Knowledge Gap: There is a need to co-develop tools that can support managers' and landowners' decision making**

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 (Panagos et al. 2020a; Briassoulis 2011). For instance, Debeljak et al. (2019) designed a decision support system to assist land managers in assessing and improving soil functions, demonstrating how such tools can be co-developed to align with practical needs. Similarly, Terribile et al. (2024) highlights how co-designed decision support systems can empower stakeholders to protect soils and land, emphasizing the role of innovative tools in facilitating decision-making for erosion prevention. Borrelli et al. (2023) showed the importance of tools that integrate complex datasets to support managers in mitigating soil erosion risks effectively, whereas a multi-model approach had a critical role in identifying erosion hotspots globally, thus providing significant data for policymakers and land managers. Stankovics et al. (2024) demonstrated the

LANDSUPPORT project which developed a geospatial Decision Support System (DSS) through a collaborative approach with policy stakeholders. This system integrates data across multiple scales — local, regional, national, and European Union levels — to assist in sustainable land management and soil protection. The co-design process involved extensive user engagement, including semi-structured interviews and questionnaires, ensuring the DSS met the practical needs of its users. In line with this, the EU SoilCare project developed an interactive mapping tool that spatially visualises where in Europe soil-improving cropping systems (SICS) can be most effectively applied (SoilCare 2025). Additionally, the ongoing TERRASAFE project (2024–2029) is building tools to map desertification hotspots in Southern Europe and North Africa through a multi-actor, co-designed approach with local communities (TERRASAFE 2025).

This engagement of end users (land managers and landowners) not only ensures the integration of their management and response needs into the tools available to practitioners, but also stimulates an architecture and configuration that promote their widespread use. These decision support tools and systems serve as an interface between scientific knowledge and practitioners, and as such, they must be easy to access and use. The joint effort of land managers, researchers and technological developers could lead to the design of tools that blend practical experience with cutting-edge technology, such as digital mapping systems, decision-support systems, or predictive models for sustainable land management. Additionally, such tools must be flexible enough to evolve continually and enhance decisions by integrating new knowledge. Therefore, by maintaining a collaborative relationship, feedback loops can be established where tools are continually tested and improved. This ensures that tools remain relevant and effective even in the face of changing environmental, economic, and regulatory conditions. Given the existence of tools already co-developed, it would be valuable to test them with a broader range of end users beyond those involved in their design in order to reach higher maturity levels.

However, soil erosion problems can also be associated with a lack of knowledge, understanding and/or appreciation of the importance of healthy soils for all aspects of human life, amongst other things (Johnson et al. 2020; Katikas et al. 2024). This lack of knowledge or understanding, referred to as ‘soil illiteracy’ is not always associated with those ‘on the ground’, although food producers, farmers, land managers and society, in general, can sometimes lack such knowledge. Indeed, although there are several drivers for unsustainable soil management practices, low levels of soil literacy is one of them. All too often, though, the lack of soil literacy extends upwards to those making decisions about land use, and land use changes, and further upwards still to those making policies. There is clearly an urgent need to build skills and knowledge in recognizing and assessing soil health related to specific local contexts and soil types, and to build an appreciation in wider society of the importance of understanding the role that soil health - and good soil management - play in securing food production, land use, and multiple other ecosystem services without which our society would be at risk of collapse (Johnson et al. 2024;Brevik et al. 2019). Given how interconnected soil health is with various economic sectors, cultural values and processes at different scales, it is equally important to acknowledge the need for systemic, transformative change towards a more sustainable paradigm (Gosnell et al. 2019; McLennon et al. 2021).

- **3rd Key Knowledge Gap: Representation of ecosystem services' losses following soil erosion**

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 (Yang et al. 2025; Vieira et al. 2024; Silva et al. 2015), metals (Campos et al. 2016), nutrient loss (Prats et al. 2023), climate change and biodiversity (Obalum et al. 2017; European Environment Agency et al. 2024). Soil is the most biodiverse ecosystem on the globe, home to more than half of all known species, and several interacting ecological processes are dependent from this compositional and functional diversity (Anthony et al. 2023). Soil erosion and diversity maintain a mutual relationship that must be integrated in soil erosion prediction models (Orgiazzi and Panagos 2018). Soil erosion has also been identified as a disruptor of the carbon cycle, reducing soil organic carbon storage and increasing greenhouse gas emissions (Zheng et al. 2025).

However, a broader representation of these losses - both on- and off-site - is missing, hindering a complete understanding of the environmental impacts of erosion. 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). The links between soil erosion and the resulting declines in agroecosystem conditions remain poorly understood. In particular, erosion-induced losses and their direct consequences, such as the diminished ability of ecosystems to provide essential services like crop production and water regulation, should be effectively quantified and integrated into sustainability frameworks (Rendon et al. 2020; Steinhoff-Knopp et al. 2021). Establishing and quantifying the relationships between soil erosion and other ecosystem services will allow the optimization of soil management solutions that contribute to maximize positive effects at the lowest cost.

Moreover, quantifying and, particularly, valuing the effects of soil erosion on other ecosystem services is of paramount importance, as it makes the assessment of the benefits more comprehensive and effective, and increases the ability to measure and implement synergies between human activities and soil ecosystem services (Fernandes et al. 2019; Petratou et al. 2023). For example, Pires-Marques et al. (2021) estimated the avoided costs of soil erosion in a mountainous region of northern Portugal at €1,144/ha/year using an indirect market valuation method. To implement effective trade-off mechanisms in planning and management, it is crucial not only to consider formal objectives but also to develop a functional contractual system and fair incentive mechanisms. These incentives must be attractive enough to discourage unsustainable land use (Fernandes et al. 2019), such as payments for ecosystem services, market-driven instruments, habitat banking, biodiversity offsetting, Tax Increment Financing, tax incentives, and subsidies. Learning from CAP implementation, it is also important that incentive requirements are ambitious (both at EU and Member State level), and that, in complex incentive schemes, assessing the results of measures that specifically address sustainable soil management is promoted (European Court of Auditors 2023).

Prioritized knowledge gaps

- **Soil erosion risk maps**

Soil erosion and degradation processes are not experienced equitably across the world. Therefore, the need for soil erosion risk maps to encompass 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. Current challenges are exacerbated by the variability in methodologies, which complicates meaningful comparisons and hinders effective policy applications. Integrating sediment connectivity modelling can significantly enhance the accuracy of soil erosion risk maps, especially when supported by validation with empirical data (Schmaltz and Johannsen 2024). Furthermore, recent advancements in Artificial Intelligence and machine learning models have the potential to significantly enhance the accuracy and adaptability of soil erosion risk maps. However, despite these technological developments, their application in soil erosion modeling remains largely unexplored. Samarinas et al. (2024) demonstrated that integrating high-resolution geospatial layers into the RUSLE model enables AI-based approaches to generate soil erodibility maps at a 10m resolution, surpassing the limitations of previous modeling assessments. These maps 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). In the European context, such tools are essential for pinpointing regions with the highest erosion risk. Soil erosion disproportionately affects vulnerable populations in the most fragile ecosystems, with impacts on health, nutrition, and development opportunities (FAO 2019; Murage et al. 2024). 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 is crucial and should be prioritized for swift action, since even large scale maps can identify hotspots requiring local investigation, which in turn can trigger action in areas with higher need for sustainable management. Their development must be accompanied by a sound delimitation methodology, as well as by effective norms regarding authorized land use and its monitoring.

- **Interactions between natural and anthropogenic soil erosion processes, and societal impacts**

While our current knowledge base is robust, there is a crucial need for a deeper comprehension of natural and anthropogenic soil erosion processes, and the societal drivers and 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). Soil health is a critical driver of the economic potential of the food production sector and, through that, inevitably impacts on the social and cultural health of agricultural communities and society in general (Davis et al. 2023). 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. In addition, climate change-induced shifts in rainfall patterns, land use, and population distribution are altering erosion dynamics. Therefore, it is essential to integrate socio-environmental drivers into soil erosion assessments. Lagacherie et al. (2018) highlighted that Mediterranean soils are particularly vulnerable to the cascading effects of drought, torrential rainfall, wildfires and changing land-use practices. Likewise, urbanization and soil sealing increase surface runoff, leading to heightened sediment transport in peri-urban areas. This underscores the need for interdisciplinary research that links soil erosion processes with societal impacts. Therefore, the above-mentioned risk maps should not only focus on the physical and environmental aspects of soil erosion but also integrate socio-economic data to identify regions where the impacts of erosion are likely to impose adversities for communities.

- **Establishing a Soil Erosion Monitoring Network at the EU level, including long-term experimental sites**

Bridging the identified gaps requires comprehensive monitoring data combined with local context-specific socio-economic and cultural knowledge, which is currently one of the primary knowledge deficits 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). Borrelli et al. (2016) identified deforestation, logging, and wildfires as key accelerators of soil erosion in Mediterranean forests. However, the absence of a standardized, long-term monitoring network limits the ability to accurately quantify their cumulative impacts, particularly those related to cover changes, land abandonment, and agricultural intensification. Integrating multiple scales is paramount for improving future soil erosion assessments, as well as for validating and improving soil erosion models. Special attention is required in the unique pedo-climatic zones of Europe, necessitating the 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, where low vegetation cover, soil crusting, and irregular precipitation patterns prevail, soil erosion is often the result of multiple interacting drivers, including wind, water, and other less-quantified factors like tillage, crop, and irrigation management, whose combined effects are particularly severe and still insufficiently quantified (García Ruiz et al. 2013; Boardman et al. 2019).

- **Raise awareness about soil erosion and its impacts**

Soil erosion poses a significant threat to ecosystems, economies, and human well-being. Steps must be taken urgently to increase public awareness of its consequences and the necessary preventive measures (Chicas et al. 2016; Prats et al. 2022). Society needs a deeper understanding of the current situation, the risks involved, and the actions required to prevent soil erosion.

One effective approach is the development of a comprehensive guide that highlights the importance of soil, the risks associated with erosion, its impacts on life and ecosystem services, and the resulting economic implications (Dazzi and Lo Papa 2022, Moscatelli and Marinari 2024). Such a guide could serve as an educational tool, starting from primary school but extending to all generations and education levels. To maximize its impact, it should incorporate concrete and relatable examples that resonate with diverse audiences. Additionally, engaging citizens in science-based activities can enhance recognition of the true scale of the issue and foster broader societal awareness.

Beyond traditional educational methods, innovative communication strategies are needed to build a shared understanding of soil challenges. Moscatelli and Marinari 2024 emphasize the importance of soil security (Montanarella and Panagos 2021) and propose using alternative communication tools beyond scientific language. They highlight the growing role of art in the era of image-based communication as a means to promote a widespread "soil culture." In addressing knowledge gaps, Thorsøe et al. (2023) analyzed the perceptions of over 1,000 individuals and review more than 1,800 documents from the European Joint Program on Agricultural Soils. Their findings suggest that closing these gaps requires a multifaceted approach, including (1) raising awareness, (2) strengthening knowledge brokers, (3) ensuring research activities and resources are relevant to land users, (4) fostering peer-to-peer communication, (5) delivering targeted advice and information, (6) improving knowledge accessibility, and (7) providing incentives.

By integrating these strategies — education, innovative communication, and knowledge-sharing mechanisms — society can develop a more informed and proactive approach to soil management, ensuring the protection of this vital resource for future generations.

- **Setting benchmarks for soil health**

One approach to improving soil health governance involves setting benchmarks that establish clear objectives and indicators across various policy instruments (Schram et al. 2024). This method aims to create a unified framework for addressing soil health across multiple sectors, ensuring consistency and coherence in policy development and implementation.

A key aspect of this approach is providing land managers with benchmarking tools that, where needed, can enhance their knowledge of the often-unseen processes and properties that contribute to soil health. These tools can support informed management decisions across different land uses (Feeney et al. 2023; Jenkins 2006; Lobry de Bruyn 2019). However, for these tools to be effective, they must be practical, require little effort, and be capable of delivering timely and accurate information. Developing such benchmarking systems is a complex challenge, as they must also account for regional variations and changes over time (Feeney et al. 2023).

In reaction to Feeney et al.'s (2023) proposal for soil health benchmarks in managed and semi-natural landscapes, Hollis et al. 2025 highlight the complexity of this task. They emphasize the need for close collaboration between institutions responsible for collecting and maintaining national soil data. Robust benchmarks require coordinated efforts to ensure they effectively inform discussions on soil health indicators and policy pathways. If designed well, these benchmarks could help reduce policy conflicts and support the development of cohesive strategies for soil health management.

- **Scientific evidence of potential benefits and context-specific trade-offs of Nature-based solutions and other approaches**

This knowledge gap is linked to the most important knowledge gap described before. There are increasing efforts to resolve problems of soil erosion and soil health caused by human activities. In farming for instance, NbS and regenerative agriculture techniques are being promoted and implemented in many areas. However, research evidence to support a deeper understanding of the potential benefits and to identify context-specific trade-offs has not kept pace. A meta-analysis on Mediterranean agroecosystems (Rodrigues et al. 2024) shows that NbS can enhance soil health and water quality, with afforestation significantly increasing soil organic carbon and conservation tillage noticeably reducing soil erosion. A qualitative understanding of the trade-offs and benefits, considering the broader, evolving context of environmental, social, and economic decision-making 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. Cerdà et al. (2022) determined a reduction in soil erosion in the plot where catch crops were applied between the rows of citrus orchards, from 3.9 to 0.04 Mg ha^{-1} h^{-1}). However, to be viable, farmers considered that this nature-based alternative had to be subsidized by a minimum amount of €131.17 ha^{-1}. Soil bioengineering techniques have also proven effective in slope and riverbank stabilization (e.g., Tisserant et al. 2021; Batista et al. 2024), and consequently in reducing soil erosion, with clear benefits for biodiversity (Cavaillé et al. 2015; Tisserant et al. 2021). However, its application is slow to become widespread due to a lack of qualified technicians, more evidence on its effectiveness in other contexts, and robust cost-benefit analyses (Bariteau et al. 2013; Pinto et al. 2016; Moreau et al. 2022), despite the most recent developments made in the ECOMED project financed under the ERASMUS+ programme.

- **Soil erosion rates inclusive of erosion processes at various scales**

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 rain splash, laminar, rill and gully erosion, subsurface erosion (such as piping and tunnelling, Boulet et al. 2015), wind and/or riverbank erosion (Prats et al. 2019). Soil erosion rates can vary by an order of magnitude depending on the spatial scale of the measurement (watershed<hillslopes<plot<point scale) and on the methodology employed (e.g., erosion pins, runoff tanks, sediment fences) (de Vente et al. 2013; Wagenbrenner and Robichaud 2014; Prats et al. 2016). The high variability in soil

erosion upscaling stems from soil management, and also from methodological constraints - certain techniques can only detect erosion at specific scales (Prats et al. 2014) - creating substantial challenges for cross-contextual model calibration across different landscape contexts (Faria et al. 2025). A multi-scale approach that combines field-scale erosion data with high-resolution techniques (e.g., close-range photogrammetry) can enhance our understanding of sediment connectivity across different scales (Nicosia et al. 2024). Some human interventions are known to increase soil erosion, such as erosion induced by tillage, vegetation removal with herbicide, levelling, soil quarrying, termite mound removal, co-extraction on root crops or timber and explosion cratering (Borrelli et al. 2021; Rodríguez Sousa et al. 2023). There is still lack of information on the key factors that may trigger soil erosion in each specific field condition, 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 variability 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 interaction 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).

Overview

Overview table

Table 2: The total number of knowledge gaps identified and details about each one (see Suppl. material 1)

Acknowledgements

Special thanks to all Think Tank members for their patience and valuable contributions.

This work was partially funded by National Funds through FCT – Foundation for Science and Technology under the Project UIDB/05183 and CHANGE (https://doi.org/10.54499/LA/P/0121/2020).

We extend our sincere appreciation to those who generously participated in the face-to-face meeting in Bulgaria. The insights gained through discussions and collaborative dynamics within and among Think Tanks and other consortium partners were invaluable.

Feedback from the reviewers who contributed to both revision phases is also highly appreciated. Thank you for enriching our work.

Finally, we thank Monica Farfan and PENSOFT for their assistance with the figures.

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Supplementary material

Suppl. material 1: Table 2 doi

Authors: The list of authors
Data type: The total number of knowledge gaps identified and details about each one
Brief description: Table 2: The total number of knowledge gaps identified and details about each one.
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